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Mars and the Earthlings: A Realistic View on Mars Exploration and Settlement



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Kirsi Lehto • Michel Viso
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To future generations.
We were silly, don't be stupid.

Foreword

Years ago, 1980 to be precise, I had the good fortune to be a graduate student involved in field work at high elevation in the Dry Valleys of Antarctica. From a human experience these are the most Mars-like places on Earth. As I hiked up and down these frozen desert valleys my mind would often turn to the results of the Viking missions to Mars just a few years earlier. Could there really be life in places as cold and dry as Mars? Could humans really go there? And could they stay? Viking and Antarctica forever changed my academic focus from theoretical astrophysics to the search for life on Mars and future human exploration. That same year I first came to NASA Ames as a summer intern and Ames has been my intellectual home ever since.

Over the past decades NASA and other space agencies have flown numerous missions to Mars. The scientific results fill volumes. Yet, the question of life remains open, and more missions are planned. And, of course, Mars remains the pre-eminent destination for human exploration. Now with serious talk of private missions and permanent human settlement. It seems we are not content with being earthlings, we aspire to be marslings as well.

We will practice on the Moon, but arguably Mars is the first big step for humans beyond the Earth. Will we go or will we stay? What will we take with us? Life? Civilization? The good or bad? Clearly our approach to Mars must begin with a careful scientific assessment of that planet. An assessment that must cover many disciplines from rocket science to rock science and most importantly astrobiology. And then we must add to the mix the social and political sciences that will be needed when more than just three humans are included. This is the book.

This book brings together a wide group of researchers from across the whole range of science, social science, and political science disciplines that bear on the question of our possible futures on Mars: from near-term robotic missions to the establishment of large human populations altering the red planet trying to make it another “blue marble”. Reading this book is a journey through this inspiring vision of what Mars might become; what earthlings might make of it.

At the core of this book I see the question of life on Mars and how it divides into three parts: The first part is the question of life on Mars in the past. If there was life,

is it still to be found there? And if so is it from a second genesis—a separate origin of life? From both the scientific and philosophical perspective this would be an extraordinary discovery. Another independent example of life would literally double the number of biology systems we can learn from. Perhaps deep insights into life will emerge with implications for medicine and ecology and all things biological. Philosophically advancing the number of known life forms in the universe from one to two is profound and predicts the discovery of diverse and numerous life forms on exoplanets.

As reviewed in this book there has been a lot of consideration on how and where to search for evidence of life, past or present, on Mars and how to determine if that life shares a common origin with life on Earth or represents a second genesis. The possibility that life on Mars and life on Earth share a common origin is not unlikely—we now know that meteorites are exchanged between these two planets and that microorganisms inside such an interplanetary transporter could have survived that trip and the landing. If we find life on Mars, the determination that it is or is not a second genesis will have fundamental implications on what we do on Mars. This is not rocket science, it is much more important—it is ethics. And we will have one chance to do this right.

The second part of the life question is human life. Everyone is assuming that humans, and the animals and plants we depend on for life support, will be fine with the 1/3 g on Mars. We know that 1 g is fine and 0 g is not. We have a few days experience at 1/6 g from the Apollo missions. But there is really no data to support the widespread optimism that we'll be fine at 1/3 g. The only way to know is to go.

The third part of the life question is the future. The future is where things are the most interesting because the future is determined by our actions—within the limits of what is possible. To me the fascinating question about the future on Mars is terraforming. The question of whether we can, and if we can of whether we should, create conditions on Mars that support a rich and diverse global biosphere. Not a second Earth, not a "Planet B", but another world with life. Looking back from the perspective of some distant future this might be the first entry in the collective resume of spaceship Earth and its crew—us Earthlings.

NASA Ames Research Center
Moffett Field, CA, USA

Christopher McKay,

Preface

Reclaiming Martian Dreams

Exploring Mars used to be a rather uncontroversial aspiration. One could dream without a second thought of walking on pristine red dust, standing on the slopes of Mount Olympus, or indulging in nostalgic memories of loved ones far away while watching a dust devil cross a barren landscape. Those who wonder about the history of our solar system, or about the uniqueness of terrestrial life, could simply long for extraordinary scientific findings. Granted, others, more pragmatic, may have called such yearning fanciful and, pointing out the lack of economic value, dismissed it as a waste of time. But beyond a bit of condescension, there was little to oppose those who hoped that humans would one day walk on Mars.

This has changed. Over the past decade, as human landings on the red planet have approached the reach of technology, this dream has been tainted. On one side, questionable statements have been made with undue confidence: that Mars will soon be colonised by the millions, be turned into a planet where one can enjoy a stroll in a shirt, or even be used as a fallback plan should the Earth be destroyed by humanity's excesses. Some, dazzled by the pace of technological progress and by a belief that this pace will keep accelerating, are inclined to believe them. On the other side, impassioned sceptics and those appalled by ethical ramifications often oppose with visceral reactions to the naivety—or dishonesty—of those who claim that we are on the verge of colonising Mars. Carried by their momentum, they also oppose the idea of even setting foot there. The simple mention of a desire to visit Mars to decipher its geological and—perhaps—biological records is often met with hostility. Part of this is fair criticism: now that pragmatic decisions must be made, it is essential to determine which among Mars-related goals are worthy. However, excesses in this direction are dangerous as well, in that they might deprive us of extraordinary discoveries and most inspiring endeavours.

Exploring, settling, colonising and terraforming differ in both their feasibility and their consequences. This point may be illustrated by an analogy with Antarctica. Claiming that we should establish large cities on this continent would be seen as

preposterous; warming it up to replace ice with fields would appear criminal; but few would despise Scott for the expeditions he led in the early twentieth century or request the dismantlement of Antarctic stations which have a low impact on the local environment. In the case of Mars, these projects tend to be assimilated. Regaining the right to advocate for exploration missions, in the name of science and perhaps of adventure, requires addressing other motives as well; and showing where they differ. It requires sorting well-informed claims from those which are naive and projects which are worthwhile from those which would be disastrous. The present book was born from a desire to do so.

We intend it to provide researchers with an objective review of the field, policy-makers with a reference to make informed decisions, and the public with a basis to form educated opinions. As the topic is highly multifaceted, reaching our goal required gathering experts from a wide range of disciplines. Authors, therefore, include astronomers, planetary scientists, geologists, legal experts, biologists, philosophers, economists, astronauts and science-fiction writers. As the loudest claims usually come from the other side of the Atlantic, we opted for a European perspective.

Authors and editors brought passionate opinions and, admittedly, preconceived ideas about what conclusions should be reached. But efforts were made to listen to both sides, and to those who did not take sides. The process led to debates, sometimes heated; but we eventually found common ground and helped each other take an objective look. This book is the outcome.

It opens with a description of Mars, based on current knowledge: its geological history, the conditions at its surface and, should we land there, the challenges and resources these conditions will provide. The robotic missions which have generated this knowledge are outlined. Potential crewed missions are then addressed sequentially, from a short visit to the Martian orbit or surface, to the establishment of research stations and then of settlements, to the use of Mars as a new home for part of humanity. Each scenario is scrutinised from multiple perspectives—technological, economical, legal, ethical, medical—to help assess both what could be done and what would be worthy of doing. The last chapter deals with science-fiction. In a scholarly book, this may come as a surprise. Yet one cannot fully explain the passion and subjectivity displayed by usually rational communities, or the perception of Mars missions by the public, without accounting for the influence of fiction.

The answers we provide are not definitive: aspirations, context and technologies will evolve. We do hope, however, that they will support healthy discussions and sensible decision-making.

Bremen, Germany — Cyprien Verseux
Pessac, France — Muriel Gargaud
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Rosny-sous-Bois, France — Michel Viso

Without the curiosity of the mind, what would we be? This is the beauty and nobility of science: an endless desire to push the boundaries of knowledge, to track down the secrets of matter and life without preconceived ideas of possible consequences.

—Maria Curie-Skłodowska
Nobel Prize (1903)
Nobel Prize (1911)

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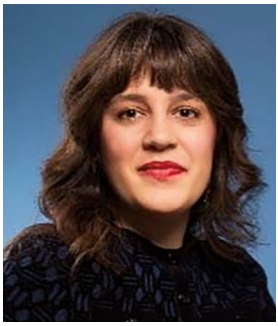


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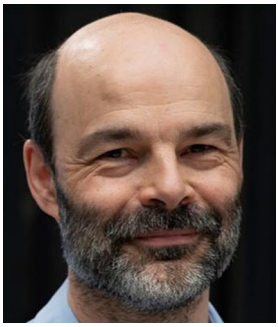
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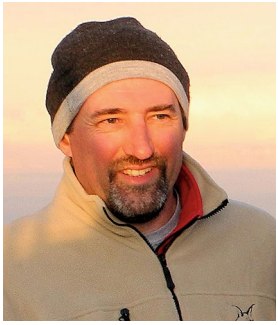
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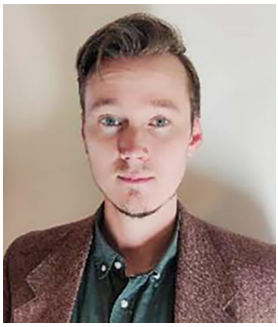
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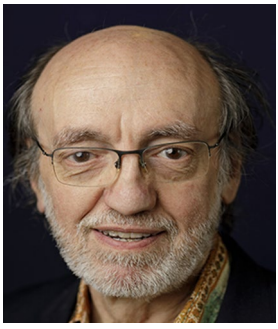
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Abbreviations

ACS	Atmospheric chemistry suite
AES	Air evaporation system
AI	Artificial intelligence
ARED	Advanced resistive exercise device
atm	Terrestrial atmosphere pressure at sea level (1013 mbar)
CaSSiS	Colour and stereo surface imaging system
CCF	Concentric crater fills
CCP	Chemical combustion propulsion
CFM	Cryogenic fluid management
CHAPEA	Crew health and performance exploration analog
CheMin	Chemistry and mineralogy
CLPS	Commercial lunar payload services
CME	Coronal mass ejections
CMSA	China Manned Space Agency
CNSA	Chinese National Space Agency
COPUOS	Committee on the Peaceful Uses of Outer Space
COSPAR	Committee on Space Research
CRISM	Compact reconnaissance imaging spectrometer for Mars
CROP	Combined regenerative organic food production
CSM	Command and service module
CSTM	Core sample transport mechanism
DC	Direct current
DNA	Deoxy ribo nucleic acid
DRA	Design reference architecture
DST	Deep space transport
EDL	Entry, descent, and landing
ESA	European Space Agency
ETEF	Ethylene tetrafluoroethylene
EU	European Union
EVA	Extra vehicular activity
FY	Fiscal year

GC/MS	Gas chromatography/mass spectrometry
GCR	Galactic cosmic radiation
GDP	Gross domestic product
GDRT	Gaseous dust removal tool
GEX	Gas exchange experiment
GHG	Greenhouse gas
Gyr	Giga years (1,000,000,000 years), i.e., billion years
H-CLVs	Heavy commercial launch vehicles
HCP	High-calcium pyroxenes
HEPA	High-efficiency particulate absorbing
HERMES	Heliophysics environmental and radiation measurement experiment suite
HERRO	Human exploration using real-time robotic operations mission
Hi-SEAS	Hawaii space exploration analog and simulation
HLS	Human landing system
HP^3	Heat flow and physical properties package
IBMP	Russian Institute for Biomedical Problems
IGO	Intergovernmental Organisation
I-MIM	International Mars ice mapper
ISE	Ion specific electrodes
ISECG	International Space Exploration Coordination Group
ISRO	Indian Space Research Organisation
ISRU	In situ resource utilisation
ISS	International Space Station
JPL	Jet Propulsion Laboratory
K	Kelvin (zero K = –273.15 °C)
kWe	Kilowatt electric
kyr	Kilo year (1000 years), i.e., thousand years
LCD	Liquid cristal display
LCH_4	Liquide methane
LDA	Lobate debris aprons
LED	Light emitting diode
LEO	Low earth orbit
LH_2	Liquid hydrogen
LIBS	Laser-induced breakdown spectroscopy
LOX	Liquid oxygen
LTV	Lunar terrain vehicle
M2M	Machine-to-machine
MADV	Mars ascent/descent vehicle
Ma-Miss	Multispectral imager for subsurface studies
MARSIS	Mars advanced radar for subsurface and ionosphere sounding
MAV	Mars ascent vehicle
MAWG	Mars Architecture Working Group
MBC	Mars base camp
MDS	Mars descent systems

MDV	Mars descent vehicle
MEDA	Mars environmental dynamics analyzer
MELiSSA	Micro-ecological life support system alternative
MIP	Meteorology instrument package
MMR	Mars Millennium Project
MOC	Mars observer camera
MOLA	Mars observer laser altimeter
MOMA	Mars organic molecule analyzer
MPa	Megapascal (1,000,000 Pa)
MRI	Magnetic resonance imaging
MRI	Mars Risk Index
MSolo	Mass spectrometer observing Lunar operations
MSR	Mars sample return
MTAS	Mars Transportation Assessment Study
Myr	Mega years (1,000,000 years), i.e. million years
NASA	National Aeronautics and Space Administration
NEP	Nuclear electric propulsion
NGO	Non-Governmental Organisation
NOMAD	Nadir and occultation for Mars discovery
NRHO	Near rectilinear halo orbit
NSS	Neutron spectrometer system
NTP	Nuclear thermal propulsion
NWA 7533/7034	Northwest Africa 7533/7034
OMEGA	Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité
OST	Outer Space Treaty
PADS	Powder acquisition drill system
PFS	Planetary Fourier spectrometer
PPP	Planetary protection policy
PPP	Public–private partnership
PPPM	Public–private partnership for Mars
PR	Pyrolytic release
pyr-GC/MS	Pyrolysis-gas chromatography/mass spectrometry
R&D	Research and development
RAT	Rock abrasion tool
REM	Rapid eye movement
REMS	Rover Environmental Monitoring Station
RIMFAX	Radar imager for Mars' subsurface experiment
ROS	Reactive oxygen species
RSL	Recurrent slope lineae
SAM	Sample analysis at Mars
SAM-EGA	Sample analysis at Mars-evolved gas analyzer
SANS	Spaceflight-associated neuro-ocular syndrome
SAP	Subsurface access point
SEIS	Seismic experiment for interior structure
SEP	Solar electric propulsion

SEP	Solar energetic particles
SF	Science fiction
SH-CLV	Super heavy commercial launch vehicle
SLS	Space launch system
SOEC	Solid oxide electrolysis cells
SSA	Space situational awareness
SST	Space surveillance and tracking
STM	Space traffic management
TCCS	Trace contaminant control system
TES	Thermal emission spectrometer
TGO	Trace gas orbiter
TOC	RIMFAX
TRIDENT	The regolith and ice drill for exploring new terrain
UV	Ultraviolet radiation
VCD	Vapour compression distillation
VIPER	Volatiles investigating polar exploration rover
WHO	World Health Organisation
WISDOM	Water ice subsurface deposits observation on Mars
WTO	World Trade Organisation
xEMU	Exploration extravehicular mobility unit

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Chapter 1
Introduction: Seeing Through the Martian Dust



Kirsi Lehto, Muriel Gargaud, Cyprien Verseux, and Michel Viso

Since the 1990s, a variety of public forums—be they peer-reviewed journals, company websites, or the popular press—have featured numerous perspectives on future crewed missions to Mars. These have come from artists, novelists, industrialists, and other professionals. Many have presented their opinions rather vividly.

Space agencies are preparing for such missions. In the 2018 ISEG Global Exploration Roadmap (ISEG is a consortium of space agencies including, for instance, NASA, ESA, Roscosmos, and CNSA), landing humans on Mars is listed as a shared driving goal. The NASA-led Artemis programme, initiated in 2019, not only aims at returning humans to the Moon but also at using the Moon as a stepping stone towards human Mars missions. Europe (through ESA) and other nations (including China, Russia, India, and the United Arab Emirates) have stated their intention to participate in what is taking the shape of a race to Mars.

Private actors are involved as well, with companies such as SpaceX and Boeing. They, too, communicate on their aspirations. Some tend to overpromise: often long-term dreams are presented as short-term plans. Their aesthetic depictions of large

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settlements, or even of a terraformed Mars with oceans and forests, have stimulated the collective imagination. Many may get the impression that humanity will form—in the next few decades—a radically different, multiplanetary civilisation.

Others sense that some among these claims are overly optimistic and opt for general disbelief. After all, ever since humans landed on the Moon, and even before that, plans to set foot on Mars have frequently been announced—a goal which seems to be postponed by a decade every decade. Such scepticism may appear excessive. While this book may long be out of print before ocean waves roll up a Martian shore, the near future may see grandiose milestones in Mars exploration. In fact, the present already does: not yet with humans but already, with robots.

One should consider, beside what can be done, what should be done. Martian cities look fantastic in artistic renderings, and some like the planet in shades of green. It may however be reasonable to examine the downsides. How healthy, for instance, would a child born on Mars be? How ethical is it to dramatically alter the surface of a planet—again, the cynical reader might say—for the sole interest of one species, or perhaps of one generation? Would the perspective of another habitable planet affect our efforts to save the one on which this book was printed? One may, here as well, opt for an unnuanced stand: that of rejecting any plan of setting even one sole on Mars, and that perhaps even robots should keep their wheels on Earth. That would however mean giving up on major scientific discoveries and inspiring expeditions.

When scientists share subjective views, and other experts distorted pictures of reality, how is the layperson to get an educated perspective? One can hardly be surprised that in such a context, debates are virulent and opinions, unnuanced. This must be remediated. Important decisions must be made and for choices to be sound, constructive discussions must be hold. The latter in turn requires unbiased overviews. This book, if it has met its goal, provides one.

It will become apparent to the reader that numerous scientists and engineers have been dedicating themselves to the design, development, and testing of machines and processes necessary for a human journey to Mars, a stay on its surface and a return to Earth. Experts in medicine, physiology, and psychology have been pondering on the physical and mental challenges that the crews would face. Legal experts, economists, and humanists have been crafting a legal and ethical framework. Some problems have been solved. Others persist: the risks posed by ionising radiation, a long exposure to microgravity, partial gravity, and toxic dust, and years spent in tight containment—in a context where an early return is virtually impossible—remain high. It is reasonable to assume that these risks can be mitigated. Space agencies follow a progressive approach where each major step—today's orbital space stations, tomorrow's lunar facilities—helps prepare the next.

It would seem a mistake to take crewed missions to Mars for granted. "The question is not whether, but when", a statement which is heard increasingly often, discounts the unprecedented need for dedication, material resources, and intelligence which must be funnelled onto this goal if it is to be reached. It is, however, not fully devoid of truth: human missions to Mars may indeed take place, and they may do so

in the next few decades. In this book, you will find an overview of what needs to happen beforehand.

The outcome of the first missions will influence the following steps. If early research stations are successful, they may progressively turn into permanent outposts, which may, if Mars's natural resources can be relied on, lead to more complex settlements. One may postulate that these might even, in a distant future, give rise to cities, possibly with their own economic systems and some level of self-governance. Asserting without nuance these steps will be taken would require naivety, but many a great thinker have been embarrassed by the emergence of technologies they had declared impossible.

Several stakeholders have displayed a strong interest in exploiting the commercial and political opportunities a sustained presence on Mars could offer. Activities beyond Earth are regulated by terrestrial rules. International law inscribed in the Outer Space Treaty (OST) adopted in 1967, for instance, which—even though it must evolve to include more specific rules that leave less room for interpretation—formulates principles that must be observed in all space operations. The OST was written and adopted at a time of fierce competition between two conflicting, space-faring nations. Its main goal was to oppose the appropriation and militarisation of outer space. It is now unclear how the state parties, through a deep revision of this treaty, could ensure an outcome that is fair to all, honour its core principles, and ensure the protection of both the terrestrial and Martian environments.

As the scale at which Mars is explored or exploited increases, the questions of what is fair and what is right become more critical. New ethical and societal issues arise when considering communities on Mars which may, progressively, gain some independence from Earth. Virtually no stakeholder would want these communities to be anything but peaceful and blooming. How could this be achieved? What model of governance would ensure safety in this harsh, poor, and restricting environment? What would be the individuals' rights, privileges, and duties there? Would they be able to return to Earth if they had second thoughts? Would it be feasible to raise children there? Would it be ethical? How could settlers comply with planetary protection guidelines? How would the development of Martian communities impact Earth's ecosystems and societies? Variants of these questions have already been faced during periods of colonisation. Answers have not, to put it mildly, always been satisfying. The distance and differences between the Earth and Mars may further complicate the choices to be made. Terraforming Mars, if it becomes possible, would once more raise fundamental questions.

Contributors to the present book come from a large number of fields and hold a diversity of perspectives. They aimed at setting aside their own biases and together painting an objective picture. They hope that their efforts will help the reader form an opinion which is more nuanced and insightful than even, when they started writing, their own.

Chapter 2
Mars in Short: Past and Present Geology and Climate



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Table 2.1 Basic parameters about Mars

Parameter	Facts about Mars
Radius (Equatorial)	≈ 53% of Earth (3396 km vs 6380 km)
Volume	≈ 15% of the Earth
Mass	≈ 11% of the Earth
Surface gravity	≈ 38% of the Earths (3.71 m/s^2 vs 9.81 m/s^2)
Solar day duration (sol)	≈ 24 h 40 min (102% of the Earth)
Solar year duration	≈ 687 days
Solar influx	Between 37% and 50% of the earth
Distance to the Sun (mean)	1.52 times Earth distance to the sun; 230 million km vs 150 million km
Seasons	Twice as long as on the Earth
Moons	Phobos ø≈ 22 km and Deimos ø≈ 12 km
Temperature	From −143 °C to +27 °C
Magnetic field	No global magnetic field
Climate/radiation	Extreme/hazardous

Mars is easily observed in the sky due to its reddish colour and has therefore been the target of inspiration since the early history of mankind. It is the second smallest planet in the Solar System (diameter: ca. 6790 km), and the fourth and farthest terrestrial planet from the Sun (230 million km). Mars differs from Earth regarding several parameters (Table 2.1).

Mars has been exposed to dramatic geological processes throughout its history. Today, the surface of Mars is characterized by extreme contrasts, such as the Martian dichotomy between the northern and the southern hemisphere, huge canyons, and some of the highest volcanoes in the Solar system (Fig. 2.1). The first map of the surface of Mars was drawn in 1840 by Johann Heinrich von Mädler. Since then, many improvements have been made, based on data from space missions to Mars. Now Mars has become the target of what may become one of mankind's most advanced technical and scientific endeavours: the first human mission to another planet in the Solar System. Knowledge about its present and past geology and environment is crucial for this endeavour and our understanding of how Mars was formed, how it developed throughout time, whether a form of life has ever existed on Mars.

2.1 Geological History of Mars

Mars was formed at the same time as the other terrestrial planets in the Solar System, approximately 4.6 billion years ago. Its geological history can be divided into different periods (Fig. 2.2).

Pre-Noachian period (4.5–4.1 billion years-Gyr-ago). Little is known about the first period of Martian history, dating back to the formation of the crust, about

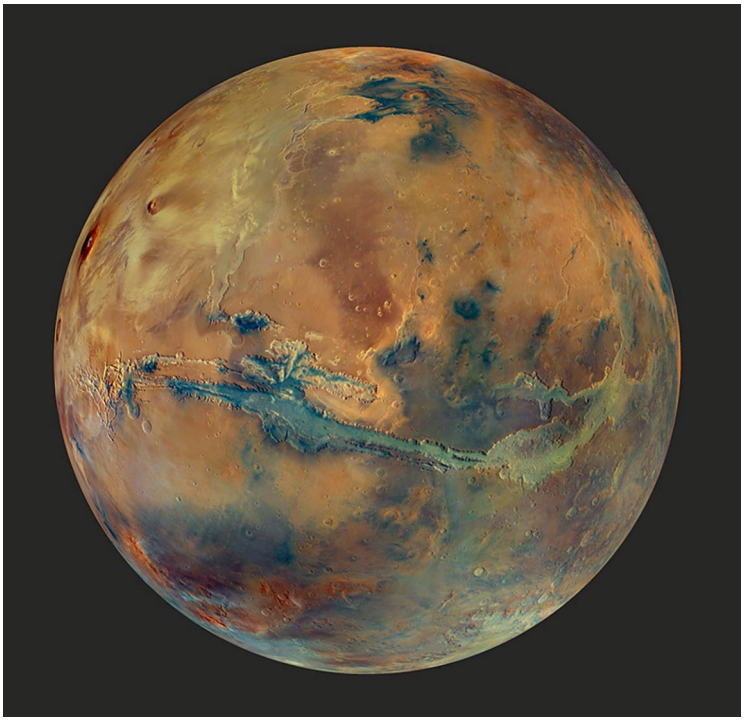


Fig. 2.1 Mars colour mosaic produced by the High-Resolution Stereo Camera team, simulating a view from 2500 km above Valles Marineris, with locally enhanced colour and contrast (Image credit: ESA/DLR/FU Berlin/https://doi.org/10.17169/refubium-40624 and https://doi.org/10.57780/esa-t4y39mj)

4.5 Gyr ago. This period was a chaotic time with an ongoing heavy bombardment and colossal basin-forming impact events, which was then presumably followed by a 400-million-year (Myr) hiatus, until the next bombardment started (Bottke & Andrews-Hanna, 2017; Burt et al., 2008). *In situ* calibration of the cratering-chronology models with cosmogenic and radiogenic isotope ages, obtained by NASA's Curiosity rover, suggests a monotonic flux decay since between 4.45 and 4.24 Gyr (Werner, 2019). During this period, the largest lowlands on Mars, the Vastitas Borealis region, which encircles the northern polar region, were formed. Presumably, Mars had initially a very dense atmosphere, resulting from impacts and mantle outgassing. Large parts of its surface, such as the Noachian Highlands, were covered with water ('NASA Astrobiology', 2023; Rodriguez et al., 2020).

Crucially, however, during this period the Sun shone less brightly than it does today (by approximately 30%). Considering that Mars is further away from our star than the Earth, its atmosphere would have had to provide strong greenhouse forcing for large bodies of water not to have been frozen at their surface. It is nevertheless likely that substantial internal heat would have resulted in a liquid water layer, in contact with the surface, that was capable of flowing and carving channel systems.

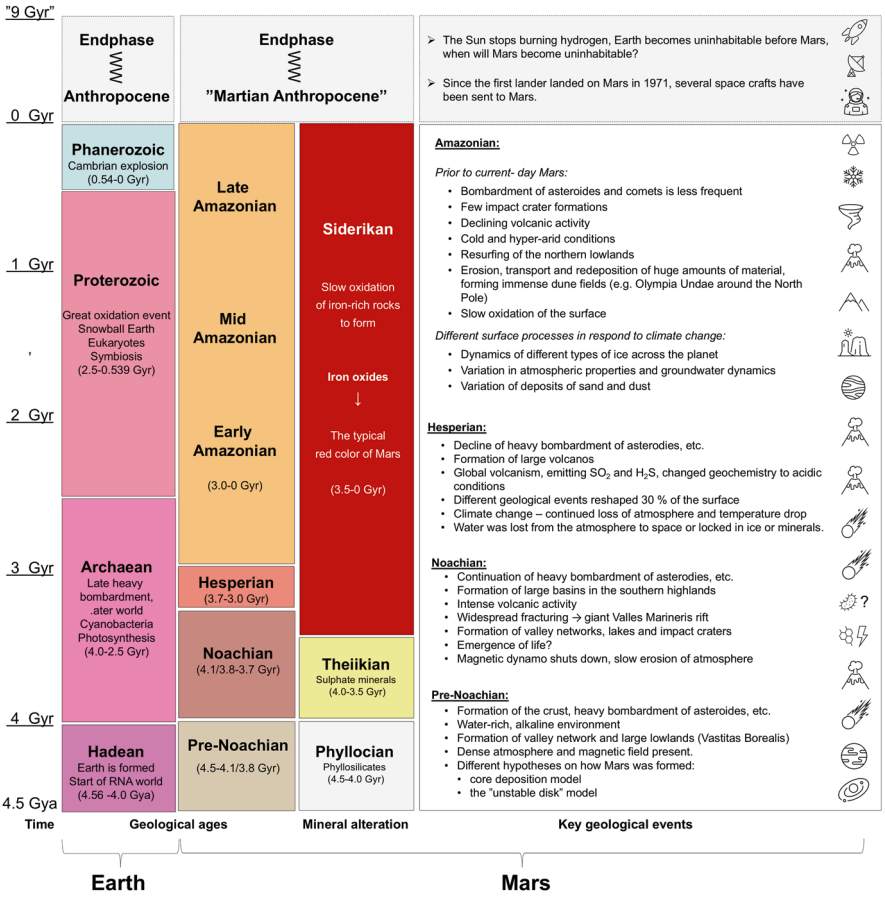


Fig. 2.2 Survey of the geological ages on Mars, based on the classical mineralogical ages based on impact crater rates and predominant type of mineral alteration (Bibring et al., 2006). For comparison, the geological ages for Earth are listed to the left. Original figure by Natuschka Lee

However, early Mars may have been cold and wet, rather than warm and wet. There is also the issue of obliquity cycles. That is, the rapid variation (on geologic time scales) of the planet's rotational axis inclination. This would have had a considerable influence on the shaping of local environments at any time, particularly regarding the possible effects of water on climate and mineralogy. One should bear in mind that over the 400 My span of this water-rich period, Mars would have undergone between 3000 and 4000 such obliquity variations. The same region could have experienced liquid water environments at one moment and 100,000 years later, freezing periglacial conditions. These considerations apply also to the Noachian but perhaps their effect gradually decreased as Mars lost most of its surface water.

The Noachian period (4.1–3.7 Gyr ago) was named after Noachis Terra, a highland region located in the south, between the large Hellas and Argyre impact basins

(Carr & Head, 2010). In this period, the heavy bombardment was intense, shaping the scarred face of the southern highlands and creating the largest impact basins (Argyre, Isidis, and Hellas) one can see today on the surface. Simultaneously, intense volcanic activity took place in many regions of the highlands and in Tharsis. With the built-up of the Tharsis rise, a widespread fracturing took place, and the giant Valles Marineris rift system formed. A warm climate presumably prevailed and precipitations took place. Many dendritic valley networks on the Martian surface date back from this period, as well as lakes in topographic lows and impact craters. A shallow ocean in parts of the northern lowlands may even have existed (Khan et al., 2021). At the end of the Noachian, the planet's interior continued to cool, and the magnetic dynamo shut down (see Sect. 2.2). Furthermore, the slow erosion of Mars's atmosphere began (see further Sect. 2.3).

The Hesperian period (3.7–3.0 Gyr ago) is named after the Hesperia Planum region, a broad lava plain, located northeast of Hellas (Tanaka et al., 2014). During this period, 30% of the Martian surface resurfaced due to a multitude of different geological events. While the impact cratering rate significantly declined with the end of the heavy bombardment, global volcanism continued. Fluid basalts extruded and created the broad highland volcanic features (paterae). In the northern lowlands, enormous volcanic plains developed. Large volcanic edifices developed, such as Tharsis Montes, Arsia Mons, Pavonis Mons, and Ascraeus Mons, which are among the largest volcanoes in the solar system, only surpassed by the younger Olympus Mons which started forming around 3.5 Gyr ago (Fuller & Head, 2002). The extensive degassing of sulphur dioxide and hydrogen sulphide created acidic conditions, which changed the overall geochemistry of Mars. Large sulphate deposits formed, mainly in the wider Meridiani Planum and Vallis Marineris regions. In the Late Hesperian, the atmosphere probably reached its present-day density (Carr & Head, 2010). The formation of valley networks ceased, the temperatures dropped, and most of the water was either lost from the atmosphere to space, trapped in the permafrost or polar caps, or bound in minerals (Carr & Head, 2019). Regional volcanic eruptions, dyke intrusions, and impact events triggered several catastrophic releases from these underground reservoirs and created immense, short-lived flash floods that carved gigantic outflow channels into the surface. The largest of them, for instance, Kasei Valles and Ares Vallis, are found in the Circum-Chryse region and discharged into the Chryse Planitia plains. The Hesperian outflow channels can be spotted in many regions, all over the planet. Collapsed source regions remain with the so-called chaotic terrains, which extend over large areas.

The Amazonian period (3.0 Gyr ago–present) is named after the Amazonis Planitia region of Mars, located in the northern lowlands between the Tharsis and the Elysium volcanic centres (Carr & Head, 2010). This is the longest of the Martian periods. It is characterized by cold and hyper-arid conditions like those observed today. Only occasional and short-lived breakouts to warmer and wetter conditions seem to have occurred, possibly due to impacts, volcanic activity, or changes in the obliquity of Mars (Salese et al., 2016; Wilson et al., 2016). Volcanic eruptions continued with declining eruption rates until very recently (2–5 Myr ago). The Amazonian period is also defined by extensive resurfacing of the northern lowlands.

Wind was a driving factor in remodelling the surface of the broad plains. Erosion, transport, and redeposition of huge amounts of material took place and formed immense dune fields, such as Olympia Undae around the North Pole. Outflow activity still happened in the Chryse region and Amazonis Planitia, but this period has been dominated by glaciation and ice-related surface processes, especially on the flanks of the Tharsis volcanoes, in Hellas and at the dichotomy boundary. As a consequence, the geochemical regime changed towards a slow oxidation of the rocks due to the sparse presence of liquid water (Bibring et al., 2006).

2.2 Mars Geology Today

Current-day Mars is dry and cold (Fig. 2.3). The northern and the southern hemispheres exhibit a sharp contrast, known as the Martian dichotomy, causing an up to 3 km difference in elevation (Watters et al., 2007). The geography and topography of Mars are extreme: the planet harbours the highest mountain, the deepest and longest valley, and some of the largest volcanoes (Olympus Mons, close to three times as high as Mount Everest on Earth) and at least one of the largest canyonlands in the Solar System, making the surface of Mars about three times rougher than Earth's. However, the amount of dry land on Mars is about the same as on Earth (Carr, 2007).

Mars has two permanent large, thick polar ice caps (a large one in the north at Planum Boreum, and a smaller one in the south, at Planum Australe), consisting mainly of water ice and to some extent, depending on the season, of dry ice (solid carbon dioxide) (Foss et al., 2017). The northern plains comprise about one third of the Martian surface and they are flattened by lava flows with few impact craters, while the southern plains (two thirds of the Martian surface, believed to be older than the northern plains) are characterized by highlands and numerous ancient impact craters. A large part of the Martian surface is characterized by igneous rock (tholeiitic) basalt; however, the boundary (the fretted terrain) between the two terrains is generally of unknown composition. The fretted terrain is characterized by a complex mixture of up to 2 km-high cliffs along flat lowlands, lobate debris aprons (rock debris below cliffs), canyons, mesas, buttes, rock-covered glaciers, channels with wide flat floors and steep walls, and deep valleys with lineations with different types of deposits (lineated valley fill, LVF). Mars's surface is dominated by ancient terrains (Noachian and Hesperian) with as much as 50% surface being older than 3.6 Gyr (Neukum & Hiller, 1981).

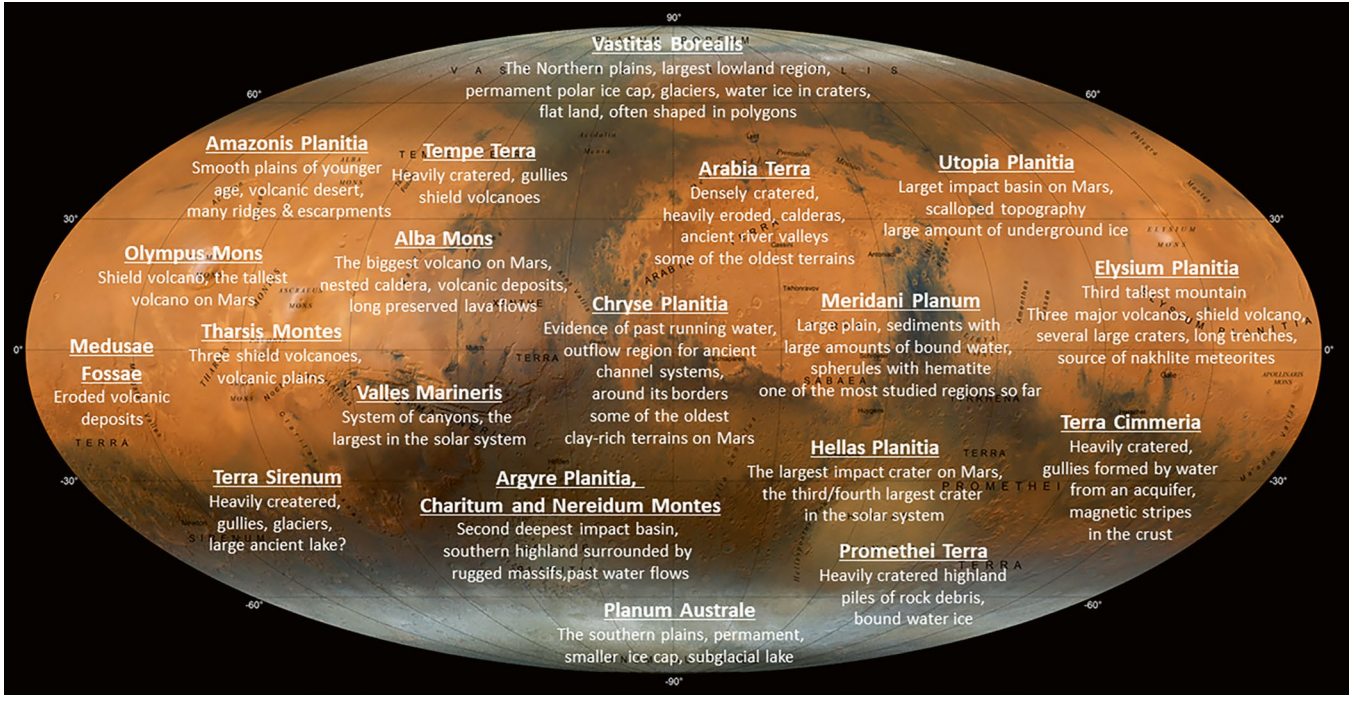


Fig. 2.3 Geological map of Mars today, showing the distribution of a selection of landforms and providing insights into the presence of resources such as frozen water. Original figure composition by Natuschka Lee based on the Mars map background created by the Dr. Dimitra Atri and the New York University Abu Dhabi team (NYUAD), using 2 years of data (>3000 observations) gathered by the Hope probe launched by the United Arab Emirates. Weblink: UAE researchers' Mars map shows Red Planet in striking detail (thenationalnews.com)

2.2.1 Mars Surface and Subsurface Conditions

The surface of Earth is a proxy for its geological history as well as for the evolution of life and the development of multicellular organisms and organized populations such as human civilizations. Today, 95% of the human population, which represents 0.01% of all life on Earth, lives on 10% of the surface of Earth. When considering the settling of humans on Mars, the question is which parts of the Martian surface would be, eventually, suitable for the first attempt. To investigate this concept, we need detailed knowledge on both the surface and the subsurface of the whole of Mars.

2.2.1.1 Current Regolith

Almost all of Mars's surface is covered by a metre-thick, reddish layer of unconsolidated material, typically referred to as regolith (Fig. 2.5) and which often covers the underlying bedrock. The uppermost part of the regolith (10 cm) is referred to as soil and typically consists of grains whose size ranges from dust to pebbles. In contrast to that of the Earth, this soil contains very little organic material. Dust is defined as particles of sizes in the 1–4 μm range.

Larger components of the regolith are derived from local bedrock while smaller components such as soil and dust have regional or even global components. Therefore, the chemistry of larger components will typically be similar to that of the local bedrock while the soil and dust have a very similar chemistry across Mars (Grady et al., 2022) (Fig. 2.4). The most relevant part of the regolith for human exploration is the smaller fraction, including soil and dust, whose size and other characteristics (composition, shape, specific gravity, relative density, cohesion, compressibility, shear strength, and thermal conductivity) make it a hazard for both equipment and humans. The elemental abundance of the soil component is shown in Fig. 2.4 (Grady et al., 2022). It consists of mixed primary igneous minerals (olivine, pyroxene, plagioclase, iron oxides) and altered materials which are partly amorphous (Bish et al., 2013; David et al., 2022; Hausrath et al., 2023). Alteration minerals include clays, iron oxides, and salts such as perchlorates, chlorides, and sulphates (Bish et al., 2013; David et al., 2022; Hausrath et al., 2023; Hecht et al., 2009; Morris et al., 2006; Wang et al., 2020). The Phoenix lander measured ~0.5 wt% of perchlorates and a moderate pH of the regolith of ~7.7 (Hecht et al., 2009). Perchlorates and other salts pose risks to human health and are corrosive to equipment. Experiments performed with Martian soil analogues doped with perchlorates in amounts found in Martian soils showed that this concentration is detrimental to plant growth (Eichler et al., 2021). In addition, nitrates have been detected in Martian dust at concentrations up to hundreds of ppm (Stern et al., 2015). Based on the existence of particle-born life in the atmosphere of Earth (Reche et al., 2018), it has been speculated that the dust could carry microbes (Grady et al., 2022).

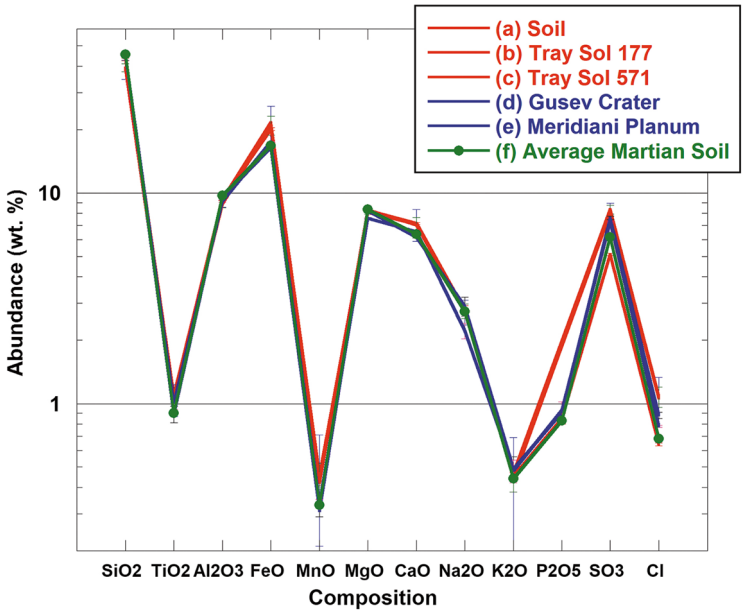


Fig. 2.4 Soil composition across Mars: the diagram shows elemental abundances in form of oxides (reprinted from Grady et al., 2022). Locations (a)-(c) are from Gale Crater



Fig. 2.5 Curiosity's view of Martian regolith and boulders at Dingo Gap (MastCam; February 9, 2014; image transformed to Earth-like atmospheric view). Credit: NASA/JPL-Caltech/MSSS

2.2.1.2 Current Bedrock

The Mars crust has been seen as basaltic since the first Mars missions in the 1960s and 1970s. Orbiters with spectrometers (both near infrared and thermal infrared) have obtained global views of the surface of Mars and showed a predominance of plagioclase and pyroxenes, as expected for basaltic rocks, locally associated with olivine as in the crust of the Nili Fossae region (Bandfield et al., 2000; Mustard et al., 2005). Pyroxenes are present both as low-calcium pyroxene (LCP) such as pigeonite, and high-calcium pyroxenes (HCP) such as augite, but with a distinct proportion between the ancient crust where both pyroxene types are in similar proportion, compared to recent volcanic regions dominated by HCP (Mustard et al., 2005). Gamma-ray spectroscopy was used to map the concentration of several elements such as Si, Cl, K, Fe, and S at a broad scale (>100 km) in the top first metre of the surface (Boynton et al., 2007). This instrument enabled scientists to determine that the crust is significantly richer in Fe (~18 wt% on average) than the mid-ocean ridge basalt on Earth crust (~10 wt%) and contains substantial abundance of sulphur (~6 wt% elemental SO_3). Given the high abundance of iron, the pore-free density of these basalts has been estimated to be ca. 3100–3300 kg/m^3 (Baratoux et al., 2014).

While this first-order view of an iron-rich basaltic planet is still predominant, these results are based on spectroscopic observations (visible infrared, thermal infrared, and gamma-ray spectroscopy) that are only representative of the surface material, leaving unknown a large part of the crust. The last two decades have also provided a lot of new observations that enable us to draw a much more complex picture of the composition of Mars's crust. In particular, felsic rocks including anorthosite and quartz have been detected locally by spectrometers (Carter & Poulet, 2013). Felsic and alkali-rich igneous rocks have been identified on out-of-place blocks and conglomerate clasts analysed by the ChemCam instrument of the Curiosity rover at Gale crater (Mangold et al., 2016; Sautter et al., 2014, 2015; Schmidt et al., 2014). These results have been echoed by the discoveries, in the Moroccan desert, of the Martian meteorite breccia NWA 7034 (paired with NWA 7533 and NWA 7475 of similar origin) that is dated at 4.4 Gyr and contains differentiated rocks with alkali feldspars (Agee et al., 2013; Humayun et al., 2013; Wittmann et al., 2015). The proportion of such more differentiated rocks in the whole Martian crust is still being debated. Phosphate minerals such as apatite (Cl, F), merrillite, and whitlockite have been detected in Martian meteorites (McSween& Treiman, 1998) and on Mars (Corpolongo et al., 2023; Rampe et al., 2017, 2020a, 2020b). Actually, Mars appears quite phosphate-rich, 5–10 times more than Earth (Adcock et al., 2013).

In addition to primary minerals, a huge variety of secondary minerals have been detected by spectrometers and by rovers *in situ*. Hydrous sulphates are present as layered deposits in various regions of the equatorial regions (Gendrin et al., 2005) where the Opportunity rover was able to analyse them in detail (Squyres & Knoll, 2005). Ca- and Mg-sulphates such as gypsum, anhydrite, polyhydrated Mg-sulphates,

and kieserite seem predominant and related to the precipitation of minerals in the presence of water and a sulfur-rich crust (Chipera et al., 2023; Ehlmann & Edwards, 2014; Siljeström et al., 2024; Vaniman et al., 2018). A huge range of clay minerals (phyllosilicates) have been observed in various contexts, including hydrothermal activity, surface weathering, and sedimentary deposits (Carter et al., 2015; Dehouck et al., 2010; Ehlmann et al., 2013; Poulet et al., 2005). While Fe-Mg bearing smectites are predominant spatially, higher-temperature minerals were also observed which include kaolinite, chlorites, talc, serpentine, and prehnite. Hydrogen has been detected by the gamma-ray and neutron spectrometers in the first metre and is bound in minerals and adsorbed water in the near-surface of equatorial regions. In addition, nitrate concentrations up to hundreds of ppm have been detected in mudrocks at Gale Crater (Stern et al., 2015).

Minor elements have been observed by several *in situ* instruments. In Gale crater, copper and zinc have been detected in abundance by the ChemCam instrument, reaching up to 1 wt.% for Cu and 5 wt.% for Zn (Payré et al., 2019). Nevertheless, this is in relation with fracture fills of a few of the outcrops around the location informally named Kimberley, potentially due to localized hydrothermal circulation. Lithium has also been detected by the ChemCam instrument in Gale crater, likely in connection with clay minerals (Frydenvang et al., 2020), but this element is not present in huge abundance (100s of ppm) and could only be observed thanks to the low detection limit of laser ablation spectroscopy. The knowledge of the distribution and abundance of minor elements on Mars is still sparse, limited to the few locations explored by rovers and by their instrument capabilities. Regarding resources available on Mars, Mars displays a diversity of minerals that is close to that of Earth. The mining of useful major elements such as iron or sulphur should be possible, as would the extraction of clays for construction. However, ore deposits on Mars would be limited compared to Earth, because they develop on Earth in relation with plate tectonics, along subduction zones, orogeny, etc., and those ore deposits are the predominant sources of rare earth elements that are of huge importance for the industry, especially for electronic components. On Mars, one can expect impact craters to have created hydrothermal conditions sufficient for ore deposits, but no *in situ* data have shown such deposits and orbital detections within impact craters are still limited to a few common minerals. It is highly uncertain that the minor elements observed locally by rovers could be extracted given their paucity. Lastly, water from hydrated minerals (sulphates and phyllosilicates) is likely to represent the main source of water in the equatorial regions (<25° N and S) where no active glacial landforms have ever been observed.

Most Martian meteorites, which are the only samples of Mars we currently have on Earth, are igneous (no sedimentary ones have been found so far) and almost all of them formed relatively recent (<1 Gyr). The samples (0.5 kg) to be returned from Mars are expected to contain a more diverse mineralogy than Martian meteorites including sedimentary rocks and regolith samples with some dust component (Farley & Stack, 2023; Simon et al., 2023).

2.2.1.3 Organic Content of Bedrock and Regolith

Dust and rocks have been analysed for their organic matter content. When looking today into rocks billions of years old, one of the biggest concerns for the detection of organic matter is the preservation potential of the molecules over geological periods of time, given the harsh radiation conditions and the presence of oxidants such as perchlorates. The ability to detect organic compounds in Martian sedimentary rocks is a function of their initial abundance and entrainment as the rock formed as well as the extent of subsequent degradation during diagenesis, exhumation, and exposure to the surface and near-surface radiation. Their detection then depends on the performance, flexibility, and robustness of operating instruments.

The Sample Analysis at Mars (SAM) instrument onboard the Curiosity rover is an analytical laboratory that has been analysing Martian samples since 2012. Molecules were detected and identified at various locations in Gale crater, by heating up the samples up to 900 °C to release their organic content. The molecules identified were in the form of chlorinated (Freissinet et al., 2015; Szopa et al., 2020) and sulfurized (Eigenbrode et al., 2018) organic compounds up to 300 ppb in weight, long-chain hydrocarbons up to 12 carbons, possibly coming from decarboxylation of long-chain carboxylic acids, and an aromatic acid, benzoic acid. Possible indigenous Martian nitrogen-containing organic molecules have also been detected in sand dunes and rocks of Gale Crater (Millan et al., 2021, 2022). The origins of the molecules detected on Mars so far remain unclear, as they could come either from Martian sources (hydrothermal, igneous, atmospheric, or biological) or exogenous carbon (meteoritic, cometary, or from interplanetary dust particles). More recent findings from the SHERLOC instrument onboard the Mars 2020 Perseverance rover, which currently explores Jezero Crater, include fluorescence and Raman signals that suggest possible one- and two-ring organic molecules (Scheller et al., 2022; Sharma et al., 2023), although inorganic sources such as cerium and defects in silicates can also explain the fluorescence signal (Scheller et al., 2024).

In addition, co-evolving CO and CO_2 in the SAM-EGA (Sample Analysis at Mars-Evolved Gas Analyzer) instrument at the Curiosity rover from samples from the shallow subsurface of Gale Crater at temperatures compatible with oxidation or decarboxylation of organics leads to the conclusion of a higher abundance of organic matter present on Mars (Sutter et al., 2017), up to ppb in weight, possibly ubiquitously on Mars, in the soil and sediments. Certain types of mineralogy favour the long-term preservation of organic matter, such as clays or sulphates. It is no coincidence that the organics-richer sample analysed by Curiosity contained 20% of smectite clay. Samples that have spent most of their time buried and have been only freshly exposed to surface galactic and cosmic rays are also most likely to have preserved organic content.

In situ investigations provide significant progress towards mapping out taphonomic windows of preservation for chemically reduced organic compounds. The ExoMars 2028 Rosalind Franklin rover is designed to enhance the detection, in abundance and diversity, of organic molecules on Mars (Vago et al. 2017). Lessons learned will feed forward to planning of future experiments and increase our ability

to select future landing sites for robotic or crewed mission, in the search for traces of any form of life. In the mid-2030s, samples returned from Mars in the Mars Sample Return (MSR) program would provide the first ground truth of these data, enable the search for other organic molecules that are not detectable by *in situ* instrumentation, and address fundamental questions on the organic material present in Mars's subsurface, as treats or threats for astronauts.

2.2.1.4 Water

The first speculations about the presence of water on Mars were made based on early telescope observations at the end of the eighteenth century, leading to rather spectacular interpretations involving Martian civilizations. As scientific instruments developed, the hypotheses on the presence of water on Mars changed gradually. The first unequivocal detection of water vapour on Mars was not made until 1963. Since then, numerous ground-breaking discoveries have been made around extraterrestrial water. Though Mars appears dry today, if its current known water resources were to melt, they would still cover the surface with an approximately 30 m layer of water (Lasue et al., 2019). Understanding the history and evolution of water on Mars will yield valuable insights into the dynamics of water and how it may influence the geology of different astronomical bodies in the Solar System, as well as how a biosphere could arise or allow Earth-like life to survive.

The history of the water resources on Mars have been perplexingly dynamic, encompassing wet phases, atmospheric exodus, and geologic entrapment of water (Scheller et al., 2021). In the early phase of the Solar System, it has been postulated that the inner planets were too hot to allow water to condense into liquid or ice. Thus, once the inner planets cooled down, new water was delivered to them by asteroids and comets. On Mars, several NASA-ESA missions have shown that water must have been present in large amounts on the Martian surface, up to 100–1000 m global layer of water (GEL), for long periods billions of years ago, and that some of these waters had a significant influence on the Martian surface (Lasue et al., 2019). However, it is believed that Mars has lost large amounts of water throughout its history. The mechanisms behind this loss have not yet been fully resolved, but some plausible hypotheses are that the solar wind stripped away some of the water in the Martian atmosphere and that the remaining parts remained frozen in, for example, the poles. Another possibility is that much of the current water is bound in various minerals such as phyllosilicates, sulphates, opaline silica, and zeolites (Mustard, 2019). It has been proposed that up to 30–99% of Mars's initial water was permanently buried in the crust already by 3 Gyr (Scheller et al., 2021).

Today, surface water ice is only permanently stable in the polar regions. At lower latitudes, it is only found beneath the surface. This is due to the direct relationship between temperature and latitude, which also means that, at locations closer to the equator, ice is buried deeper. The Phoenix lander discovered ice within the top few centimetres of the surface at 68°N (Smith et al., 2009) and fresh impact craters have excavated nearly pure water ice, probably more than 90% by volume, within a metre

of the surface as near to the equator as 43°N (Byrne et al., 2009). Gamma ray and neutron spectroscopy maps revealing water-equivalent hydrogen suggest a widespread ice presence in the mid-to-high latitudes within about 1 m of the surface (Wilson et al., 2018). An ice-rich, latitude-dependent near-surface material varies from a few to tens of metres in thickness in both northern and southern mid-latitudes (Squyres & Carr, 1986). An abundance of glacial features, such as lineated valley fill and concentric crater fill, can be found in numerous regions. Through combined geomorphic and radar analysis, lobate debris aprons have been identified as remnants of nearly pure ice glaciers covered in debris (Holt et al., 2008). Additionally, radar sounding has found subsurface interfaces believed to represent the bottom of massive ice sheets buried in the northern plains region of Arcadia Planitia (Bramson et al., 2015) and Utopia Planitia (Stuurman et al., 2016). Scarps near the latitudes of 55° display thick, massive ice and seem to extend nearly to the surface (Dundas et al., 2018). However, the structure of the near subsurface, including the depth to the ice table as well as the lateral and vertical extent, remains largely unknown, particularly at lower latitudes where the ice is likely less stable.

In summary, the screening of water on Mars remains a crucial task for future Mars missions. Efforts are being made by different institutions to create useful maps of the various water sources there.

2.2.1.5 Mars Subsurface

The thickness of the Martian crust is between 24 and 72 km, depending on the location (Knapmeyer-Endrun et al., 2021). In contrast to the surface, the subterranean sphere offers shelter from extreme weather and temperature variations, radiation, and meteoroid and asteroid falls. Exploring the subterranean sphere on Earth as well as on other planetary bodies like Mars helps us understand both the complex construction and the history of a planet, and geological phenomena such as earthquakes and volcanoes. On Earth, the subsurface has also been an important source for many valuable natural resources, such as groundwater, minerals, metals, and energy (oil, gas). The same, for certain aspects, is expected to be true for Mars. Figures 2.6 and 2.7 show the modelled underground temperature and depth of ground water on Mars.

Mars also harbours large amounts of caves. Caves (or caverns) are usually described as natural cavities in a rocky environment where at least some part is dark, be it in the subsurface or inside mountains or lava from volcanic vents. Since the early beginning of human history on Earth, caves have played an important role in different ways, from dwelling sites for early humans to fascinating exploration sites for interdisciplinary science fields, such as geochemistry, hydrochemistry, geomicrobiology, and geo-biotechnology. Cave-based sciences play an important role in exploring the history of Earth, in the survey of valuable resources such as aquifers, and for expanding our concepts about the boundaries of life and the evolution of dark life ecosystems (Lee et al., 2012). A recent study concluded that caves, or at least subsurface access points (SAPs) are expected to be ubiquitous across the whole solar system, from Venus to Pluto, on rocky or icy bodies (including comets)

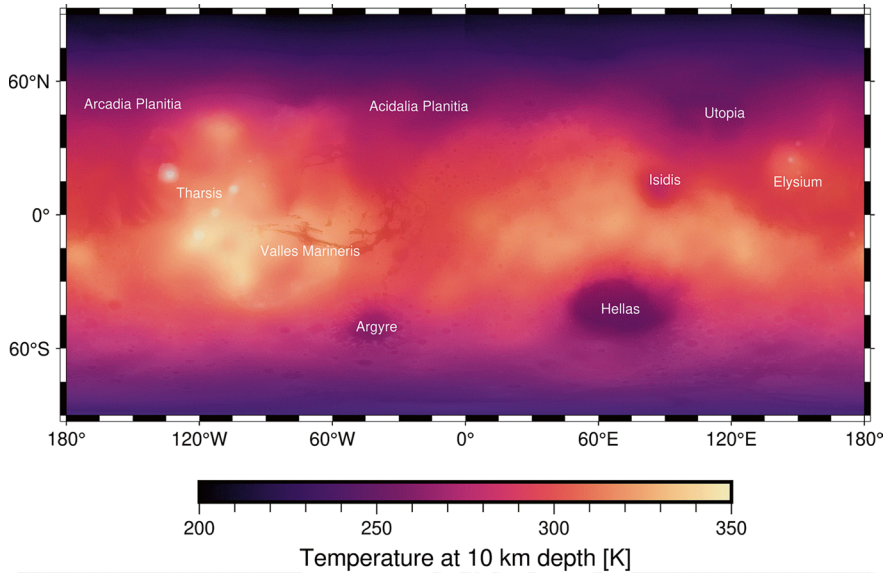


Fig. 2.6 Cartesian map showing modelled temperature at 10 km depth on Mars. Courtesy of Ana-Catalina Plesa

of a size sufficient to allow at least one of the six speleogenic processes recognized

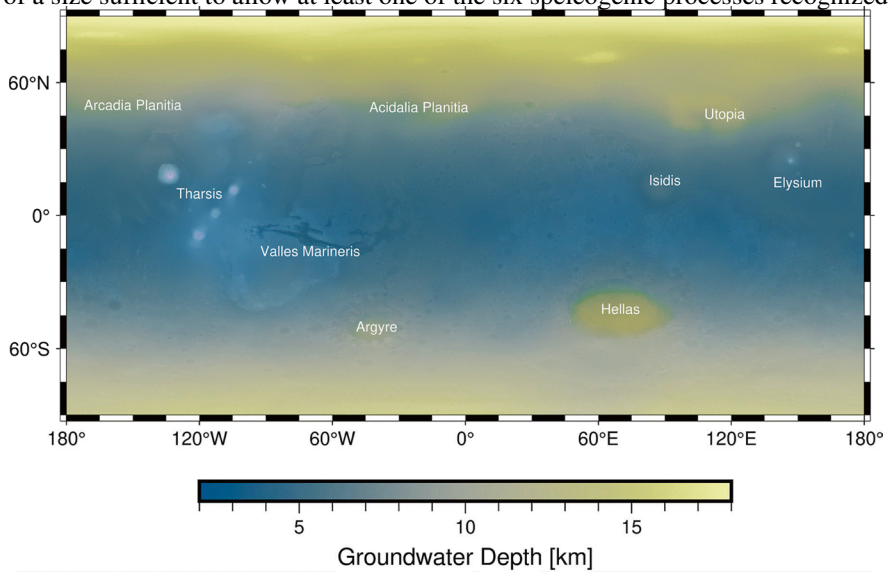


Fig. 2.7 Cartesian map showing modelled depth beneath the surface of Mars where groundwater is expected to be found. Courtesy of Ana-Catalina Plesa

so far for cave formation (Wynne et al., 2022a, 2022b). To date, the bulk of our knowledge is based on high-resolution imagery data on SAPs on Mars (>1162 SAPs) and on the Moon (>276 SAPs). The majority of the SAPs on Mars are found in volcanic edifices and lava fields, with several different morphologies. The width of these cave entrances is around 100–250 m, and their depth is believed to reach at least 130 m. Approximately seven SAPs are believed to be found in a karst-like terrain and may thus contain dissolution caves, which may have been formed by draining surface water or by acting as pathways for hypogenic fluxes (Parenti et al., 2020). Theoretically, caves could be useful for the first settlers of Mars, since they can provide protection from intense solar radiation, micrometeorites, dust storms, and extreme temperature fluctuations. Further, they may also serve as an access route to explore potential resources for industrial activities as well as the geological, palaeohydrological, and potential biological histories of Mars. However, so far, none of the SAPs have been verified as 'genuine' caves—thus, physical evaluation on site is needed before further realistic plans can be made about the usefulness of SAPs on Mars for future settling.

2.2.2 Mars Interior

The shaping of a planet and its surface is complex, based on a multitude of different processes in the core of the planet, such as the generation of the magnetic field and heat, which in turn influence processes such as volcanism and tectonics.

Beyond the regolith layer lies the bedrock, which consists of solid rock. The internal structure of Mars is differentiated like that of the Earth, and the inner part consists of a metallic core overlaid by less dense materials. During the last years, several new observations revealed the nature of the Martian bedrock and core, confirmed the size of the molten core (radius 1830 km), and described some of the characteristics of the Martian mantle and its different crusts (Khan et al., 2023; Stähler et al., 2021). For a long time, it was believed that Mars was tectonically inactive, but like the surface of the Earth, the surface of Mars has evolved significantly throughout time, however in quite different manners. In contrast to the Earth, Mars does not have several continental plates but one big continental plate. Still, it is believed that the surface of Mars was also shaped by various tectonic processes. Even today, rock fractures can form in the Martian crust, and since November 2018, the InSight mission has recorded more than 1300 seismic events on Mars (Banerdt et al., 2020). Monitoring marsquakes has revealed several interesting new features, such as that the thickness of the crust of Mars is about 70% thicker than the crust of the Earth, and that it is inconsistent across Mars, thus possibly explaining the significant elevation difference between the northern and the southern parts. Thanks to these observations, it also became possible to hypothesize that a large fraction of heat producing elements are confined in the crust rather than in the underlying mantle, which in a longer term could imply that Mars still has some volcanic activity (Fernando et al., 2023; Giardini et al., 2020; Kim et al., 2023).

2.2.2.1 Internal Evolution and Volcanism

Mars is smaller than the Earth: its mean radius is 3390 km while the mean radius of the Earth is 6371 km. One could therefore expect that Mars has cooled down more rapidly than the Earth, since heating is by a large factor driven by radiogenic heat sources distributed in the mantle, whose volume scales with planet radius cubed, whereas cooling occurs at the planetary surface, which scales with radius squared. A smaller planet should therefore cool much faster than a larger planet. However, there is a fundamental difference between the two planets: Mars is a one-plate planet (also called a stagnant-lid planet) while the Earth has plate tectonics. On Earth, this leads to efficient cooling of the mantle by subduction of cold plates into the mantle, and increased heat loss at the surface at diverging plate boundaries.

Telluric planets have formed by accretion from the solar system disk of dust and gas. During their formation stage, high-density materials sink towards the centre, resulting in a planet differentiated in a metal core and a silicate mantle. The evolution of the upper part of the mantle, the lithosphere, and (at least in the case of the Earth) the onset of plate tectonics is affected by several factors, among which the most important ones are the planet size, the temperature, and rheology (e.g. Stamenkovic & Breuer, 2014). During the formation stage of terrestrial planets, it is expected that large fractions of the mantle are molten (possibly multiple times) due to large impacts, leading to a magma ocean. The processes of magma ocean formation and solidification are important for the later onset of thermally driven mantle convection and plate tectonics (see, e.g., Elkins-Tanton, 2012). At the beginning of its evolution, Mars formed its core, and this event was accompanied by a large-scale silicate differentiation of the Martian mantle and by crust formation. Using isotopic analysis on Martian meteorites, Kruijer et al. (2020) showed that this event likely happened during the first tens of million years (Myr) of the Solar System's evolution. The solidification of a global magma ocean may have led to a heterogeneous mantle, which may never have efficiently mixed (Plesa et al., 2014). This is supported by Barnes et al. (2020), who demonstrated by using light and heavy hydrogen D/H (deuterium/hydrogen) isotopes, that the Martian crust has had a constant D/H ratio over the last 4 billion years and that there were two isotopically distinct reservoirs in the Martian mantle. The presence of two mantle reservoirs indicates that the mantle is heterogeneous and has not mixed. The present-day thermal state of Mars and its evolution can be constrained from geophysical data, assumptions about its bulk composition and formation history. While studies that analyse the long-term tidal interactions between Phobos and Mars and the orbital evolution of Phobos around Mars provide constraints about the thermal history (e.g. Samuel et al., 2019), the present-day thermal state can be inferred from the actual measured secular acceleration of Phobos orbiting Mars (e.g. Nimmo & Faul, 2013) or from the very recent seismic and geodetic observations obtained during the NASA InSight (Banerdt et al., 2020) mission (Khan et al., 2021; Le Maistre et al., 2023; Stähler et al., 2021; Samuel et al., 2023; Khan et al., 2023). Studies that inform about the present-day thermal state based on geophysical data usually assume that

the mantle is chemically homogeneous, although it has been reported recently (Samuel et al., 2022) that a chemically isolated reservoir located at the bottom of the mantle can be in agreement with InSight data (Le Maistre et al., 2023; Samuel et al., 2023; Khan et al., 2023). Geodynamic modelling has been utilized to infer Mars's present-day thermal profile, mantle viscosity, and heat producing radiogenic elements, incorporating constraints derived from seismological data, geodesy observations, and crust thickness determinations (e.g. Plesa et al., 2022). The present-day surface heat flux of Mars is found to vary between 15 and 33 mW/m^2 and the core-mantle boundary (CMB) temperature is estimated to be close to 2000 K. However, if a molten chemically isolated reservoir exists at the bottom of the mantle the CMB temperature can be significantly larger (Samuel et al., 2023).

Further information on the thermal state is gained if the recently obtained geophysical constraints are included in global geodynamic models of Mars. Plesa et al., (2022) demonstrated that the magnitude of surface heat flow and elastic thickness variations depends on the magnitude of crustal thickness variations. These authors discuss several possible crustal models based either on a two-layer crust with strong seismic discontinuities (at depths of about 8 and 20 km), or on a three-layer crust that included a third layer (with a weak discontinuity at about 39 km depth). Plesa et al. (2022) also show that mantle plumes and cold downwellings may be present in the interior of Mars at present day and would lead to temperature variations in the interior and to variations in the thermal lithosphere thickness. The convection patterns in the mantle are characterized by the presence of several mantle plumes and downwellings, with stronger plumes preferentially focused in the Tharsis region due to the existence of a thick insulating crust at this location, which is directly linked to the volcanic history of that region.

Mars has important volcanoes, which are highly visible on images of the Martian surface. They are in the province of Tharsis. The largest volcano of the Solar System is on Mars; it is Olympus Mons (600 km wide and 27 km high). Three other volcanoes, Ascraeus, Pavonis, and Arsia Mons, are also situated in the Tharsis province. They were all initiated in the Noachian, more than 3.8 Gyr ago. There are low-shield volcanoes as well, such as the Elysium volcanic province or the Syrtis Major volcanic province. Besides the most dominant volcanic Tharsis region and the low-shield volcanoes, there are small early Noachian volcanoes (with diameters ranging from 50 to 100 km and heights of 2–3 km) in the circum-Hellas-basin volcanic province. The volcanoes in both regions were mainly formed in the Noachian to early Hesperian periods (3.7–3.6 Gyr). But volcanic activity persisted after that period until recently: lava flows as young as 2 Myr have been discovered (Hauber et al., 2011; Neukum et al., 2004). Horvath et al. (2021) or Broquet and Andrews-Hanna (2022) have also identified an active mantle plume in the Elysium Planitia region (south of Elysium volcanoes) and hypothesize the presence of an active mantle plume underlying the region.

2.2.2.2 Magnetic Field

Among the four rocky planets in the solar system, Earth is today the only one with a strong magnetic field. This field is pivotal to Earth's biosphere for several reasons, the most important being that it produces a protective shield against, e.g., cosmic radiation, such that Earth's atmosphere and water are not stripped out to space.

Although the liquid core state of Mars was inferred from measuring tides, monitoring its rotation, and acquiring seismic data (Yoder et al., 2003; Stähler et al., 2021; Le Maistre et al., 2023), Mars at present does not possess a global magnetic field. However, early in its history, 4 billion years ago, it harboured a dynamo in its core (e.g. Mittelholz et al., 2020). The presence of an early dynamo was deduced from remnant magnetization in the southern hemisphere, which was observed by the Mars Global surveyor spacecraft and more recently by MAVEN. No crustal field was observed in the Martian northern lowlands. In the heavily cratered and old surface of the south, alternating stripes of positive and negative remnant amplitudes were observed (Acuña et al., 1999). The lineation of the stripes (long E–W trending alternating stripes, see Figure 1 of Connerney et al. (1999) is of course damped out when looking from the point of view of the spherical surface. These stripes, however, are not linked to a plate-tectonics-like behaviour as on Earth, but are either attributed to repeated dike intrusions (Nimmo, 2000) or to a non-dipolar magnetic field (Dietrich & Wicht, 2013). The dichotomy in the remnant magnetic field observation could come from a demagnetization related to rock melting after a giant impact (Connerney J.E.P. et al., 2005). Another explanation has been provided by Zhong and Zuber (2001) (see also, e.g., Roberts & Zhong, 2006), where degree-1 mantle convection with one upwelling in one hemisphere and one downwelling in the other hemisphere can produce a single-hemisphere dynamo. However, magnetized crust in the low-land northern hemisphere may also be covered by dust and may be as old as the southern hemisphere (Frey H.V., 2006) and therefore older than the end of the magnetic field, which is assumed to have ended before the Hellas impact basin 3.9–4.1 Gyr ago (Acuña et al., 1999; Hood et al., 2003; Lillis et al., 2008a, 2008b).

2.2.2.3 Gravitational Field

The gravitational field of Mars is the consequence of its internal and surface mass distribution. It has been measured with high accuracy from orbiting spacecraft (e.g. Genova et al., 2016; Konopliv et al., 2016, 2020; Marty et al., 2009; Smith, 2009). The gravitational field is expressed using spherical harmonics that can represent global (low-degree) features as well as small-scale (high-degree) anomalies. One individual spacecraft is not sensitive to all intermediate degrees and orders as these depend on the orbit geometry as well as the geometry of the measurements from the Earth ground stations (orbit edge-on or face-on). For this reason, researchers working on the determination of the gravity field combine different spacecraft. The last static gravity field determined around Mars was provided by Konopliv et al. (2016).

It must be noted that the gravity field may be described by a geoid, which represents the shape of an equipotential surface. The geoid height with respect to the mean radius can vary within the range of −12 to +8 km. When compared to the hydrostatic figure of the planet, the geoid depicts values between −1 and +2 km (Wieczorek et al., 2019). There are also time variations of the field related to changes in the masses in the atmosphere. They can be used to constrain the dynamics of the Martian atmosphere and icecaps. The static field is used together with the topography to determine the thickness of the Martian crust (e.g. Wieczorek et al., 2022; Wieczorek and Zuber 2004). The admittance obtained from this data allows to characterize the compensation of surface features and the thermal evolution of the planet.

2.3 Mars Atmosphere and Climate

The atmosphere and the climate are two important features which define the environment of a planetary body and determine its potential for habitability. Therefore, a better understanding of the atmosphere and climate on Mars is important to predict how humans and hardware can cope during long stays on Mars.

2.3.1 Atmosphere Composition

The main components of the Martian atmosphere are (values are typical annual means) 96% carbon dioxide (CO_2, can vary by up to 25% seasonally), 1.9% dinitrogen (N_2), and 1.9% argon (Ar) (see Fig. 2.8) (Rafkin et al., 2013). A minor fraction of the atmosphere consists of the so-called trace gases, which including 0.13 wt% dioxygen (O_2), 0.07 wt% carbon monoxide (CO), 0.013 wt% nitrogen oxide (NO), 2.5 ppm water (H_2O), neon (Ne), Krypton (Kr), and Xenon (Xe) (Rafkin et al., 2013). Small amounts of methane have been detected by Curiosity and various orbiters and Earth-based telescopes, which is surprising considering the short half-life of methane in the Martian atmosphere (Formisano et al., 2004; Mumma et al., 2009; Webster et al., 2015). The TGO (Trace Gas Orbiter) failed to detect any, indicating that methane could only be present at very local scale (Korablev et al., 2019).

Atmospheric water is detectable near the surface very close to the exposed regolith between ~0% and 100% relative humidity, which is changing in diurnal cycles. Changes in the amount of dust in the atmosphere, which can be large due to diurnal or seasonal wind events—up to global planetary dust storms—should not be neglected.

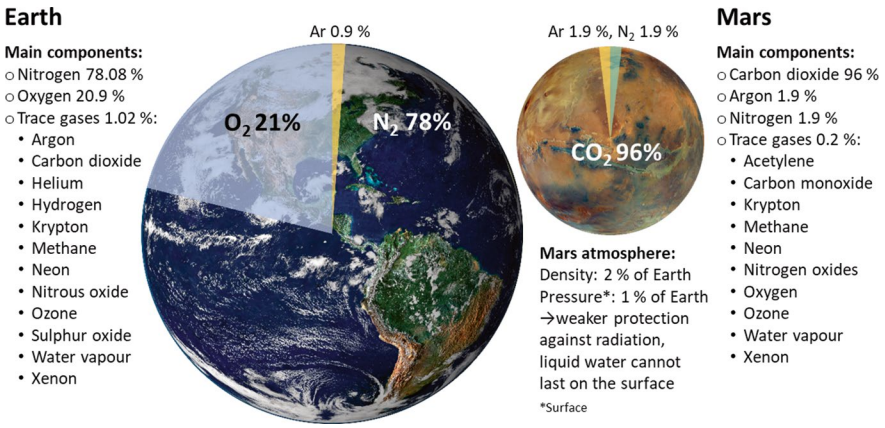


Fig. 2.8 Comparison of the atmospheres of Earth and Mars. The listed values are approximate averages, since some of the values may vary with season. Original figure composition by Natuschka Lee, based on publicly available photos of Earth and Mars. Image credit of Mars: ESA/DLR/FU Berlin/G. Michael. Image credit of Earth: https://eoimages.gsfc.nasa.gov/images/imagerecords/0/885/modis_wonderglobe_lrg.jpg

2.3.2 Current Climate of Mars

Most life forms on Earth seem to have evolved circadian rhythms that allow them to anticipate, prepare, and exploit dynamic resources, such as light, food (prey, growth of plants, etc.), and weather. To mark the time on Mars, it is common to use the local time in Martian hours, which corresponds to a sol (a day on Mars) divided by 24, and the areocentric longitude of the Sun (Ls) as viewed from the centre of Mars. This is equivalent to ecliptic longitude (Ls). The Martian year starts and ends with the northern spring equinox, which is defined as the Martian solar longitude Ls 0. The solar day on Earth (24 h and 11 min) is fairly similar to that on Mars (24 h 37 min). However, the year is about twice as long as on Earth (Fig. 2.9).

The atmosphere of present-day Mars has a very low density, and its average pressure at ground level is about 6 mbar, which is only about 1% of Earth's atmospheric pressure at sea level. The pressure varies depending on the altitude and the season. The seasonal changes in atmospheric pressure are due to the fact that CO_2, the main constituent of the Martian atmosphere, condenses and freezes to CO_2 ice at polar regions during the winter and therefore decreases the atmospheric pressure (Rafkin et al., 2013). The opposite happens in summer when CO_2 ice sublimates and returns CO_2 to the atmosphere and therefore increases the pressure. As there are two polar caps, the pressure is highest around the summer and winter solstices. Figure 2.10 shows the variation between two Viking lander sites during 1 Martian year with the highest pressure recorded during the northern winter solstice (summer solstice at the Martian southern hemisphere) and the lowest at the northern autumn equinox. The measured pressure is different for the two Viking Landers due to Viking 2 being about 900 m lower than Viking 1.

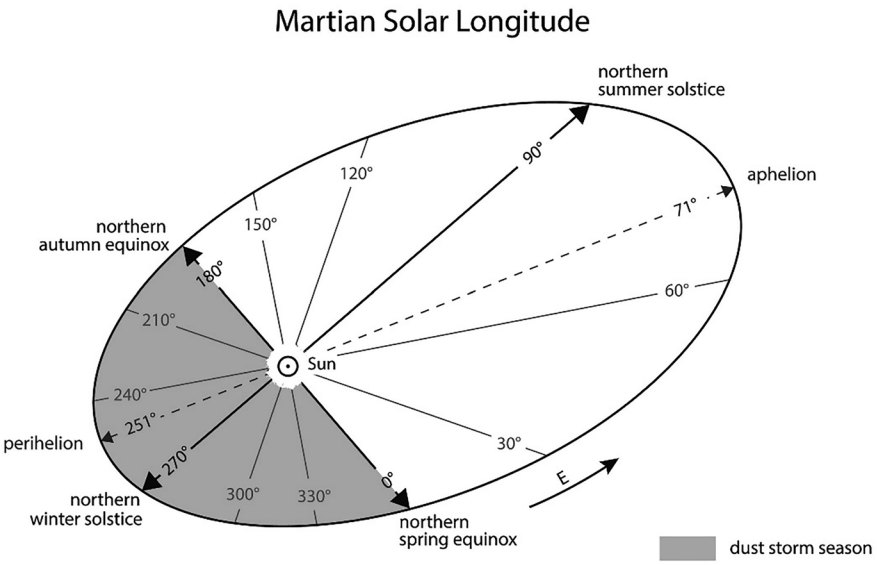


Fig. 2.9 Martian solar longitude. A Martian year is 668.59 Martian days (sols) long, which is equal to 687 Earth days, because a sol is 24.623 h long, ~40 min longer than a day on Earth (Clancy et al., 2000). Reprinted from Pál et al. (2019)

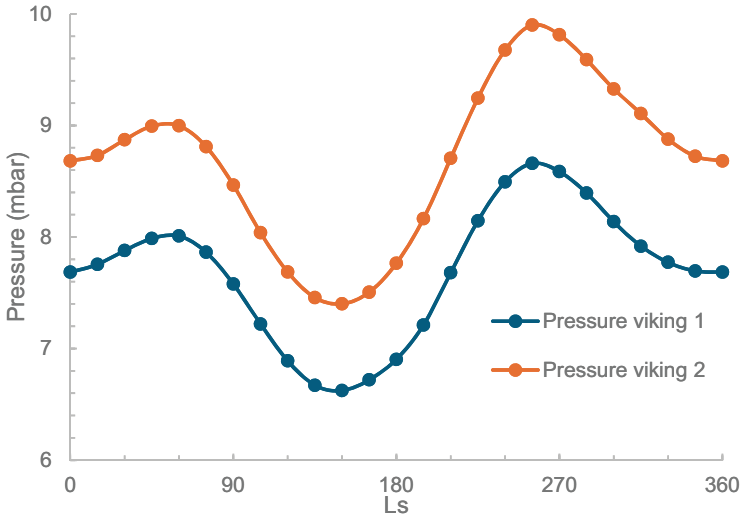


Fig. 2.10 Atmospheric pressure data from the two Viking landers during 1 Martian year. Atmospheric pressure at the surface of Mars varies over the course of the year with the ebb and flow of the seasonal polar caps. (Reproduced from Viking data using Mars Climate Database (MCD-v6.1), 2024)

The temperature range on Mars also varies with day-night cycles, time of year, and latitude. The planetary mean value is about −55 °C to −60 °C at the surface. The highest temperatures, up to about +27 °C, are observed at the equatorial regions and the lowest, down to −143 °C, are reached in the polar regions (Dickson et al., 2013). Figure 2.11 shows variations in temperature at the surface during a sol in different seasons, at the equator, while Fig. 2.12 shows nighttime temperature variations across the surface of Mars.

The relative humidity on the surface of Mars varies according to the time of the day, season, altitude, latitude, and longitude, from below detection limit (0%) to 100% (Figs. 2.13 and 2.14). The driest time is about midday and the highest relative humidity values are detectable in the night up to the early morning. During the most humid conditions, between midnight and 6 AM, brines might form on a few sols—as happened at the Phoenix landing site, close to the north pole—via deliquescence (Fischer et al., 2019), i.e. the formation of a solution on the surface by absorption of moisture from the atmosphere.

The climate on Mars is affected by the abundant dust, which absorbs and scatters visible and solar light and therefore affects atmospheric temperatures and hence winds (Haberle et al., 2017; Rafkin et al., 2013). For example, the dust cover increases the albedo which lowers the daytime warmup. The abundant dust also produces frequent dust devils and dust storms. Dust devils are particle-loaded vertical convective vortices characterized by high rotating wind speeds (estimated to reach up to 100 m/s), significant electrical fields, and low pressure (Balme & Greeley, 2006). The dust devils on Mars are frequently up to a few kilometres high, hundreds of metres in diameter (with narrower bases and broader tops). Most occur

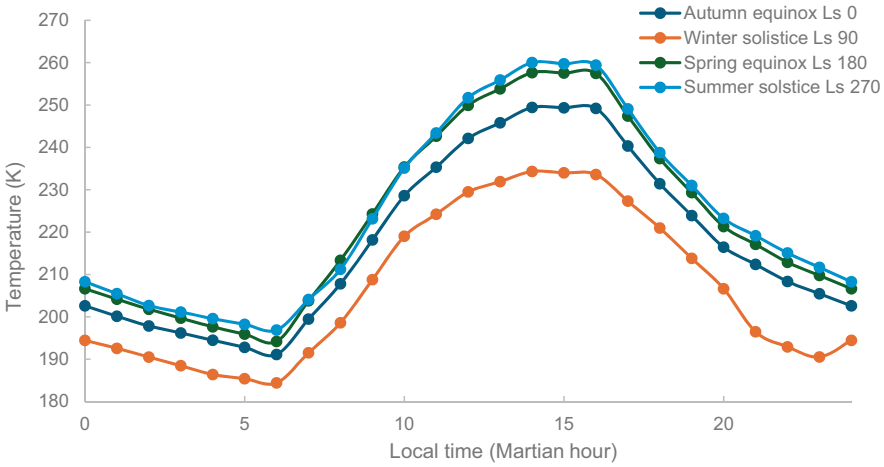


Fig. 2.11 Daily temperature variations in different seasons. Reproduced using Mars Climate Database (MCD-6.1, 2024) with climatology average solar scenario, latitude 0° N, longitude 0° E, and altitude 1.5 m. Note that 180–270 K equals to −93 °C to –3 °C

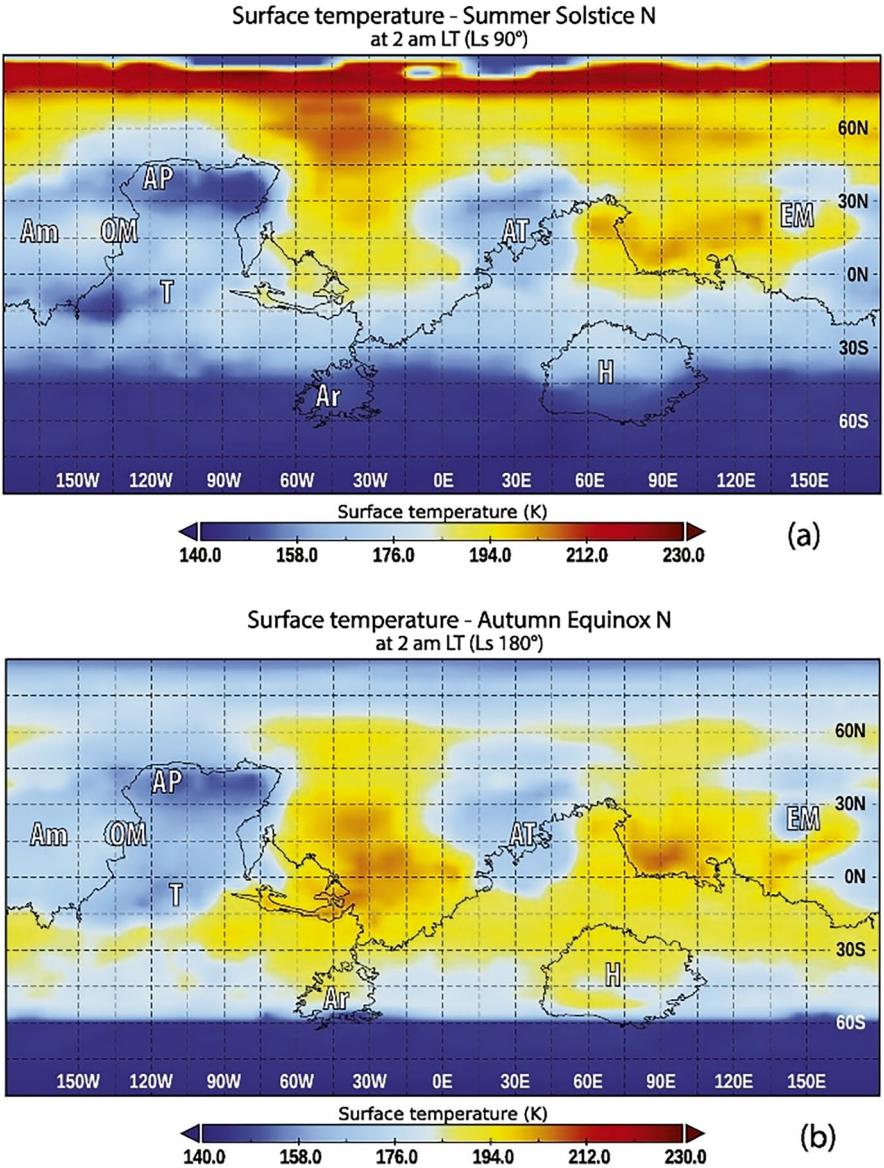


Fig. 2.12 Seasonal dependence of the nighttime surface temperatures. Data from GCM (Global Climate Model) at the northern summer solstice (**a**) and northern autumn equinox (**b**), at 2 AM LT everywhere. Amazonis (Am), Olympus Mons (M), Tharsis Montes (T), Olympus Mons (OM), Alba Patera (AP), Arabia Terra (AT), Elysium Mons (EM), Hellas Plantia (H) and Argyre Plantia (Ar). Reprinted from Pál et al. (2019). Note that 140 K–239 K equals to −133 °C to −34 °C

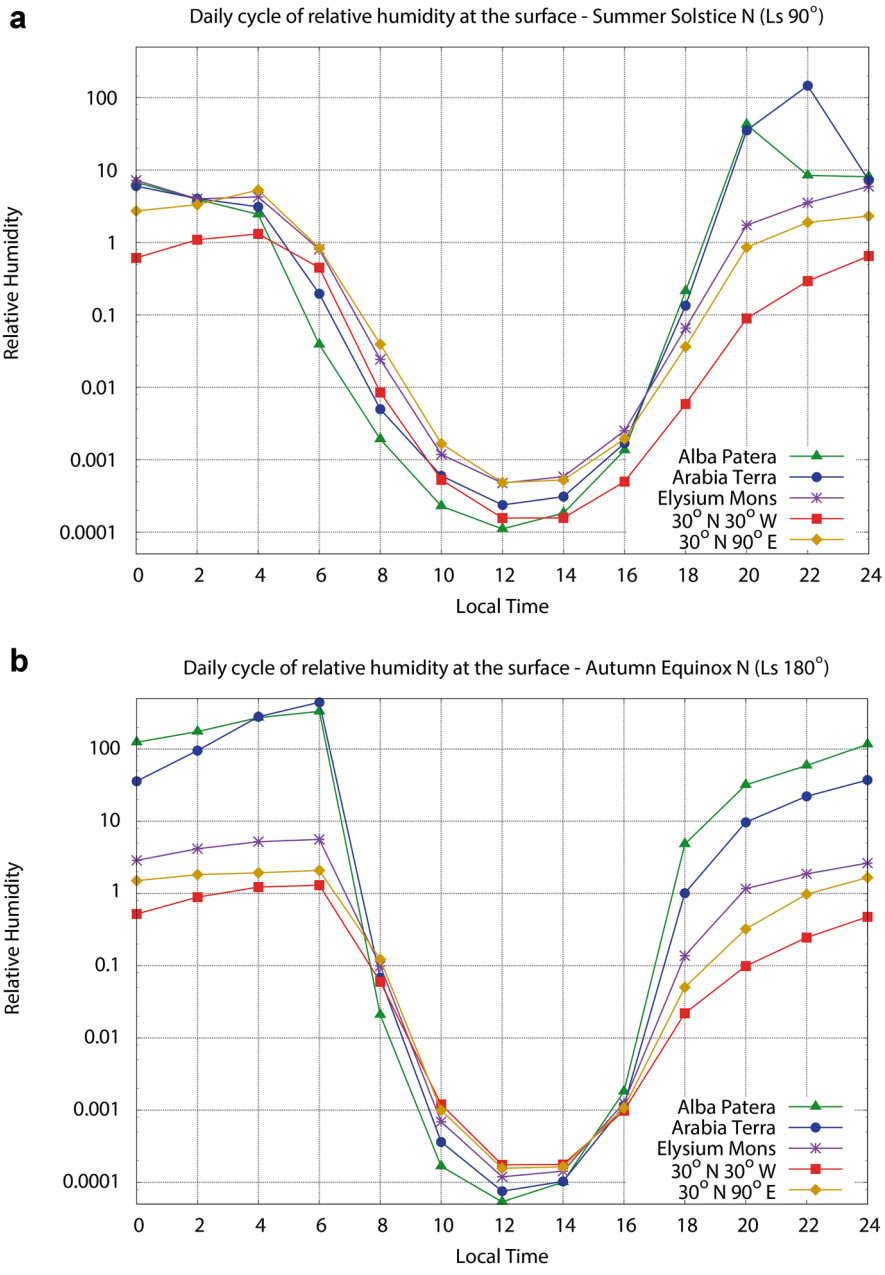


Fig. 2.13 Daily cycles of near-surface humidity at the northern summer solstice and northern autumn equinox (northern summer solstice—Ls 90; Fig. 2.13a) and (northern autumn equinox—Ls 180; Fig. 2.13b) calculated from GCM (General Circulation Model) data. The five locations examined are Alba Patera (30° N 120° W), Arabia Terra (30° N 30° E), Elysium Mons (30° N 150° E), one location at 30° N 30° W and the other at 30° N 90° E. Modified from Pál et al. (2019)

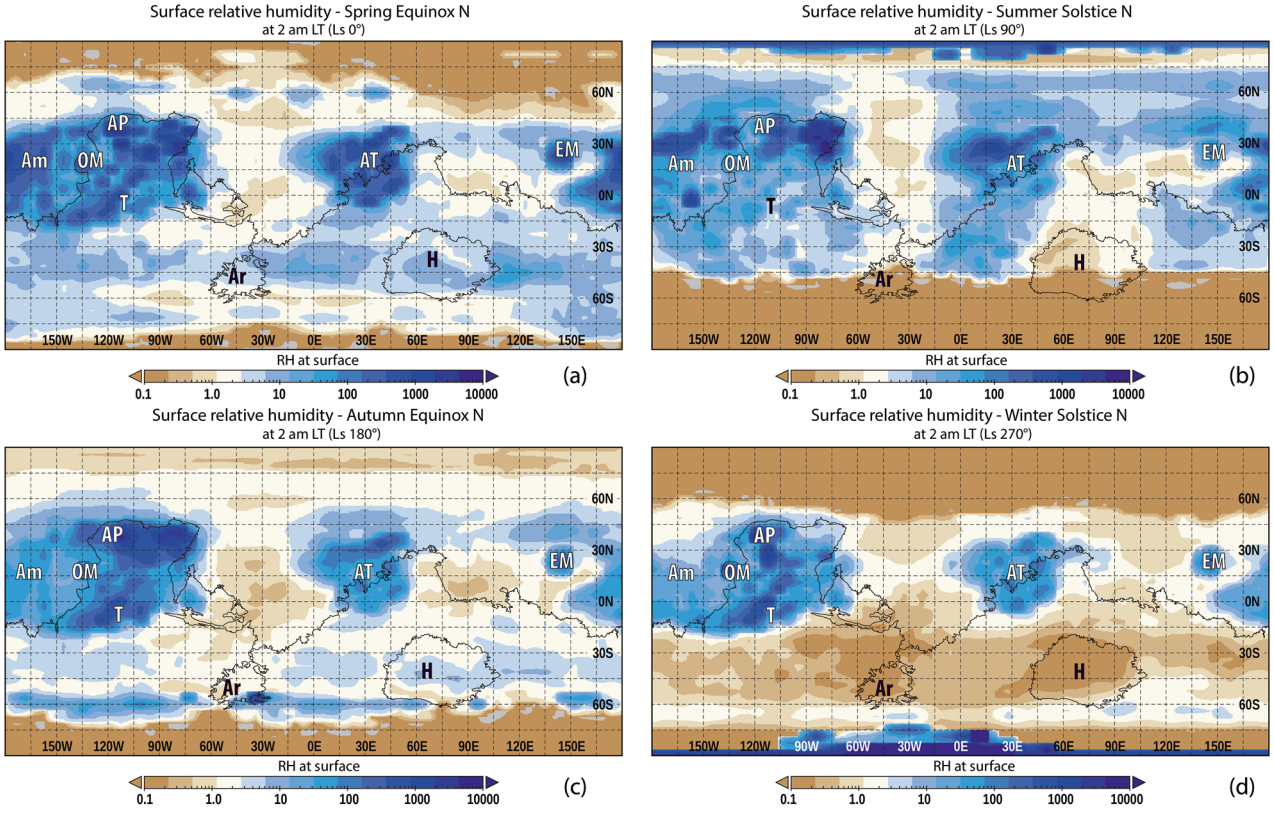


Fig. 2.14 Seasonal dependence of the nighttime humidity distribution. The relative humidity values were derived directly above the surface from GCM model calculation at the time of northern spring equinox (**a**), northern summer solstice (**b**), northern autumn equinox (**c**), and northern winter solstice (**d**), 2 AM LT at everywhere on the map. Amazonis (Am), Olympus Mons (M), Tharsis Montes (T), Olympus Mons (OM), Alba Patera (AP), Arabia Terra (AT), Elysium Mons (EM), Hellas Plantia (H) and Argyre Plantia (Ar). Modified from Pál et al. (2019)

during spring and summer (Balme & Greeley, 2006). It is believed that dust devils are part of the reason for the haze of dust observed on Mars.

Another prominent feature of Mars is dust storms, with speeds up to 160 km/h. They are large (some of the largest in the solar system) and can cover the whole planet, block out the sun and last for weeks or even months (Wang & Richardson, 2015). They preferentially occur in places and seasons—typically, northern autumn and winter (Ls 135–360°; dust storm season)—with above-average surface wind stress (Guzewich et al., 2017; Rafkin et al., 2013; Wang & Richardson, 2015). Global dust storms tend to appear roughly every 3 years (Rafkin et al., 2013). Figure 2.15 shows the distribution of dust during such as dust storm event during Mars Year 34 (1997–1998).

2.3.3 *Fields, Currents, and Escapes*

Today, Mars has a tenuous atmosphere and no global magnetic field and consequently the surface is almost not protected from hazardous external radiation. A magnetosphere, as exists for Earth, forms where flowing plasma (solar wind) is deflected around a planetary object by magnetic fields. In the absence of a magnetic field, solar wind induces a stronger escape of the atmosphere. However, the relevance of a magnetic field for the shielding of an atmosphere has been strongly

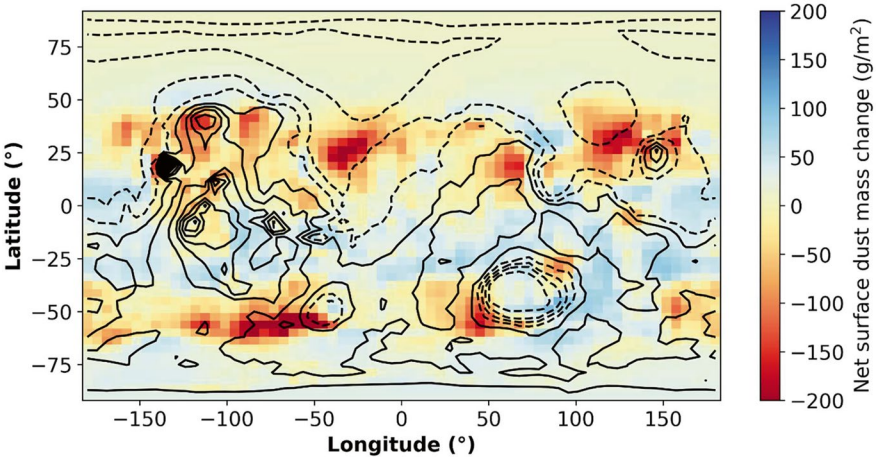


Fig. 2.15 Net surface dust deflation and accumulation throughout the Mars Year 34 global dust storm (Ls 180° to 300°), as simulated by the LMD Mars Global Climate model. A change by 100 g/m² corresponds to a dust layer thickness change of approximately 100 µm. The model assimilates interpolated maps of the column dust optical depth from remote sensing observations (Montabone et al., 2020). The black lines show the Martian topography. Credit: Demetrius Ramette

debated, since observed mass escape rates from Earth, Venus, and Mars are relatively similar, even though only Earth has a magnetosphere (Way et al., 2023).

Escape proceeds through several mechanisms: the removal of neutral particles (thermal escape, photochemical escape, and sputtering) and the removal of ions (ion pickup, magnetic shear and tension-related escape, and pressure gradients). Gunell et al. (2018) have modelled the effects of a global magnetic field on these major atmospheric escape processes and have shown that the escape rate can even be higher for a magnetized planet over a wide range of magnetizations, due to the escape of ions through the polar caps and cusps. It must be noted that this modelling of escape rates depends on the solar flux in all frequencies (X-ray, UV, and extreme UV radiation), on the properties of the solar wind and the atmosphere, which all change over the lifetime of the planet (Lammer, 2013).

Although Mars lacks an Earth-like global magnetic field, it has an ionosphere that results from its upper atmosphere being ionized by solar radiation. This ionosphere is also a highly conductive obstacle to the solar wind plasma.

Related to the magnetic field, there is the potential of having plasma and induced electric currents around Mars, which would help shield the surface from ionizing radiation. Indeed, there is an induced magnetosphere around Mars as Mars is conductive and there are electrodynamic interactions with a magnetized flowing plasma, such as the solar wind. This implies the existence of induced currents (Ramstad et al., 2020). Five years of magnetic field measurements from the Mars Atmosphere and Volatile EvolutioN (MAVEN) orbiter have been used by these authors to map these currents. They found an asymmetry between the northern and southern hemispheres, probably due to the difference in current closure that occurs in the polar regions and found a twist in the near-Mars current system (Sunward current) due to the presence of electric connection between the ionosphere and the solar wind.

2.4 Mars in Its Cosmic Environment

Mars is embedded in the solar system and will therefore be affected by its environment in a multitude of ways—which in turn will influence its potential for habitability for life as we know it. One significant influence is of course the radiation that is emitted from the Sun and from other astronomical bodies outside our solar system. Another significant influence is that of the debris falling to the surface of Mars from space.

2.4.1 Frequency of Meteorite and Asteroid Bombardments

Mars has been subject to bombardments since its formation, as recorded on its surface. So far, hundreds of thousands of impact craters larger than 1 km have been found there, with over 40,000 larger than 5 km wide. Most of these impacts

took place in the Noachian (Scott & Carr, 1978; Tanaka, 1986), but impacts are still occurring (Garcia et al., 2022). Current-day impactors can be divided into several categories: comets, with nuclei ranging between 0.34 and 56 km (Meech et al., 2004); asteroids, ranging from 1 m (Rubin & Grossman, 2010) to 1000 km; meteoroids, 30 μm to 1 m; and micrometeoroids and interplanetary dust particles in general smaller than meteoroids (Rubin & Grossman, 2010). Of these categories, dust and micrometeorites have the largest contribution to the current-day impacts, with a global estimate between 0.71 and 2.96×10^6 kg/year (Nesvorný et al., 2011; Borin et al., 2017; Crismani et al., 2017). Geocentric velocities of micrometeorites have been estimated from observations to be between 15 and 50 km/s (Janches et al., 2003), and micrometeorite craters between 1 μm and several mm have been observed in lunar rocks (Hörz et al., 1971) and space station materials (e.g. Smirnov et al., 2000). Micrometeorite impact velocities for Mars recently have been estimated between 5.7 and 15 km/s (Tomkins et al., 2019), potentially leading to impact craters of similar dimensions as in lunar rocks and space station materials. Considering the damage done on space stations, micrometeorites are an impact phenomenon to be considered in habitat and equipment design. Impact velocities for comets and asteroids on Mars are generally estimated at around 35 km/s for comets and between 7 and 10 km/s for asteroids (Ivanov, 2001; Head et al., 2002; Artemieva & Ivanov, 2004; Frantseva et al., 2018). In addition to crater formation—with crater size depending on impact velocity, impactor material, and impacted material (Holsapple, 1993; Holsapple & Housen, 2007)—a 7.1 km/s impact of a 1-km asteroid can result in a layer of ejecta hundreds of metres thick within tens of metres of the impact crater, tapering off to centimetres at a distance of 500 m (Frantseva et al., 2018). Impact estimates of asteroids and comets have been calculated based on the asteroid and comet distributions tabulated in the Minor Planet Center Orbit Database (MPCORB). These calculations yielded impact rates of 4.34×10^{-3} comets/Myr and 3.3 asteroids/Myr, which are much lower than the annual influx of micrometeorites and interplanetary dust and also lower than the current estimate of an asteroid impact on Earth in the next 900–1000 years (Fuentes-Muñoz et al., 2023).

2.4.2 Radiative Environment

When preparing for human missions, Mars's current radiation environment needs to be considered. This is particularly true of ultraviolet (UV) and ionizing radiation, because of the danger they pose to humans (see Sect. 6.4.3). By definition, UV radiation ranges from 100 to 400 nm, and ionizing radiation includes solar energetic particles (SEPs) and galactic cosmic rays (GCRs).

2.4.2.1 Ultraviolet Radiation

The UV spectrum is often divided into three ranges: UVA: 315–400 nm, UVB: 280–315 nm, and UVC: 100–280 nm. A second, also commonly used division is: near-UV: 300–400 nm, middle-UV: 200–300 nm; far-UV: 122–200 nm, Lyman-alpha radiation: 121–122 nm, and extreme UV: 10–121 nm. On Earth the ozone (O_3) layer, itself produced through UV-photodissociation of oxygen (O_2) and subsequent reaction of the produced molecular oxygen O with O_2 into O_3, absorbs most UVB radiation (but transmits just enough for vitamin D to be produced in primates) and all radiation with wavelengths shorter than that. Mars has no ozone layer and a thin, ca. 6 mbar atmosphere predominantly consisting of CO_2. CO_2 is transparent to wavelengths down to 190 nm, making UV radiation a factor to be considered. Several UV models exist, for varying zenith angles (Cockell, 2000), ancient Mars conditions at 3.5 Gyr ago (Molina-Cuberos, 2001), varying atmospheric dust loads (Patel et al., 2002) and aerosol content (Córdoba-Jabonero et al., 2003), and biological effects of these different UV scenarios (Rontó et al., 2003). The Rover Environmental Monitoring Station (REMS) onboard NASA's Curiosity rover provided the first UV measurements on the surface of Mars (Gómez-Elvira et al., 2012). REMS measures the total UV dose in six bands: 210–360 nm, 215–277 nm, 270–320 nm, 315–370 nm, 230–298 nm, and 311–343 nm, but due to the horizontal placement of the sensor on the rover deck, the sensor suffers from dust deposition, making correction of the measured data necessary (Vicente-Retortillo et al., 2020). The dust-corrected data suggest a daily 210–360 nm UV flux ranging from 9 W/m^2 at 7.00 local mean solar time (LMST) to 22 W/m^2 at noon, and back to 9 W/m^2 at 15.00 LMST (Vicente-Retortillo et al., 2020).

Many studies have focused on the effect of UV radiation on organic compounds on Mars, predominantly within the context of organic detection by missions such as Viking, Curiosity, Perseverance, and ExoMars. Exposure to UV for timescales up to 10 years will destroy organic compounds exposed on the surface (Dartnell et al., 2012; Dartnell & Patel, 2014; Poch et al., 2014; Stalport et al., 2009; ten Kate et al., 2005). This is merely a surface problem, as UV penetrates down to 500–1000 μm, depending on the mineral, but a layer of minerals thicker than 2 mm already has a nearly full shielding and protecting effect on the organic compounds (Ertem et al., 2017; Carrier et al., 2019). In addition to degrading or destructive effects on biological or meteoritic organic compounds, UV radiation also has damaging effects on a range of synthesized organic materials (plastics), including materials often used in spaceflight. For example, material properties including morphology, absorption, mechanical properties, and charge transport of polyimide, the material used as insulator in spacecraft, are affected by UV radiation (Plis et al., 2019). Depending on the wavelength and the dose, UV radiation could be deadly for microorganisms and harmful for organisms which are directly exposed. It is detrimental for some exposed organs (skin, retina, leaf…) of several species.

2.4.2.2 Ionizing Radiation

The ionizing radiation environment around Mars is dominated by GCRs and SEPs. GCRs are composed of ~2% electrons and 98% atomic nuclei, of which 87% are protons, 12% are Helium, and ~1% are heavier atoms ($Z \geq 3$) (Simpson, 1983). SEPs consist mainly of protons and electrons accelerated by solar eruptions, such as coronal mass ejections and flares. Mars lacks a magnetic field and has a very thin atmosphere, resulting in a surface exposed to nearly the full range of ionizing radiation, but variations occur due to heliospheric influences, Mars's atmospheric changes, topographical changes (Zhang et al., 2022), and solar particle events (Guo et al., 2019). Even though the Martian atmosphere is very tenuous, with a column depth of ~20 ± 5 g/cm^2, it still has a small shielding effect, causing primary particles to lose energy, but also causing secondary particles to be formed via spallation and fragmentation (Guo et al., 2019). The Radiation Assessment Detector (RAD) onboard the Curiosity Rover has made continuous radiation measurements since the launch of Curiosity in November 2011, first of the deep space radiation environment during the cruise phase and of the cosmic ray induced energetic particle radiation locally in Gale Crater since its landing on December 7, 2012 (See Sect. 7.4 for more information). The thickness of the Martian atmosphere and the composition of the surface material determine the fraction of particles reaching the surface and being able to penetrate. The composition of the regolith does influence the penetration depth to some extent, where pure ice transmits radiation down to 5 m and wet, hydrogen-rich regolith has slightly better shielding properties then dry regolith. The neutron flux and effective dose reach their maximum at around 30 cm depth, which is important both for the preservation of organic compounds and biosignatures (Dartnell et al., 2007; Alexander Pavlov et al., 2012, 2022) and for the use of Martian regolith as building material. For example, a maximum annual effective dose of 100 mSv requires a shielding depth of 80–250 cm.

The long-term preservation of chemical traces of putative early Martian life is only possible if they are shielded against ionizing radiation damage—that is, protected in the geological record underground at sufficient depth. Although the dose is not that high, its action over billions of years is deleterious and can degrade exposed bioorganic molecules beyond recognition.

2.5 Habitability and Potential for Extant Martian Life

The concept of habitability has been subject to many intense discussions within ecology, astrobiology, and planetary science. Rather than defining it just based on static environmental conditions, habitability should be regarded as a dynamic, complex function and interface of environmental conditions, space, geological timescales, and species type. Thus, according to Cockell et al. (2016), different categories of habitability can be distinguished, e.g., instantaneous habitability and continuous planetary habitability, and the nature of the habitability will also differ depending

on whether the considered astronomical body has surface liquid water (like Earth) or interior liquid water (such as icy moons or rocky planets with liquid water in the interior), and how available this water is—as availability may be reduced due to hypersaline conditions (Cockell et al., 2016). Further, that an astronomical body may be habitable does not automatically imply that it contains (or contained) life. Where does Mars fit within these concepts? The Mars of today is generally regarded as hostile due to high radiation, lack of magnetic field, microgravity, dust storms, meteorite or asteroid falls, toxic compounds in soils and bedrock, and other tough conditions, as described above in more detail (Checinska Sielaff & Smith, 2019). However, Mars does have reservoirs of water, oxygen could be produced from local sources, elements important for life such as phosphorus and nitrogen are present in the soil, elements and compounds used in construction materials such as iron and clay are available, and there are even protective sites such as caves in the subsurface. Further chapters will analyse whether those resources may be used by humans and the terrestrial life forms they will bring with them to survive on Mars for a long time period. Could advance in research and technology truly overcome all the hostile conditions as outlined in other chapters?.

Mars is a planet of great interest in the search for signatures of past or present life beyond Earth. The years of research, and more advanced instrumentation, have yielded a lot of evidence which may be considered by the scientific community as proof of past or present habitability of Mars. Recent discoveries including seasonal methane releases and a subglacial lake are exciting, yet challenging findings. Concurrently, laboratory and environmental studies on the limits of microbial life in extreme environments on Earth broaden our knowledge of the possibility of Mars habitability. In this review, we aim to: (1) discuss the characteristics of the Martian surface and subsurface that may be conducive to habitability either in the past or at present; (2) discuss laboratory-based studies on Earth that provide us with discoveries on the limits of life; and (3) summarize the current state of knowledge in terms of direction for future research (Checinska Sielaff & Smith, 2019). The field of astrobiology aims to understand the origin of life on Earth and searches for evidence of life beyond our planet. Although there is agreement on some of the requirements for life on Earth, the exact process by which life emerged from prebiotic conditions is still uncertain, leading to various theories. In order to expand our knowledge of life and our place in the universe, scientists look for signs of life through the use of biosignatures, observations that suggest the presence of past or present life. These biosignatures often require up-close investigation by orbiters and landers, which have been employed in various space missions. Mars, because of its proximity and Earth-like environment, has received the most attention and has been explored using (sub)surface sampling and analysis. Despite its inhospitable surface conditions, Venus has also been the subject of space missions due to the presence of potentially habitable conditions in its atmosphere. In addition, the discovery of habitable environments on icy moons has sparked interest in further study. This part of chapter 2 provides an overview of the origin of life on Earth and the astrobiology studies carried out by orbiters and landers (De Mol, 2023). Data

collected from recent spacecraft missions to Mars are making it possible to scientifically evaluate whether habitable environments are present, or existed in the past, on the planet. Determining where, when, and how such environments occur will play a crucial role in guiding future exploration efforts. Mars appears to possess the critical elements for life as we know it, including the required chemical elements, energy sources, and the presence of water. Identification of potential habitats for life therefore depends on the convergence of these factors under favourable circumstances. Spacecraft observations are more clearly defining the history of water on Mars and appear to indicate that significant amounts of liquid water have been present at the surface in the past. Most of this water has been lost over time or retreated underground, although there is some evidence for periodic near-surface water in particular eras. If Mars did indeed have a warmer, wetter past, the possibilities for habitable environments were substantial and diverse. On the other hand, the inhospitable nature of the present surface indicates that potential habitats for extant life are much more limited. Nevertheless, habitable environments might exist in the subsurface or at the surface during more favourable climatic periods (McCollom, 2006). Recent findings suggest that Mars was more habitable in the past because of the presence of liquid water on the surface, as demonstrated by morphological, mineralogical, and chemical analyses. Several potential sites have been identified as ancient habitable environments including Gale and Jezero Crater (explored by the Curiosity and Perseverance rovers) and potentially caves or/and the subsurface (Checinska Sielaff & Smith, 2019; De Mol, 2023; McCollom, 2006; 'NASA Astrobiology', 2023). On Earth, the subsurface is a target site for research on extreme microbial life forms which are independent of solar energy and other resources available on Earth's surface (e.g. Suzuki et al., 2022). Some of these extremophiles, which largely remain uncharacterized, have played an important role for virtually all biogeochemical processes throughout Earth's history, providing essential support to many life forms on Earth surface, for instance by altering the composition of minerals and groundwater. In fact, these microbes are even assumed to make up a large part of all life forms on Earth, and they have been found on next to all types of subsurface systems, including marine sediments and the terrestrial subsurface (bedrock pores and veins, where the geological processes strongly influenced the selection within the populations and their evolution).

The most likely life forms to be found on Mars would be or have been polyextremophilic (i.e. tolerant to multiple extreme conditions) microorganisms because of the multiple extreme environmental factors there (Westall et al., 2013) (Table 2.2). Several types of metabolism that exist on Earth have been suggested to be compatible with the sourcing of nutrients and energy on Mars, such as those of metal cyclers or methanogens (Sauterey et al., 2022; Nixon et al., 2013). However, the question is whether current technology is sufficient to detect these, considering a number of foreseeable biases such as sampling technique (depth, volume), sampling location, preservation issues of samples prior to analyses, and the detection method used (Westall et al., 2015).

The question of whether extinct or extant life can be found on Mars is tightly connected to these pertaining to human exploration. Part of the reason for this

Table 2.2 Overview of extremophile categories whose features could help survival (or even proliferation) on Mars. Adapted from Merino et al. (2019)

Category of extremophiles	Organisms that can grow and reproduce	Example of taxa on Earth
Anaerobes	Without atmospheric oxygen	Many species within Archaea, Bacteria, and some Eukaryotes
Acidophiles	In low pH	Many species within Archaea, Bacteria, and some Eukaryotes
Cryptoendoliths	In rocks (pores, fissures)	Many species within Archaea, Bacteria, and some Eukaryotes
Hypoliths	Beneath rocks in cold deserts	Many species within Archaea, Bacteria, and some Eukaryotes
Osmophiles	With high osmotic pressures, e.g. high sugar or salt concentrations	Several species among fungi (yeast) and bacteria
Oligotrophs	In low nutrient concentrations	Many species within Archaea, Bacteria and some Eukaryotes
Psychrophiles	Under low temperatures	Many species within Archaea, Bacteria, Eukaryotes (lichens, algae, plankton, fungi, insects)
Radioresistant	Under high dose rates of ionizing radiation, including nuclear radiation	Some species within Archaea, Bacteria, and some Eukaryotes
Sulphophile	With high concentrations of sulfur	Sulfur-oxidizing and sulfur-reducing species.
Xerophiles	Under a low water activity (a_w)	Bacteria: *Bacillus* spp., *Clostridium* spp., *Salmonella* spp. Fungi: *Aspergillus* spp., *Penicillium* spp., *Xeromyces* spp., *Zygosaccharomyces* spp.

comes from potential risks to planetary protection: indigenous life forms on Mars must be protected from humans and vice versa (for more details, see Sect. 4.5).

2.6 Take-Home Message

Mars, the third closest planet to Earth, formed at approximately the same time: about 4.6 billion years ago. It has since undergone a complex geological evolution. Four billion years ago, the environmental conditions were probably warm and wet enough to be supportive of prebiotic chemistry. A dramatic climate change later made Mars inhospitable: it turned into a dry, cold planet with a thin atmosphere. Scientifically, several questions remain open on the origin and evolution of Mars, and on potential development of life; answering them requires further exploration.

Robotic missions have demonstrated that Mars's environmental conditions are, by comparison with the other non-Earth planets of the Solar System, benign. These conditions seem compatible with the preservation of traces of putative life forms from the past. It also cannot be ruled out that life exists somewhere on Mars today.

After robotic investigations, a logical next step would be to explore Mars with crewed spacecraft. Mars is the most distant celestial body which human explorers can expect to reach with today's or tomorrow's, technologies. An abundant literature therefore promises a bright future for Mars exploration, or even settlement. Some local resources have been identified which could be used for long stays or to supply a permanent base. Before such human missions can become reality, however, many obstacles remain to be overcome and knowledge gaps to be filled.

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Chapter 3
Robotic Missions to Mars

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From the mid-twentieth century, after the Second World War and because of the Cold War between the United States and the Soviet Union, the space agencies of both countries began a race whose first objectives were to orbit the Earth with robotic and crewed spacecrafts, to reach the Moon and to set foot on its surface. In the same period, sights were set on Mars and, from the 1960s onwards, missions were aimed at that goal. In the early years, the number of failures outnumbered the successes, but the problems inherent of such a complex process were efficiently solved. It was possible to fly over the red planet in July 1965 (with the American Mariner 4 mission), to orbit it in November 1971 (with Mariner 9) and to successfully reach its surface in December of the same year (with the Soviet Mars 3 mission) (Fig. 3.1).

In total, 52 missions from different space agencies have been launched to Mars by 2024, and about half of them have achieved their objectives. As a result, an enormous amount of scientific data, of increasingly high quality, has been (and continues to be) obtained, complementing that acquired from ground-based and space-based telescopes over the last century and a half.

The orbiters, landers, and rovers of different space agencies that have operated (and operate) around Mars or on its surface contain a growing number of scientific

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Launch year	Mission
1960	Korabl 4 (AKA Marsnik 1, Korabl 4M No.1)
1960	Korabl 5 (AKA Marsnik 2, Korabl 4M No.2)
1962	Korabl 11 (AKA Sputnik 22, Mars 1962A)
1962	Mars 1
1962	Korabl 13 (AKA Sputnik 24, Mars 1962B)
1964	Mariner 3
1964	Mariner 4
1964	Zond 2
1969	Mars 1969A
1969	Mars 1969B
1969	Mariner 6
1969	Mariner 7
1971	Mariner 8
1971	Kosmos 419
1971	Mars 2 Orbiter/Lander
1971	Mars 3 Orbiter/Lander
1971	Mariner 9
1973	Mars 4
1973	Mars 5
1973	Mars 6 Orbiter/Lander
1973	Mars 7 Lander
1975	Viking 1 Orbiter/Lander
1975	Viking 2 Orbiter/Lander
1988	Phobos 1 Orbiter
1988	Phobos 2 Orbiter/Lander

Launch year	Mission
1992	Mars Observer
1996	Mars Global Surveyor
1996	Mars 96 (AKA Mars M1)
1996	Mars Pathfinder
1998	Nozomi
1998	Mars Climate Orbiter
1999	Mars Polar Lander
1999	Deep Space 2 Probes (2)
2001	Mars Odyssey
2003	Mars Express Orbiter/Beagle 2 Lander
2003	Mars Exploration Rover - Spirit
2003	Mars Exploration Rover - Opportunity
2005	Mars Reconnaissance Orbiter
2007	Phoenix Mars Lander
2011	Phobos-Grunt
2011	Mars Science Laboratory - Curiosity
2011	Yinghuo-1
2013	Mars Orbiter Mission (AKA Mangalyaan)
2013	Mars Atmosphere and Volatile Evolution
2016	ExoMars Trace Gas Orb. / Schiaparelli EDM
2018	InSight
2020	Hope (AKA Al-Amal)
2020	Tianwen-1 / Zhurong
2020	Mars2020 - Perseverance

Fig. 3.1 List of the missions for the study of Mars, with indication of the country that operated it, and the year of launch. Green: success, according to the goals set; red: failure, either due to launch, cruise, or landing issues

instruments that include cameras and spectrometers, as well as microscopes, radars, environmental stations, seismometers, and even a small helicopter. The combined results of such a technological deployment have greatly advanced our knowledge into the geological history of Mars, and have allowed characterizing its topography and surface composition, analysing its caves and subsurface in some regions, or studying its residual geological activity as described in Chap. 2.

This has shown that liquid water was abundant on Mars in the past, and that the surface may have been habitable until about 3 Gyr ago. Thus, scientists have postulated that a form of life may have originated on this planet at about the same time as life was beginning on Earth. This form of life may still be present in its subsurface. Therefore, after NASA's pioneering Viking missions in 1975, and thanks to the interdisciplinary framework provided by astrobiology, the search for organic molecules and possible biomarkers of extinct or extant form of life is regaining priority.

The robotic exploration of Mars has a history which is still short but full of very relevant findings. It is currently living a vibrant era and, thanks to international and future possible public–private collaborations, is expected to bring about numerous new discoveries.

3.1 Robotic Missions: Technology Drivers

3.1.1 Leaving the Earth

Despite a certain maturity in the rocketry reached during the 1940s and 1950s, the developed power was not sufficient to send spacecraft out of Earth orbit and put them on the way to Mars. A fierce competition pitted the United States and the Soviet Union to gain "firsts". Both countries endowed their incipient programs with the necessary resources, thus gaining experience that is still used today.

During the 1960s only, numerous missions failed, especially in the URSS (nine attempts, all of them failed): launch, communication, or orbit insertion or trajectory failures were the most common ones. One of the great technical challenges of the Soviet program was the adaptation of previous engine and rocket designs, including military ballistic missiles, to put interplanetary spacecraft into orbit. For example, the Marsnik 1 mission (also called Korabl 4 or Mars 1960A), the first attempt to send a probe fly over Mars, was launched by a Molniya rocket (8K78): a variant of the base design of the R-7 Semyorka that was widely used during the Cold War as an intercontinental ballistic missile, as well as serving as a launcher to put the first artificial satellite (Sputnik 1), and the first human (Yuri Gagarin), into orbit.

In that first launch, the launcher faced problems with its third stage, probably caused by resonance vibrations that affected the structure of the system and caused the third stage to fail to ignite. The launcher did not reach the proper velocity and control was lost. As a result, the payload, the Mars 1 probe, re-entered the atmosphere after reaching an altitude of about 120 km and disintegrated over Siberia.

The same fate befell the Marsnik 2 mission (Korabl 5 or Mars 1960B), Sputnik 22 (Korabl 11 or Mars 1962A), and Sputnik 24 (Korabl 13 or Mars 1962B), and the subsequent attempts Mars 1969A, Mars 1969B, or Kosmos 419. The recurrent problem of rocket reliability, coupled in some cases with failures in the radio systems, led to multiple failures within these missions, of which only three could reach Earth orbit.

The Mariner program, NASA's workhorse for Mars exploration, was somewhat more successful, although it was not exempt from similar problems. Within this program, which ran from 1960 to the end of 1973, six robotic interplanetary probes were designed and built which aimed at exploring Mars (the Mariner 3, 4, 6, 7, 8, and 9), of which only one had problems during launch: Mariner 8. Mariner 3, launched in 1964, was also unsuccessful due to the protective casing which did not separate properly, preventing the probe from deploying its solar panels and communicating with the Earth.

The trial-and-error period of those first two decades of Mars exploration programs provided important lessons. This laid the foundation for future successes in the race to explore the red planet.

3.1.2 On the way to Mars

Interplanetary travel involved a significant number of challenges, and each mission brought new knowledge and experience gradually improving navigation or technology over time.

A first challenge was the definition of the transfer orbits that should take interplanetary spacecraft from Earth to Mars. The German space engineer Walter Hohmann, in his 1925 book "Die Erreichbarkeit der Himmelskörper" ("The Reachability of Celestial Bodies") (Hohmann, 1925), established the theoretical basis for efficiently moving a spacecraft between two different orbits around a celestial body. The transfer principles defined by Hohmann, or some close variants, have been applied since then in the missions that all space agencies have sent to Mars. These principles take in account the alignment of, and distance between, the Earth and the red planet, as well as their efficiency in terms of time and fuel consumption. In the case of Mars missions, this high energy efficiency translates into a minimum number of thrust manoeuvres to leave Earth orbit at the perigee of the elliptical transfer orbit, when entering a trajectory to Mars. A similar manoeuvre is performed to insert into the Martian orbit (or to land on the planet, if such is the goal) at the apogee of the transfer orbit.

The time when the alignment and synchronization of the planets allow the spacecraft to move from Earth orbit to Mars orbit in an energy-efficient manner through a Hohmann transfer is known as a "launch window", an interval that occurs approximately every 26 months. Such windows can last several weeks, although the optimal time within them is usually much shorter, often very few days, depending on the specific mission objectives and the capabilities of the launch vehicle.

Typically, once the spacecraft is on its way to Mars, some trajectory corrections may be necessary, that will put the probe in a trajectory to reach its target with spatial and temporal accuracy. Thrusters onboard the spacecraft itself allow these adjustments to its speed and/or trajectory. Determination on when and how these corrections should be made are based on navigation and tracking data obtained from communications between the spacecraft and the Earth. The pointing and proper design of the positioning and communications equipment are critical elements for this phase. And it was precisely with these challenges that Soviet engineers failed to face. As was the case with the Mars 1 mission (launched in November 1962, lost contact halfway to Mars), or with Zond 2 (launched 2 years later, and which was the first flight test of ionic engines).

The American Mariner probes used a combination of guide stars and solar sensors (sensors that always pointed at the Sun) to determine their orientation in space. For example, Mariner 4 used a Sun sensor and another sensor for the star Canopus (selected for its brightness) for navigation (Goss, 1970). The radio signals sent to, and from, Earth were also used to determine the distance and speed of the probe (by the Doppler effect). Based on all this data, trajectory corrections were planned. The Soviet missions also used navigation systems based on stars and solar sensors, although these were not as reliable or accurate as the American equivalents. This led

Soviet engineers to carry out tests on each mission, varying the systems from one to another.

In successive years and up to the present, the technology and the design of the missions have gained maturity, reaching almost a total success as far as the path to Mars is concerned. For the moment, off the 52 missions sent to date by the various space agencies, not considering the 12 that had problems at launch, only 4 have had problems on their journey to Mars: the Soviet Mars 1 and Zond 2 missions already mentioned, the Soviet Phobos 1 mission (Harvey, 2007), and the Japanese mission Nozomi (Yoshikawa et al., 2005).

The Phobos 1 mission was launched in 1988, and its objective was to study the planet and its two satellites, Phobos and Deimos. In a communication attempt 2 months into the cruise, no signal from the probe was received. After analysing the data, Soviet engineers realized that in the previous communication an erroneous command was sent to deactivate the attitude motors (specifically, a "+" sign was sent instead of a "-"), which resulted in the probe losing its solar panels' orientation towards the Sun and running out of power. Thus, although the loss of the mission on its way to Mars cannot be attributed solely to a technological failure or mission design errors.

As for the first Japanese interplanetary mission to Mars, the Nozomi mission (formerly called Planet-B), was launched in 1998 and was intended to study the Martian upper atmosphere, as well as its interaction with the solar wind. However, several problems concatenated to prevent it from entering an orbit around Mars: due to a problem in engine's valves, it consumed more fuel than planned in its gravity assist around the Moon, so it did not have enough propulsion for its planned trajectory directly to Mars. To compensate, it had to perform gravity assists around the Earth, which prolonged the trip much more than expected. During this time, it had to endure a huge solar storm that occurred in 2002, which affected the communication systems (and probably other instruments) on board. Finally, a lack of fuel and communication problems resulted in the impossibility of performing the safe insertion manoeuvre around Mars.

It was not until 1964, and later in 1969, with the American missions Mariner 4 (Reiff, 1966), as well as Mariner 6 and Mariner 7, respectively, that this major challenge of the space race (i.e. successfully reaching the orbit of Mars) could be completed. These missions were able to send a sufficient number of images (21 for Mariner 4 (Leighton et al., 1965), 75 for Mariner 6, and 126 for Mariner 7), which give a Mars close-up for the first time.

Another major accomplishment was touching the surface of the red planet. This occurred at the beginning of the next decade when the Soviet Mars 3 landed successfully—despite a dust storm—in 1971. Although the lander remained functional for 110 seconds only, it was the first time a descent could be monitored in the middle of a storm, and an image of the surface, albeit in grey and with little detail, was sent back to Earth.

It should be noted that Hohmann transfers are not the only possible interplanetary transfer manoeuvres. Some trajectories needing more energy and probably new nuclear engines would allow other and larger launch windows for the missions and

the spacecrafts to reach Mars faster. Some transfer could use a Venus gravity assist manoeuvre. However, to date, there have been no known missions that have used anything significantly different from the Hohmann transfer. To simplify the Hohmann-like transfer missions to Mars are described as "conjunction missions"; most of the other transfer using gravity assistance are described as "opposition missions".

3.1.3 Getting to Mars: The Tough Challenge of Landing on Its Surface

A first mission category that could be considered "less complex" encompasses those that pass close to Mars, without entering in orbit or landing on the planet: these are the so-called flyby missions. During the early stages of Martian exploration, missions of this type were more common (although many of them failed, as we have seen above). They were technically less challenging and less risky and costly than orbital insertion or landing missions. In general, flyby missions offer a unique opportunity to study the object at close range, although the observation period is usually very short and the amount of collected data small.

The failed Soviet Mars 1 mission, discussed above, was intended to flyby Mars. On the American side, Mariner 4 (1964), 6 and 7 (1969) were successful flybys. NASA's Mariner 4 not only became the first mission to Mars to complete its intended objectives, but also transmitted the first 22 images (there were a few more which were only partial) of the Martian surface up close. These images, startling at the time despite being black and white, showed an apparently cratered and desert-like Mars, which challenged previous expectations and theories about the planet, including assumptions that a form of life could have developed on Mars and that there might be signs of its activity on the surface. A few years later, Mariner 6 and 7 sent back 75 and 126 images, respectively (along with other valuable spectral data, which helped refine the comprehension of the planet's atmosphere and surface).

The next category of missions, of greater complexity, is orbital insertion, a manoeuvre by which the spacecraft moving through interplanetary space at high speeds is braking to be inserted in a specific orbit around, in this case, Mars. This manoeuvre is precise and applicable both to enter orbit around the planet and to land on its surface. Insertion is generally achieved by firing the spacecraft's engines or thrusters at a specific orientation and duration, thus reducing velocity, and allowing the planet's gravity to capture the spacecraft in an orbit.

NASA's Mars Odyssey orbiter, after activating the main thruster to enter in orbit, used a technique called "aerobraking", to circularize the orbit. Repeated frictions with the upper layers of the Martian atmosphere over 76 days allowed it to gradually reduce its speed and, therefore, its orbital altitude. This manoeuvre saved propellant, which is used for more than two decades. The spacecraft is still active. It is the Martian satellite which is in operation since the longest (it was launched in 2001).

The European spacecraft Trace gas orbiter used a similar technique for 11 months beginning in March 2017.

To save more fuel a "passive" technique for orbit insertion would be the "aerocapture". It consists in crossing the atmosphere at a quite low altitude (around 30 km) to be slowed down up to the speed needed to orbit (about 3 km/s). Then aerobraking could be used to circularize or reach the desired orbit. This technique envisioned for some project has never been used and is considered at high risk.

The Indian Mangalyaan (Indian Space Research Organization, ISRO, Department of Space, 2013) probe (Mars Orbiter Mission, launched in 2013), on the other hand, used the typical strategy of firing up its main engines, which it did for 24 min, during which time the spacecraft was sufficiently slowed down. With this mission, low budget compared to other Mars missions, India became the first Asian country to reach Martian orbit and did it on its first attempt, propelling the country as an emerging power in space exploration.

Something similar happened to the United Arab Emirates with the Hope mission (Amiri et al., 2022), launched in 2020, which became the first interplanetary mission led by an Arab country. Hope executed a critical orbital insertion manoeuvre that lasted about 27 min, burning 50% of its fuel. Following this, the probe entered an initially highly elliptical orbit, which subsequently adjusted to an orbit with a perihelion of 20,000 km and an aphelion of 43,000 km. From this orbit, Hope studies the climate and atmosphere of Mars globally.

Slightly more complex was the global manoeuvre performed by the Chinese Tianwen-1 mission (Ye et al., 2017), also launched in 2020, which performed an insertion manoeuvre that lasted 15 min, placing the probe in very elliptical orbit, with a perihelion of about 280 km and an aphelion of about 59,000 km. The probe remained in this parking orbit for several months before releasing its lander to the surface. The rover Zhurong exited the landing platform in May 2021. The audacious Tianwen-1 mission developed by CNSA placed China as the second country, after the United States, to successfully operate a rover on the surface of the red planet. In addition, China became the first country to successfully reach Mars's surface on its first attempt, doing so with an orbiter, a lander, and a rover, all at once.

The Martian atmosphere is very tenuous, about 1% of the density of Earth's, it does not provide as much deceleration as Earth's atmosphere. Despite this, Mars's atmosphere is very active, atmospheric conditions can vary relatively quickly, depending on location and season. The rugged Martian terrain (featuring meteor craters, canyons, volcanoes, etc.) poses additional risks when landing.

Over the decades, to overcome these difficulties, innovative and highly advanced technology to reach the surface safely and accurately has been developed:

(a) A heat shield that protects the landing platform during the entry of the atmosphere is providing an initial deceleration through the aerodynamic drag and reduces hypersonic velocities before deploying the parachutes. In this phase, the friction between the tenuous atmosphere and the spacecraft generates intense heat. Usually, the heat shield is made of soft materials which, as heats

up, decomposes, and erodes, taking the heat away. This phase results in a typical speed reduction from 25,000 to 2000 km/h.

(b) Supersonic parachutes, designed to slow down spacecraft once it has reached denser atmospheric layers (such as NASA's MSL mission with the rover Curiosity, launched in 2011, which deployed its parachute at Mach 2). The speed reduction of a supersonic parachute is roughly from 2000 to 700 km/h. Thereafter it is possible to deploy a subsonic parachute (the case of ExoMars Rosalind Franklin, to go from 700 to 300 km/h) or go directly to the propulsive descent stage.

(c) Retrorockets, which are usually activated after the stage of parachute deceleration, further reducing the descent speed in a controlled manner. This combined parachute-retro rocket technique has been used since the beginning of the space race and to this day, when mission design has permitted: within the Soviet Mars 2 and Mars 3 missions (1971), the first attempts to reach the surface; the Chinese Tianwen-1 mission (2020), which relied on retro rockets on the landing platform housing the Zhurong rover; and numerous American missions since Viking 1 and 2 (1976).

(d) Airbags, systems that absorb the impact of landing and, once on the ground, retract so that the vehicle can deploy. This technique has proven very useful on missions with relatively low weight and intended to land on terrains which are not very rocky or steep, as was the case for NASA's Mars Pathfinder (1996), as well as for the Mars Exploration Rovers (MERs) Spirit (Arvidson et al., 2006) and Opportunity (Squyres & Knoll, 2005), launched in 2003 (as an example, the latter had four large airbags, with six lobes each, to make them more resistant). The airbags were usually inflated after a first stage of deceleration by parachutes.

(e) Skycranes, overhead cranes that have allowed the most recent heavy rovers, Curiosity (Vasavada, 2022) and Perseverance (Farley et al., 2020) (launched in 2011 and 2020, respectively), to descend gently to the ground while suspended by cables from a descent stage that controlled their propulsive position. Once the rover touched the ground, the cables were cut with pyrotechnic charges, and the descent stage moved away to land at a safe distance. In addition to allowing much heavier systems to descend (which would otherwise have required very large airbags), this technique offers the possibility of landing with greater precision, even near interesting geological features, without endangering the rover.

(f) Landing radars, which have made it possible to determine the altitude and speed (horizontal and vertical) of the descending spacecraft as it approaches the surface. As an example, Curiosity employed a Ka-band Doppler terminal descent radar (TDR) in its last 8 km to obtain accurate, real-time information that was crucial to the manoeuvre dubbed "seven minutes of terror", which involved a series of automated operations to safely descend into Gale Crater. This technology made it possible to reduce the mission's landing ellipse to 7×20 km, comparable to but still larger than what was achieved with Perseverance (7.7×6.6 km). For comparison, let us recall that on the preceding Spirit and Opportunity rovers, the ellipses were 150×200 km.

Perseverance incorporated an additional system called Terrain Relative Navigation (TRN), which used cameras that took images during the descent. Comparing these with maps archived in the on-board computer allowed the system to determine the accurate location of the descent system in relation to the surface and geological features it saw. This sophisticated system made possible to automatically identify a safe landing location without slopes and boulders. The overall system allows a precise landing location within one kilometre from the centre of the landing ellipse (7.7 × 6.6 km wide).

3.1.4 Instruments to Explore Mars

The selection process to choose the right landing site is carried out in several stages: initially, the scientific community is invited to propose landing sites, based on specific scientific criteria and mission objectives; workshops and meetings are organized to discuss and evaluate the proposals received, considering both the scientific value and other technical and safety aspects of the landing; the team engineers evaluate the proposed sites in detail to ensure that they are reachable and can be landed safely, a process which includes an analysis of topography, potential obstacles, availability of sunlight for missions employing solar panels to generate electricity, risk mitigation, etc. Finally, after a thorough review process, a site is selected based on scientific potential, landing feasibility, and overall mission goals. The final decision is made based on the recommendations of the scientific community and the mission team.

This landing site selection is also influenced, inevitably, by the technological and scientific capacity of the instruments of the payload. Not all Martian missions have had a purely scientific objective, especially at the beginning of the space race. Even nowadays countries that join this adventure without much experience of interplanetary spaceflight design missions mainly intended as a technological test or demonstration, rather than one with a solid scientific purpose and sophisticated instruments.

Nevertheless, scientific instrumentation has evolved significantly over the decades, incorporating increasingly advanced technological capabilities aimed at answering more complex questions about Mars.

3.1.4.1 Cameras

The most recurrent elements in all missions are perhaps cameras, devices that have played (and continue to play) a crucial role in the exploration of Mars, to understand what we are up against.

The first Soviet missions, launched in the 1960s and 1970s, were equipped with primitive television cameras, specially adapted to work in the harsh Martian environment. It was unfortunate that they did not have the opportunity to send back images. the American Mariner missions were able to send the first close-up images of Mars: 21 images from Mariner 4, 75 from Mariner 6, 126 from Mariner 7, and an

outstanding number of more than 7000 from Mariner 9. The cameras evolved over the years, showing an increasingly detailed Mars. The general conclusion drawn from the first images sent by Mariner 4, which only reached a resolution of 1 km depicted Mars as an "arid and cratered terrain, similar to the Moon". While Mariner 9 obtained an almost total coverage of the planet's surface. This latter mission was equipped with two Vidicon cameras, one wide-angle and one telephoto. The latest could reach a resolution of up to 98 m per pixel at an altitude of about 2000 km. The provided images were still in black and white, but details of volcanoes and canyons, and evidence of the action of wind and water in the past, could already be seen.

For their part, the Viking missions (launched in 1975) contributed to an unprecedented advance in Martian geology and meteorology, through panoramic images of the landing sites that showed rocks, dunes, and the distant horizon. Those pictures became iconic, playing a crucial role in the understanding of the planetary environment at that time. The lander cameras possessed a field of view of approximately 1.5 × 1.5 degrees per frame, and high-resolution panoramas could be composed to study fine details of the rocks and soil nearby. They also incorporated several spectral filters, which made it possible to capture images in different bands, from UV to near IR, making it possible to study the composition and other properties of nearby rocks. The orbiters' visual exploration cameras (VIS), which also incorporated several spectral filters, were used to map the surface, helping to identify the landing sites of the landers, and later to complement the geological and meteorological studies.

The latest-generation cameras are significantly more advanced using electronic sensors like CCDs or CMOSs. The most modern ones improve by orders of magnitude their resolution, spectral capacity, miniaturization, and versatility (being used for navigation and scientific studies): CaSSiS on ESA's ExoMars Trace Gas Orbiter mission, a colour and stereoscopic system that allows obtaining 3D images of the surface, with a resolution of up to 4.5 m per pixel; or HiRISE on board NASA's Mars Reconnaissance Orbiter (McEwen et al., 2007), which is capable of capturing colour images with resolutions of up to 25 cm per pixel, to mention two examples.

3.1.4.2 Optical Spectrometers

Spectrometers are used to identify and map the mineral composition of rocks and soil, even from Martian orbit and to study the atmosphere using various techniques. A wide variety of such devices have been used: thermal infrared, Raman, Laser-Induced Breakdown Spectroscopy (LIBS), etc. These optical spectrometers can be used also in conjunction with mass spectrometers.

Examples are the Thermal Emission Spectrometer (TES), on board the NASA's Mars Global Surveyor mission, which was designed to observe the planet through infrared emissions from the surface, in the wavelength range of 6–50 μm, providing key information about mineral types; the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM), on NASA's Mars Reconnaissance Orbiter, an imaging spectrometer operating at visible and near-infrared wavelengths

(0.36–3.92 μm), which provides important information for detecting minerals that were formed in the presence of liquid water; ISRO's Mangalyaan mission's spectrometers, a thermal IR spectrometer for recording surface temperature and studying geology, and a mass spectrometer for studying the atmosphere as well as the loss of the exosphere to space; or the spectrometers of the Emirati Hope mission, an IR spectrometer similar to the previously mentioned ones to study the temperature of the atmosphere in low layers as well as the presence of water vapor and ice, and a UV spectrometer to measure the emission in the exosphere, and thus to study the loss of hydrogen and oxygen to space.

This type of spectrometric techniques has also been particularly useful in surface analysis, as is the case of ChemCam (on Curiosity) or SuperCam (on Perseverance), which use pulsed lasers to vaporize samples remotely (at about ten meters), and then record the plume generated by a telescope. The radiation received is then analysed by a UV spectrograph to determine the elemental composition of the targeted rock. This device is completed on SuperCam with an infrared and a Raman spectrometer.

Curiosity also employs a very complex and innovative instrument suite to study the chemistry and isotopic configuration of atmospheric gases and solid samples: the Sample Analysis at Mars (SAM) instrument (Mahaffy et al., 2012), which combines a quadrupole mass spectrometer (QMS), a gas chromatograph (GC), and a tuneable laser spectrometer (TLS) able to work together to analyse Martian air and samples of the regolith.

3.1.4.3 Radars

Ground-penetrating radars have also provided valuable information about the interior of the planet using low-frequency radio waves either from Martian orbit or from its surface. From the orbit, these devices enable the study of the sub-surface of Mars by penetrating it up to several kilometres down. This has provided evidence of large bodies of salty water or mud beneath the surface, as will be discussed below. The Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) instrument, on board ESA's Mars Express orbiter pointed to the possible existence of a subglacial lake, 1.5 km below the south polar ice cap. It detected the interesting difference between the dielectric constant of the northern and southern high latitude regions, which could be interpreted as evidence of an ancient ocean in the north. The Water Ice Subsurface Deposits Observation on Mars (WISDOM) aboard the European Rosalind Franklin rover will contribute to the study of terrain stratification, while assisting in drilling (Ciarletti et al., 2017). Radar Imager for Mars' subsurFAce eXperiment (RIMFAX), aboard the Perseverance rover (Hamran et al., 2020), which probes the surface to a depth of about 10 m, allowing the subsurface layers of Jezero Crater to be identified and thus providing clues to the geological and climatic history of the site; or the subsurface radar incorporated in the Tianwen-1 mission.

3.1.4.4 Microscopes and Close-Focus Cameras

These tools allow obtaining fine details of rocks or regolith at microscopic scales, which is very essential for understanding Martian mineralogy, geology and possible biochemistry.

For example, the Spirit and Opportunity rovers were equipped with a system that was not a traditional microscope, but rather a close-focus camera, the Microscopic Imager, which could obtain images with a resolution similar to that of a low-power optical microscope (can resolve objects 0.1 mm across (Herkenhoff et al., 2008). Something similar is used by the Curiosity rover, the Mars Hand Lens Imager (MAHLI) instrument. In contrast, NASA's Phoenix Mars Lander (launched in 2007) was equipped with a real optical microscope, which could magnify samples up to 40×, and detect particles down to 4 μm in size. In addition, that mission also carried an Atomic Force Microscope (AFM), which was capable of imaging details at the nanometre level, something unprecedented on a planetary mission.

3.1.4.5 Seismometers

Some missions have incorporated seismic instruments to study the internal geological activity of the planet. The first of them were the landers of the Viking missions, but these had problems to characterize the seismic activity of Mars, as they did not work as expected: one of them failed to deploy properly, and the other was located on top of the lander, being limited in its sensitivity and usefulness.

Among the seismometers sent to Mars, perhaps the most notable was the one on NASA's InSight mission (2018): the Seismic Experiment for Interior Structure (SEIS) instrument (Lognonné et al., 2019), an extremely sensitive seismograph, with which mission scientists were able to detect and measure multiple marsquakes, aiding in better understanding the Martian crust, mantle, and core.

3.1.4.6 Environmental Stations

It is common for Martian rovers to incorporate environmental or weather stations to study the planet's atmospheric environment and the conditions at the landing site: from temperatures and pressures to wind patterns and radiation levels. Not only can these data enable a better understanding of weather and atmospheric phenomena: they are also crucial to the planning of future potential crewed missions.

The first weather station operating on Mars was the one built into the Viking landers, which were equipped with a Meteorology Instrument Package (MIP). With these sensors, the mission collected data on temperature at different altitudes (including surface), pressure, wind speed and direction, and humidity (even if inaccurate). All these data were laying the foundations for the technological designs for missions that followed. Later, the Mars Pathfinder mission (1997) also recorded pressure, temperature, and wind data at specific times of the Martian day. Similarly,

the Meteorological Station (MET) instrument of the Phoenix lander provided, as a novelty, daily details of the atmospheric environment near the north pole, including details on ice sublimations, and interactions between the atmosphere and the surface.

There was a turning point in environmental characterization with the Curiosity rover's Environmental Monitoring Station (REMS) instrument suite (Gómez-Elvira et al., 2012). This instrument suite has been comprehensively and continuously recording UV radiation, pressure, relative humidity, atmospheric and soil temperature, wind speed and direction since its arrival on Mars in 2012. It provides a much better understanding of the atmospheric dynamics in Gale Crater. A new generation of such technology is Perseverance's Mars Environmental Dynamics Analyzer (MEDA) (Rodriguez-Manfredi et al., 2023) which, in addition to the above magnitudes, monitors suspended dust (particle quantity and size), and solar radiation at the surface. It is noteworthy that, during the years when the three instruments (REMS, TWINS on InSight, and MEDA) have been operating simultaneously on the surface of Mars, they have constituted the first mini-environmental network on another planet!

3.1.4.7 Helicopters

The Perseverance rover introduced a very significant technological innovation with the inclusion of Ingenuity (Balaram et al., 2021), a test helicopter that demonstrated the feasibility of flight in the low-density Martian atmosphere. With this small drone weighing just under 2 kg and with a wingspan of 1.2 m, a very important door has been opened to a new dimension in planetary exploration.

3.1.5 Accessing the Subsurface

Exploring the Martian subsurface is needed to have a chance to find organic molecules, traces of a prebiotic chemistry, and eventual chemical biosignatures. It also supports possible in situ resource utilization (ISRU) activities. Drilling through the chemically altered (by UV irradiation and oxidant compounds) topmost layer requires centimetre-penetration, while accessing layers protected from long-term ionizing radiation damage may require a borehole depth of about 1.5–2.0 m.

The Rock Abrasion Tool (RAT) (Gorevan et al., 2003) onboard the Spirit and Opportunity rovers was designed to polish the surface of rocks to be analysed, grinding away the looser weathering crust (Arvidson et al., 2004). RAT has a mass of 0.7 kg, a size of 8.5 × 12.8 cm, and a power requirement of up to 30 W. On a disk that rotated at 0–1 rpm, two 23 × 6-mm-sized cog-like synthetic diamond containing resin wheels were installed, which also rotated, up to 3000 rpm. The system was able to drill a hole up to 45 mm in diameter and 5 mm deep in a few hours. Finally, two steel brushes swept the dust away to expose the target below the weathered rock surfaces for other instruments. Using laboratory tests on Earth, a positive

correlation was found between rock strength and RAT grind energy (Thomson et al., 2013). During the survey on Mars, the Adirondack-class rocks showed compressive strengths 70–130 MPa weaker than fresh terrestrial basalts, while rocks at the Columbia Hills had compressive strengths <50 MPa (they probably were impactites or volcanoclastic materials).

The performances of RAT indicated that there is a weathering-altered crust on boulders, and the rock interiors are accessible in such a way. During future crewed Mars mission, astronauts will also need to grind away the surface weathering crust. If there are several interesting potential target boulders, but only few of them might be useful for detailed analysis (for time-consuming hand-hold instrumentation in the field, or for sampling and later analysis), RAT-like instruments will be needed. RAT was almost equal in function to the rock hammer of field geologists on Earth, though hitting with a hammer might be somewhat dangerous, and geologists either use protective glasses or close their eyes in the very second when they hit the rock. On Mars, the situation might be a bit different. A strong helmet will likely be part of the spacesuit; however, for safety reasons, it must be decided whether a hammer will also be used there or whether using a RAT-like system would be more feasible.

The Powder Acquisition Drill System (PADS), onboard the Curiosity rover and located on the turret assembly at the tip of the rover's arm, carries two sparse bits. It can drill (by hammering and rotating the bit) a hole 1.6 cm in diameter and up to 6.5 cm deep, to acquire pulverized sample. Two stabilizer posts make the physical contact with the rock to fix the arm. Having this contact, a first "light drill" makes a shallow hole. During the process, the arm gives Curiosity's onboard computer a sense of progress, to avoid getting stuck and to adapt to the rock strength. To do this, it starts with the lowest percussion power (at 5 mm depth, as mentioned above) and progressively increases the Voice Coil Level by modifying the percussion power (Bieniawski & Bernede, 1979). After drilling, retract happens, and the acquired material is transported to either the SAM instrument or the CheMin (Chemistry and Mineralogy) instrument onboard.

The drilling process can provide information on the compressive strength of rocks by comparison with terrestrial samples (Peters et al., 2018a). There is a correlation between the energy per unit-volume (measured in J/cm^3) and the unconfined compressive strength (MPa), which can be used to characterize the rock, and compare it with terrestrial samples. The weakest rocks at Gale Crater were no stronger than bricks (1.5–5 MPa), and the strongest was close in strength to a standard concrete driveway (15–30 MPa). The fine powder occasionally looks like less reddish, indicating a less oxidized and weathered interior than at the rock surface. A strong correlation between the calcium sulphate content provided by the CheMin instrument and the estimated rock strength indicates the presence of a cement that increases with bedrock resistance (Bristow et al., 2018; Peters et al., 2018b).

The drill on Perseverance rover can produce solid cores. It is located on the arm and has interchangeable bits: coring, regolith, and abrader bits. First, a shallow hole is realized by rotary percussive drilling (the bit is pushed against the rock while spinning and hammering) to create an abraded patch. During drilling, an algorithm controls the force and percussion, and the Gaseous Dust Removal Tool (GDRT)

removes the cuttings with nitrogen gas exhalation. The drill performs a hole 27 mm in diameter, and up to 60 mm long, inside the rock, which leaves the central 13 mm intact as a continuous solid rock unit, thus preserving the original structure. When the core is inside the sample tube, the closure mechanism is shut and combined with the tube's push-like movement, breaks the core off the host rock. An eccentric sample tube is used to prevent the core from slipping out of the bit as it is pulled out of the hole, and the closure mechanism prevents any fragment from coming out of the tube.

The Heat Flow and Physical Properties Package (HP^3) instrument onboard InSight, nicknamed "mole", is a penetrator that was planned to dig itself, by "self-hammering", down to a maximum depth of 5 m. In reality, it only went about 0.35 m deep: the soil on Mars did not enable the necessary friction, so the mole bounced and made a pit around itself, and was unable to achieve in-depth access (Spohn et al., 2022).

One of the most sophisticated drilling systems is the one built for ESA's Rosalind Franklin rover (ExoMars mission) (Vago et al., 2017). This mission has been delayed several times but has now a 2028 planned launch date. The ExoMars drill has a maximum reach of 2 m. It can collect 3-cm-long, 1-cm-diameter small core samples in various rock targets (whether intact, fractured, or powdered). The drill head hosts the Mars Multispectral Imager for Subsurface Studies (Ma-Miss) instrument, an IR spectrometer able to study the borehole wall's mineralogy. The ExoMars drill consists of the following main elements: a 700-mm-long Drill Tool with sample acquisition device, shutter, movable piston, and various sensors; three Extension Rods; a Rotation-Translation Group with motors, sensors, and gear mechanisms; a Drill Box Structure with a clamping and automatic engage-disengage mechanism; and a back-up Drill Tool. During the mission, the drill will be used in the following manner: Drilling operations, particularly when accessing deep samples, will take several sols and will typically end in the afternoon. After collecting a sample, the drill rises and rotates to deposit it on a small drawer—the Core Sample transport Mechanism (CSTM)—where it can be imaged using different cameras. Thereafter, the CSTM closes, and the sample goes into the rover's analytical laboratory where it spends the first night. Early in the next morning, while the analytical laboratory is cold, the sample is crushed—low temperatures are important for preserving the chemical integrity of organic molecules. The resulting powder is then distributed by the Sample Processing and Distribution System (SPDS) where it is dosed appropriately to perform a sample's scientific analysis using the analytical laboratory's instruments (Vago et al., 2017).

3.1.6 Drilling for Future Human Missions

The development of boreholes would be an objective to support future crewed Mars missions either for scientific and maintenance-related activities or to detect several target materials for ISRU which could be hidden below the surface (Drake, 2009).

However, and although some concepts exist, Mars core deep drilling technologies are not mature, and no relevant breadboard is available yet.

While, when aiming for pure ISRU activities, the mass of the acquired material may be the most relevant data and the target consistency or contamination may not matter. Extractive activities would be more excavating than drilling (it is not supposed to acquire liquid or fluid components). Continuous core samples should be extracted to retrieve scientific data, which requires the actual drilling methods. The potential contamination must be avoided, and the protection of the original composition and state of the sample must be ensured, including the preservation of volatiles and the maintenance of instable minerals in their original state. Another aspect is the mechanical state of the core: experience with Perseverance shows that the percussion drill causes some fracturing, and it is clear that unfractured and unbroken cores provide better information (Wadhwa et al., 2022).

Methods to handle subsurface ice sublimation-driven gas currents should be developed, as well as remote control and autonomy for adapting the applied force and speed of drilling, while arrays of detectors in the borehole should also provide information. Beyond the "classical" mechanical drilling methods, the so-called thermal drill is possible inside water ice when the target has been warmed up and melted, thus producing liquid water. However, a sublimation-driven, slower and less energy-consuming H_2O acquisition is also possible, which consumes the target material unpredictably and could produce stochastic shaped voids inside the buried ice. Ultrasonic drilling, which uses vibrations to hammer its bit through materials, was also proposed for Mars (Horne, 2015), but more experience and tests are needed to better evaluate this method.

Any future activity on drilling must also consider the possibility of forward (human) contamination, which would be particularly serious if it affected the so-called Special Regions (Sanders & Mueller, 2015), if some are found.

3.2 Robotic Missions: Scientific Drivers

3.2.1 Geologic History

Although the geological activity of Mars has been continuously decreasing over the last 4 Gyr, it can still be detected at present, thus showing that the planet has retained part of its liquid iron alloy core and its internal dynamics. The mission that allowed detecting and quantifying such a residual activity was NASA's InSight lander, which reached Elysium Planitia in 2018. Using data gathered by the SEIS instrument of InSight, seismic waves propagating through Mars' core were detected for the first time in April of 2019, with a signal coming from the nearby region of Cerberus Fossae. Since then, a total of 1319 marsquakes were detected until the end of the mission in December of 2022, traveling from two seismic events detected on Mars and being the largest of them measured in May of 2022 with a magnitude 5. Based

on the analysis of those marsquakes, seismically constrained models for the elastic properties of Mars's core and mantle have been constructed. The seismically-based estimates of Mars's core composition suggest that it is rich in sulphur, with smaller fractions of oxygen, carbon, and hydrogen (Irving et al., 2023).

3.2.2 Follow the Water Along the History of Mars

After first datasets from Mariner 4 suggested that Mars was a Moon-like planet, NASA's Mariner 9 orbiter displayed the first traces of past water flows ever observed on Mars (Sharp & Malin, 1975). This finding has oriented Mars researchers over nearly 50 years, as most missions sent to the red planet have been oriented towards the search for past or present liquid water (the so-called Follow the water approach), in connection with the search for past or present traces of form of life. Yet, when the Viking landers touched the ground, they found a rather hostile world, a touch of Sahara landscapes with the temperature variations of Antarctica. While the presence of a form of life in soils was still debated due to the ambiguous results of the Labelled Release Experiment onboard Viking (Levin & Straat, 1979), as will be discussed below, most scientists admitted that finding a form of life (in particular, some kind of extremophilic microorganisms) on current Mars surface would have been challenging. These disappointing observations cut the mood for Mars missions in the 1980s, apart from the Mars Phobos Russian mission in 1988 (which was lost after 2 months of acquisition).

Hence, the new missions starting at the end of the 1990s and during more than two decades were built around two key goals linked to liquid water, and past or present habitability: (1) Investigate ancient Mars, especially in terrains formed when liquid water was possible, understand this past climate, find habitable environments and eventually traces of extinct form of life; and (2) Investigate the modern Mars environment, map the distribution of surface and subsurface water ice, find evidence for current liquid water and possibly of extant form of life.

The investigations of early Mars required to have a closer look at ancient rivers, palaeolakes, and sediments. NASA's Mars Global Surveyor was the first of a series of well-suited spacecraft with several key instruments. The laser orbiter Mars Observer Laser Altimeter (MOLA) set up the stage for the global topography of Mars. In turn, the Mars Observer Camera (MOC) sent the first high-resolution images of the surface, which enabled to describe a huge amount of terrains on Mars, including fluvial valleys and sedimentary outcrops (Malin & Edgett, 2000).

Fluvial landforms are key in the understanding of early Mars climate. They have been, and are still, intensely debated. Ideas developed during the Viking era were that most valleys could have formed by geothermal heating of a permafrost, and so without any warmer climate. These ideas have been ruled out by observations showing densely branched valleys. The fluvial landforms are diverse in style and in age. The ancient ones (Noachian and Early Hesperian) correspond to the most Earth-like hydrological networks requiring sustained precipitation (e.g. Irwin et al., 2005).

However, we still do not know whether rainfall occurred, or whether snow and subsequent melting were predominant, if not the only source of liquid water. Dozens of palaeolakes have been identified throughout the whole planet, from their connection to fluvial valleys and/or the identification of deltas (e.g. Goudge et al., 2016). However, well-preserved deltas are not always the oldest features, and some of them could be the result of late-stage, episodic water activity. Some recent fluvial landforms (Late Hesperian and Amazonian) also formed from river flows but are usually more patchy and poorly branched. These late-stage landforms are often found in relation with local heat sources (such as impact craters or volcanoes), but a climatic optimum in these periods could also have been invoked (Kite et al., 2019).

The Thermal Emission Spectrometer (TES) on board NASA's Mars Global Surveyor was the first to provide a global mapping of the surface composition, which should enable detection of primary and secondary minerals. However, TES detected only primary minerals such as olivine, pyroxene, and feldspars (e.g. Christensen et al., 2005). No secondary minerals such as those formed by alteration were detected, except for a few terrains displaying crystalline hematite, which later became the focus of the Opportunity rover (see below). Thus, in the early 2000s, the lack of hydrated minerals was interpreted as a negative sign for a wet past of Mars. In this context, the *Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité* (OMEGA) onboard ESA's Mars Express provided a series of fundamental observations, which modified this paradigm: hydrated sulphates were detected on layered deposits, and clay minerals were mapped in ancient terrains in connection with a diversity of rock types (Bibring et al., 2006). These detections of hydrated minerals were confirmed with the more spatially resolved spectrometer Compact Reconnaissance Imaging Spectrometer for Mars (CRISM), which added tens of minerals to the initial list built by OMEGA, including carbonates and hydrated silica (e.g. Murchie et al., 2009).

Most geological studies of ancient Mars terrains now feature integrated approaches, with morphology, subsurface features, and composition, thus providing the most in-depth analyses that orbiters can provide. The OMEGA-based paradigm distinguished three periods: a roughly Noachian age dominated by alteration into clay minerals and mild to neutral conditions, followed by more acidic conditions dominated by sulphates during the Hesperian, before dry conditions in which only oxidation remained (Bibring et al., 2006). The most relevant observations to the past climate are the regional pedogenetic profiles, in which aluminium-rich phyllosilicates such as kaolinite overlie Fe-Mg smectites such as nontronite, a compositional stratigraphy typical of long-term alteration at ambient temperature (Carter et al., 2015). These findings draw the image of a planet on which liquid water played a strong role, thus keeping the door open for the search of traces of past form of life (see below).

Sedimentary deposits are of huge interest to the search for traces of past form of life, especially when linked to palaeolakes and fluvial activity. Field scientists would be frustrated by only sending landers scratching rocks around the spacecraft, as the Viking landers did. Progressively more and more complex rovers were designed to

enable the mobility loaded with the scientific tools of a petrology laboratory to analyse the texture, chemistry, and mineralogy of the rocks.

The Mars Exploration Rovers, Spirit and Opportunity, have done a fabulous job in analysing rocks along their traverses. Opportunity will remain the first tool ever to have analysed sedimentary rocks, presumably sulphate-rich sediments formed by liquid water in relatively low water/rock ratio and in acidic conditions (Squyres & Knoll, 2005). On the other side of the planet, Spirit landed in Gusev Crater, which is suspected to have been a lake in the past, but the terrains analysed were mostly volcanic. Nevertheless, the area of the Columbia Hills, an explosive volcanic land inside Gusev, enabled Spirit to make interesting findings such as siderite (Fe-rich carbonate) and silica-rich concretions that were the subject of speculations on a potential biological origin (Ruff et al., 2011).

In 2012, Curiosity landing became the milestone of a new era in the in situ analysis of Mars. After previous orbital instruments had found palaeolakes and hydrated minerals, the definition of landing sites became obviously driven by these two types of evidence. So were chosen Gale Crater for Curiosity and, later, Jezero Crater for Perseverance. The Curiosity rover was able to find not only hydrated minerals (both clays and sulphates) and lacustrine mudstones, but also organic compounds and chemical volatiles usually associated with life as we know it (see below). These detections enabled scientists to conclude that palaeolakes might have hosted habitable environments on the surface of Mars (Grotzinger et al., 2014). Curiosity subsequently found more lacustrine and fluvial deposits, as well as diverse mineral phases, including those produced from diagenesis during the burial of sediments along more than 30 km of traverse and 500 m of elevation difference.

Two decades after these new analyses, there is little doubt that Mars's ancient climate (>3 Gyr ago) was different from the current one, with sustained liquid water on the surface, and a huge diversity of chemical processes. Yet, there many questions remain on the duration and amplitude of the fluvial activity, their link to the past climate, and the role of subsurface processes. Was the climate warmer for geologically long periods (i.e. >1 Myr), or only episodically warm (<10 kyr) in an overall cold early Mars? Was the climate like that in the Arctic today, or much warmer?

3.2.3 A Cold, but Geologically Active Planet

The history of water on Mars did not stop 3 Gyr ago. Apart from the 1 to 3 km-thick polar caps that were accepted as being composed predominantly of water ice deposits in the twentieth century, the discovery of many other water-ice rich landforms was made possible by the large amount of data acquired by different missions along the twenty-first century. Martian mid-latitudes contain landforms such as lobate aprons and concentric crater fills. These features are now clearly related to viscous flow of relatively pure ice glaciers, as deduced from their topography, morphology, and radar signature (Holt et al., 2008). High latitudes also display a huge number of terrains with periglacial landforms, such as polygonal cracking typical of ice-rich

terrains. These landforms are correlated with the presence of abundant water ice in the first meter of the ground, as evidenced by the Neutron Spectrometer onboard Mars Odyssey (Feldman et al., 2002; Mangold et al., 2004). The Phoenix Lander was able to confirm in situ the presence of water ice in the ground at 69°N of latitude (Mellon et al., 2009).

Estimates of the amount of liquid water available, a value usually defined in the literature as the Global Equivalent Layer (GEL), may vary depending on the mission and the method used. More details on this discussion can be found in Chap. 1. Where is the water gone? The current polar caps only account for 10–15 m of GEL. In turn, the mid-latitude glaciers account for less than 1 m, but as much as 200 m of GEL are possible if the porosity of the ground of the mid- and polar latitudes is filled with water ice (Lasue et al., 2019). The detection of more hydrated minerals at the surface by OMEGA and CRISM spectrometers lead to the idea that a substantial amount of water is preserved in these minerals, especially in clay minerals such as serpentine, which can be deeply buried and still hydrated (Ehlmann et al., 2010). Yet, it is known that some of the water has left the Martian atmosphere, especially since the loss of the magnetic field (ca. 3.8 Gyr ago) as solar winds played a strong role in atmospheric escape. The loss rate corresponding to solar wind interactions measured by ASPERA-3 on-board Mars Express is lower than these earlier estimates, thus suggesting that this escape was not that high (Barabash et al., 2007). However, the strong D/H ratio, four to five times higher than on Earth, and the Ar^{36}/Ar^{38} ratio measured by Curiosity in situ, have demonstrated a significant loss of atmosphere, probably 85–95% (Atreya et al., 2013). For planet Earth, the current GEL is evaluated to 3000 m.

While the distribution of ground ice and related landforms attracted many questions in the 2000s, new observations of the surface also triggered huge interest within the scientific community. The so-called recent gullies are landforms formed by an alcove and a channel that are present only on hillslopes of the mid- and high latitudes (e.g. Costard et al., 2002). They never develop over flat areas, suggesting a process controlled by mass wasting (such as debris flows) rather than a pure fluvial process, but could have formed due to the melting of near-surface water ice present at these latitudes. Periglacial landforms suggestive of freeze-thaw cycles, such as solifluction lobes, a common process on Earth, have also been identified on hillslopes (Johnsson et al., 2012). Recurring Slope Lineae (RSL) are dark slope streaks that are currently active as they appear seasonally on the flank of hillslopes, including those in equatorial regions. Their seasonal frequency also suggests the role of volatiles, at least as brines, which have melting points much lower than 0 °C (down to –50 °C) for some types of perchlorate-rich soils (Ojha et al., 2014). Hence, could water be liquid at the surface currently or, at least, have recently been so? This possibility is contrary to most of what we know from the Martian climate, which dried out surface terrains because of the very low partial pressure of water vapour. RSLs have also been explained by purely dry granular flows (e.g. Dundas, 2020) and recent gullies by CO_2-driven mass wasting (e.g. Pilorget & Forget, 2016), making liquid water unnecessary to the explanation of these landforms. Thus, such controversial landforms are at the centre of lively debates and the final word remains

unknown. The main take-home message is that Mars's current atmospheric activity can generate unexpected landforms.

Whatever the conclusion on present liquid water will be, the question of extant form of life triggered by these observations has become, over the years, less exciting to scientists. Rover missions have shown that the soil is strongly oxidized and chlorine-rich (Leshin et al., 2013), creating conditions which disfavour life as we know it (see below). If RSLs are triggered by liquid brines at cold temperatures, the presence of perchlorates could hinder the presence of current form of life there. However, recent studies performed on Earth have shown that certain microorganisms can survive in perchlorate-rich environments (Al Soudi et al., 2017; Cassaro et al., 2022; Heinz et al., 2020, 2022). As a result, the possibility of finding extant form of life has been an important question for most space agencies for decades. For instance, it has been a major motivation for the European ExoMars rover programme, and its 2 m-deep drilling system which is supposed to reach areas unaffected by radiations and more favourable to extant form of life.

In any case, while the current surface is hostile to any form of life, the presence of an ice-rich permafrost keeps the debate going about the possibility of extant form of life preserved in the deep subsurface. In theory, water could be liquid at depths of 2–4 km, depending on the geothermal gradient, and possibly closer to the surface if brines enable melting at temperatures below 0 °C (Clifford, 1993). The MARSIS ground-penetrating radar was devoted to the task of deep subsurface water detection. Unfortunately, the high-iron content rocks from the Mars crust played against a deep penetration of the signal. The MARSIS radar never reached depths of more than 100 m in rocks, though it was able to penetrate through the whole thickness of polar caps (Orosei et al., 2015). Hence, the question of the presence of deep liquid water is still unsolved and remains one of the most intriguing possibilities to be investigated with future missions.

3.2.4 Detection of Organics

The existence of organic matter on Mars has been studied by analysing Martian meteorites retrieved on Earth, as well as by using the instrumentation for in situ chemical characterization on board of the latest NASA rovers sent to the red planet. The presence of organic molecules can be due to the electrochemical reduction of atmospheric CO_2, the mineral carbonation and serpentinization reactions within water–rock interactions, as well as the delivery from carbonaceous chondrite meteorites or other exogenous sources (Steele et al., 2016). Additionally, they could hypothetically be the outcome of biotic processes related to extinct or extant form of life.

The use of pyrolysis-gas chromatography/mass spectrometry (pyr-GC/MS) has revealed the presence of high-molecular-weight organic matter in Martian meteorites such as Nakhla and ALH84001, though in concentrations that could not be distinguished from terrestrial contamination. Endogenous polycyclic aromatic

hydrocarbons (PAHs) have also been found in other Martian meteorites using Raman spectroscopy and laser desorption MS. In turn, a detailed analysis of the Tissint Martian meteorite has revealed the presence of aliphatic and branched carboxylic acids containing three to seven carbon atoms, aldehydes, olefins, as well as PAHs with and without heteroatoms such of magnesium (Schmitt-Kopplin et al., 2023). In some of the analysed Martian meteorites, the colocation of mineral and organic phases has been confirmed.

Since 2012, NASA's Curiosity rover mission has been playing a key role in the characterization of Mars's soil at a molecular level. Its instrument SAM detected the presence of the six fundamental elements required for the origin and maintenance of life as we know it (the so-called CHNOPS group) in rocks formed 4.5–3.9 Gyr ago. Additionally, in several samples analysed by pyrolysis experiments within Gale Crater, SAM has detected endogenous organic material on the planet for the first time. Peak temperatures and isotopic compositions of evolved CO_2 and O_2 have shown that carbon is present in multiple macromolecular and mineral phases, and the possibility that it comes from contaminants of terrestrial origin carried on the rover has been excluded. Their characterization has been very complicated, because the perchlorates that abound in the Martian regolith alter organic matter when heated for GC/MS analysis (Franz et al., 2020). Some researchers have claimed that the organic carbon found at Gale Crater could represent the remnants of the complex mixture of hydrocarbons known as kerogen, thus being the result of decomposition of living beings in the past. Of course, in the absence of strong evidence to support that such compounds are true molecular biomarkers, one has to lean towards their abiotic origin on Mars, or their transport by carbonaceous chondrite meteorites and interplanetary dust (Royle et al., 2022).

The Scanning Habitable Environments with Raman and Luminescence for Organics and Chemicals (SHERLOC) instrument on board NASA's Perseverance rover is being used to analyse the fine-scale spatial association between minerals and organic compounds in the sampled areas of Jezero Crater, an ancient lake basin that (as discussed above) contains carbonates, sulphates, and clays, among other minerals. The retrieved deep ultraviolet (248.6 nm) Raman and fluorescence spectra are consistent with the presence of a diversity of aromatic organic molecules in the Máaz and Séítah formations within this crater, thus showing that such compounds have persisted in the rocks (most of them, linked to aqueous processes) despite their extended exposure to the harsh conditions of the Martian surface. The fluorescence signals, which are not very specific, detected by Perseverance can also be due to some inorganic sources.

The repertoire of organic molecules includes both single ring aromatics and PAHs. Their distribution in the analysed geological formations suggests that different aqueous alteration or deposition processes (operating roughly 2.6–2.3 Gyr ago) contributed to the diversity of organic matter currently detected in that area (Sharma et al., 2023). Studying the preservation of organic matter on the surface of Mars provides data which is fundamental to understanding the carbon cycle on the planet throughout its geological history. Clarification will occur when the Mars Sample Return mission enables the analysis in terrestrial laboratories of the samples being

collected by the Perseverance rover. It will be possible to determine the origin of the organic compounds contained in the retrieved materials, as well as to specifically identify the repertoire of molecular species.

Over the past few years, a renewed interest in the possibility of finding extant form of life on Mars has had to do with methane (CH_4), the simplest hydrocarbon, which is found in a gaseous state at both the pressures and temperatures of the Earth's surface and those of Mars (Yung et al., 2019). Since 1999, observations from ground-based telescopes had shown the presence of methane in the Martian atmosphere at very low concentrations, around ten parts per billion (ppb, i.e., ten molecules of methane per billion gas molecules in a given volume). Subsequent determinations had extended the range to between 0 and 50 ppb. In 2004, the Planetary Fourier Spectrometer (PFS) instrument on board ESA's Mars Express orbiter had measured similar values: 0–30 ppb. By comparison, the concentration of methane in the Earth's atmosphere is currently about 1800 ppb. However, on 15 June 2013, the SAM suite detected a point spike of 6 ppb of methane at the surface of Gale Crater, while the usual levels of this hydrocarbon, as measured by the instrument, had always been below 1 ppb. This was the first evidence of a transient accumulation of methane on Mars. The following day, Mars Express measured from orbit a concentration of 15 ppb over Gale Crater, as was revealed years later, when the retrieved data were re-analysed. After this peak, methane has no longer been detected by either Curiosity or Mars Express.

The origin of Martian methane has been debated. On Earth, this gas can come from geological processes such as the serpentinization reaction, which occurs in hydrothermal vents. If the environment is rich in carbon dioxide (as occurs in hydrothermal environments), this gas can combine with the molecular hydrogen produced, thus generating methane and water. In addition, on Mars, solar ultraviolet radiation can react with organic matter deposited on the surface by micrometeorites or cometary dust, also producing methane. Therefore, methane is not a molecular biomarker as it can originate chemically. However, on Earth, methane is mainly produced by biological processes, by the metabolic activity of about sixty species of anaerobic methanogenic archaea belonging to the classes *Methanobacteria*, *Methanomicrobia*, *Methanococci,* or *Methanopyri*. The rapid disappearance of methane measured on Mars is also difficult to explain, unless one assumes that it was absorbed in rocks or consumed by methanotrophic microorganisms somehow analogous to those that metabolize it on our planet.

Since 2013, Curiosity has detected seasonal variations in methane between only 0.2 and 0.7 ppb. Consistently, the Nadir and Occultation for Mars Discovery (NOMAD) and Atmospheric Chemistry Suite (ACS) instruments on the ExoMars Chemistry Suite (ACS), onboard ESA's ExoMars Trace Gas Orbiter (TGO), since 2017 the most sensitive gas analyser ever operating on or around Mars (with a detection limit of 0.05 ppb), never confirmed the presence of either methane or formaldehyde (HCHO, a product of its photochemical degradation). However, during the night of 9 June 2019, Curiosity's SAM again detected methane to the highest concentration ever measured at ground level: 21 ppb. Interestingly, neither Mars Express nor TGO detected this hydrocarbon when they flew over Gale Crater the

next day. However, although TGO instruments in Sun occultation mode are highly sensitive, the presence of airborne dust in the lower atmosphere limits their observations to a minimum altitude of 3–5 km, whereas Curiosity's detections are at the surface. Meteorological models of atmospheric circulation have been used in attempts to explain the transport and mixing of methane over this crater during the day and at night. Their results suggest that the rate of degradation of the molecule could be higher than that on Earth, or, alternatively, that it could be rapidly reabsorbed by Martian rocks.

These apparently contradictory observations could find common ground in the assumption that they pertain to very small methane emissions from sources located at the northwest rim of Gale Crater, and relatively close to the rover, thus excluding the existence of globally widespread sources of methane. This could lead to point detection by Curiosity, and non-detection by TGO, and favours the non-existence of a global background, larger than the upper limit (0.02 ppbv) observed by TGO. Therefore, ruling out the extreme coincidence that Curiosity landed right next to the only source of methane on the planet, the interpretation of the data collected either by SAM or TGO instruments is more complex than anticipated. There is still a true scientific debate around the Martian methane.

3.2.5 Search for Extinct or Extant Forms of Life

NASA's Viking missions were, as discussed above, an unprecedented technological and scientific success. The Viking 1 and Viking 2 orbiters had a mass of 3527 kg and were launched on 20 August and 9 September 1975, respectively. They were inserted into Martian orbit on 19 June and 7 August 1976, respectively. Thereafter the two orbiters investigated the planet's atmosphere and surface using infrared spectroscopy (to analyse traces of water vapor) and infrared radiometry (to thermally map the surface). In addition, their cameras took more than 50,000 high-resolution images of the planet's surface. After selecting the landing sites for 1 month, the ca. 600 kg landers detached, and soft-landed at Chryse Planitia (22.27° N, 312.05° E: Viking 1, on 20 July 1976) and Utopia Planitia (47.64° N, 134.29° E: Viking 2, on 3 September 1976). The science instruments of the Viking landers included a biology suite, GC/MS, X-ray fluorescence spectrometer, seismometer, magnetometer, meteorology instrument, and stereo colour cameras (NASA-JPL, 1988).

Both Viking landers took surface samples using a robotic arm and analysed them for composition and signs of a form of life. The biological suite contained three different and complementary experiments (Klein, 1978; Klein et al., 1972). The first was called Labelled Release (LR), whose rationale was simple and straightforward: aliquots of the retrieved portion of Martian soil were supplemented with various biomolecules in solution (including some amino acids and formic acid), all of them radioactively labelled with ^{14}C isotope. After 7 days of incubation, the production of labelled carbon dioxide was measured: its detection would indicate the existence of metabolic activities, i.e. heterotrophic microorganisms that would consume the

labelled nutrients and release CO_2. In parallel, heat-denatured samples (incubated for 3 h at 160 °C) of the regolith were analysed as a control.

The second instrument was the Pyrolytic Release (PR), which was based on the controlled degradation of the organic matter present in the regolith by heating it under controlled conditions and in the absence of O_2, followed by the identification of the small molecules generated. The experiment consisted in taking a sample of Martian soil (and in parallel another as a control, which was sterilized as for the LR), illuminating it for 5 days with visible artificial light (avoiding UV radiation), and then adding the gases CO_2 and CO labelled with ^{14}C. Thus, if any photosynthetic (or, in general, autotrophic) microorganisms were present in the sample, they would fix the labelled CO_2 and produce radioactively labelled organic matter, which could be identified after decomposition by pyrolysis.

The third biological instrument was the Gas Exchange Experiment (GEX). It worked by introducing a sample of Martian regolith (and, in parallel, a sterilized control) into a small container filled with a controlled gas mixture, providing nutrients, and then studying the exchange of gaseous molecules that might occur between the sample and this "synthetic atmosphere". Specifically, the possible emission of CO_2, CH_4, and N_2 was analysed, as these gases could be indicative of the presence of different metabolic activities.

The results obtained by the suite of biological instruments were initially controversial, as the LR of the two Viking landers produced positive results from samples analysed over several days at their respective sampling sites, while the corresponding controls rendered negative results (Levin & Straat, 1979). In parallel, other control experiments conducted in different environments on Earth never produced false positives or false negatives. Therefore, the production of labelled CO_2 could indicate that unknown microorganisms capable of degrading organic matter were indeed living in the soil on Mars. However, the results obtained by the other two instruments in the suite were negative. Additionally, it was not possible at that time to detect the presence of organic matter in the Martian regolith with the GC/MS. Therefore, most of the scientific community assumed that the positive values obtained by LR were due to the poor signal-to-noise ratio of this instrument, and that the production of labelled CO_2 had been due to abiotic chemical processes operating on the surface of Mars. Consequently, NASA's official explanation of the analysis was that no signs of form of life had been detected on Mars by Viking missions (Soffen, 1976, 1978), although the controversy remained (Levin & Straat, 1981).

Since then, Microbiology has gained a lot of knowledge. Just few microbial species can be cultivated. Some need years or more to duplicate meaning that they have a very slow metabolism. This direct cultivation in such a different environment has very few chances to give any result. Then the goal is to determine, using "robotic geologists or geochemists" rather than "robotic biochemists or microbiologists" (Fairén et al., 2020; Huidobro et al., 2022), which places could be the most favourable to the preservation of traces of ancient biochemistry or possible traces of any form of life.

The scientific community awaits with much interest the scientific findings of the 2028 Rosalind Franklin Mission. This interest stems from three unique features: (1) The age and mineral composition of Oxia Planum, the selected landing site; dated at 4.0 billion years in age. Oxia will be the oldest site to be explored so far; its mineralogy is dominated by regional, finely layered clay deposits that record the interaction of liquid water with the very early crust. (2) The Rosalind drill will reach as deep as two meters, accessing increasingly preserved subsurface samples that have remained protected from the ionizing radiation thus preserving chemical organic molecules and possible relics of past form of life. (3) Its very advanced instruments can interrogate the exact same mineral grains for mineralogical and organic composition. The instrument tasked with characterizing organic molecules includes a laser desorption capability able to bypass the perchlorate obstacle; the complementary combination of multiple techniques within MOMA (Mars Organic Molecule Analyzer) enables both the detection of high molecular weight, non-volatile organics and patterns, and the identification of volatile and semi-volatile lower molecular weight molecules. The MOMA instrument is able to desorb organic molecules without dissociating oxidants mixed in the soil—something that has complicated most organic detections since Viking (Vago et al., 2017, and articles in the same issue).

3.3 Robotic Missions: Perspectives

The next expected step was the final leg of the Mars Sample Return (MSR) program, with the significant contribution of Europe through the providing by ESA of a rover to pick up the samples prepared by Perseverance and laying on the ground (the Fetch Rover) and the spacecraft receiving the sample container in orbit and bringing it to the Earth. After the success of Ingenuity, NASA decided that the samples will be retrieved by one or several Martian US drones. At the beginning of 2024, NASA reviewed the overall programme and costed the remaining leg at more than 11 billion of dollars. NASA decided to put this return leg on hold and intends to ask private companies to propose an affordable alternative. This is pushing this sample recovery on Earth beyond any foreseeable future.

On the other hand, it seems that China is preparing their own Martian sample retrieval for the beginning of the next decade. India also intends to continue the success of Mangalyaan and prepare a new mission. Finally, the Exomars second leg, the Rosalind Franklin Rover, is due to be launched by the end of the twenties through a new cooperation between ESA and NASA.

Beyond these robotic missions, both private entities and public institutions are placing crewed visits of Mars in their priorities. At this stage, beyond claims, there are several knowledge gaps to fill up. Numerous hypotheses are on the table (see Chaps. 5 and 6), including very ambitious ones requiring a revolution with nuclear (thermal or electric) propulsion and a shortcut through the Solar System using a gravity assist manoeuvre around Venus.

In short, the future of Mars exploration is full of promises, presenting exciting challenges but in an uncertain future. NASA put Mars robotic and crewed exploration high in priority but in sequence with lunar exploration. Both China and India presented the next steps to Mars as imminent while using the crewed exploration of the Moon as a training ground. The coming decades augur significant innovations in our knowledge and possible visits of the red planet.

3.4 Take-Home Message

The scientific and technological research strategy on Mars has so far relied on robotic missions, which have provided us with valuable information about the red planet. The space race initiated by the Soviet Union and the United States led to the first successes of Mars's robotic exploration in the 1960s and 1970s, by means of flyby missions, orbiters, and the first controlled landings on the surface. As of June 2024, a total of 52 missions led by a range of nations (Soviet Union, United States, Japan, Europe, Russia, India, United Arab Emirates, and China) have been launched to Mars, about half of which were successful.

Two main drivers have supported the development of these missions. The first is technological progress, including improvements in launch systems, communication and control of the trajectory during the journey to Mars, orbital insertion, entry-descent-landing phase, rover mobility on Martian regolith, surface drilling, or controlled atmospheric flight. The second is scientific: a desire to understand Mars's geological history, to investigate the presence and loss of surface liquid water as well as the existence of hydrated minerals and subsurface regions with liquid brines or subglacial lakes, to understand the geological activity that still exists today, to find and map organic compounds including methane, and to search for traces of extinct or extant life.

One of the main lessons learned from these missions is that Mars had a large amount of liquid water at a time when life was emerging on Earth (about 3.8 Gyr ago), and that its surface may have been habitable until about 3 Gyr ago. Therefore, some form of life (related or not to Earth's microorganisms) may have existed on early Mars. If this has been the case, Martian life might have evolved to adapt to the profound environmental changes that took place during the Noachian and early Hesperian periods. Chances remain, however, that it keeps persisting in residual habitable environments, perhaps in the deep subsurface. Despite all we have learned about our neighbouring planet, grand discoveries remain to be made.

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Chapter 4
Mars Historical and Ethical Context: Past, Present, and Imagination



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The ethical, societal, and political issues of Mars settlement seem like very distant problems, both spatially and temporally. However, there is a certain urgency to these matters. Whatever humanity does in the coming decades will affect generations

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upon generations of future humans and other living beings, as well as their environments. The initial agreements about how resources are governed and what kind of regime is established can persist for a long time. There can be a "Founder Effect" in space (Elvis, 2022, 164). This engenders questions about where to begin. Are the primary goals scientific, political, or economic? Will they be realised through international cooperation, or as a private enterprise? Will the first steps be taken in a just manner and for the common good? A settlement can become "locked-in" to initial technological, economic, behavioural, or political solutions, or caught in *path dependencies* (cf. David, 1985; Goldstein et al., 2023; MacAskill, 2022). Inertia can take hold. Moreover, the process of designing and planning Mars settlements can itself become locked in this way, burdened by problematic histories, colonialist ways of thinking about settlements, and problematic values [On colonial histories and decolonial futures related to space, see Salazar & Gorman 2023 part 3 of their volume *The Routledge Handbook of Social Studies of Outer Space* (2023)]. It may even be the case that humans are neither technologically *nor* socially ready to settle other worlds (Billings, 2019).

Whoever gets to Mars first may set the pattern for future Mars activities, so the underlying reasons shaping the planning for Mars missions, the motivations and justifications, are not a trivial matter. Space ethics literature has identified multiple reasons of this sort, ranging from adventure, resource extraction, science, spiritual insight, and human survival (Schwartz et al., 2021). In *Sovereign Mars*, Jacob Haqq-Misra (2023) discusses Mars settlement in terms of risk mitigation, exploration, and transformative value. The desired goals and underlying values are important, because they motivate this extremely expensive and risky endeavour. These questions are important for *pre-settlement* discussion. Understanding some of the pre-settlement issues may also help us to anticipating problems and dilemmas that humans will face on Mars. However, this is a pre-settlement discussion, whereas our focus in this book is mainly upon *in-settlement* issues, that is, issues that we anticipate encountering in a settlement (Puumala et al., 2023).

Our core aim is to look at the most pressing societal, political, and ethical issues across time, at different stages of Mars settlement, starting from crewed missions and proceeding step by step towards larger settlements, all the way to self-sufficient Mars societies and ultimately, the (unlikely but still possible) prospect of a terraformed Mars as a fully habitable planet (a "planet B"). Ultimately, what can be learned from these pre- and in-settlement issues may affect the justification for settling Mars. If the ethical consequences of settling Mars are severe and negative, they may give reasons not to pursue such a goal.

Although it might still take some time to actually set foot on Mars, the planning has already started, and public declarations about Mars settlement have been made. These plans and declarations have been made in certain historical and cultural context, and now that these plans are on the table we need philosophy, humanities, and political and social sciences to evaluate and address them. Mars settlement is surely a massive undertaking of engineering and scientific rigour, but we need to also carefully consider what is a good life and a good society, and how they can be realised on a planet so different from the one we inhabit now.

4.1 Cultural Context and Symbolic Aspects

Aspirations for crewed missions and human settlements on Mars arise within a historical and cultural context. The collective memory of humanity has a significant impact on motivation, and upon our understanding of what it is possible to strive for. In many cases in history, conceptualisation and visualisation have been instrumental in the realisation of what was previously just a dream. In that sense, imagination precedes realisation. The planet Mars has been known since prehistoric times (Hartzman, 2020; Hotakainen, 2009; Markley, 2005; Shindell, 2023). Visible to the naked eye, early stargazers easily recognised it as a celestial light that wandered over the sky, distinctly from the fixed stars. It was known in prehistoric China, Egypt, India, and Assyria, and it was included in ancient mythologies. The Mesopotamians associated it with Nergal, the god of war, death, and disease. As red planet, associated with blood, it was named after the god of war, Ares, by the Greeks. The Romans called it Mars after their own god of war. As one of the five known planets of antiquity it was assumed to have an impact upon life on Earth, and the rise and fall of kingdoms. It figured prominently in classical and early modern astrology as the planet associated with the head, heat, dryness, and short-tempered choleric temperament. In alchemy, the planet corresponded with iron (for obvious reasons of colour) and shared variations of the same symbol.

The planet was first observed through a telescope by Galileo Galilei in the seventeenth century, but the astronomer did not detect any details (Dick, 1984; Morton, 2003). The first detailed observations were made by Christiaan Huygens, who observed the southern polar cap and a huge dark triangle on the surface of Mars. William Herschel studied the surface of Mars and concluded that the polar caps were made up of snow. He further calculated the revolution around its axis to 24 h 37 m and in 1784 announced to the Royal Society that Mars has an atmosphere and inhabitants.

During the late nineteenth century, Mars was still regarded as a prime candidate for extraterrestrial form of life (Crowe, 1986). In 1877, Giovanni Schiaparelli published the first detailed map of the planet, including 79 lines that he called *canali*, which connected patches on the surface, whether they were rivers or artificial canals. Percival Lowell eagerly defended the idea that Mars was inhabited by an intelligent civilisation and wrote three books about the planet (Basalla, 2006). He observed 200 lines that he assumed to have been dug by an advanced civilisation in order to drain the water from the polar regions to water their farmlands.

Mars played a significant role in the twentieth-century popular culture and science fiction (Clark, 2022; Crossley, 2011; Hendrix et al., 2011; Miller & Stein, 2016), as the legendary crisis stricken Barsoom of Edgar Rice Burroughs novels (1911–41) where the canals had dried up, as the source of the alien invaders in H. G. Wells' *War of the Worlds* (serialised in 1897), as well as Orson Welles' radio play of 1938. It is the location for Ray Bradbury's collection of short stories *The Martian Chronicles* (1950), and appears in movies such as *The Angry Red Planet* (1959), *Total Recall* (1990), and *Mars Attacks!* (1996). Kim Stanley Robinson's

Mars trilogy (1992–96) assumes a lifeless planet and is a continual reference point for terraforming discussions. Optimistically it sets the start of the process in 2027.

The debate about whether Mars was inhabited continued until the first photographs of the surface were taken by the US spacecraft Mariner 4 in 1964. The Soviet Mars 2 and 3 in 1971 were the first probes that landed on the surface of Mars. But of these two, only Mars 3 survived, and only for 14.5 s. Viking 1 and 2, which landed on Mars in 1976, gave a final blow to the idea that Mars was thriving and full of life, when sending back to Earth pictures of an apparently barren, stony desert. However, Viking 1 also took photos from the region Cydonia Mensae on the northern hemisphere that showed a formation resembling a humanoid face, which was soon called the Face on Mars. The formation was interpreted by some enthusiasts as a structure sculptured by ancient intelligent inhabitants. A high-resolution picture taken in 2001 by Mars Global Surveyor of the same area showed that it actually looked like any other mountain. The appearance was a combination of shadows and the human tendency to recognise faces (pareidolia). Be that as it may, it is important to highlight the fact that the discovery of the very first extremophilic microbes (in a hot spring in Yellowstone National Park, USA) was made in 1969 and that this started the hunt for other types of extremophilic microbial life up to the present day. This discovery showed that life can be found even in apparently barren and stony landscapes, and even under the most extreme conditions. Thus, with the advance of our understanding of extremophilic life forms and of our abilities to detect any form of life, our chances of finding extraterrestrial form of life have improved, and this further motivates the search for rudimentary forms of life on Mars and the hope that humans may be able to look for form of life in situ.

From a low orbit, Mars Global Surveyor, launched in 1996, managed to chart the entire surface of Mars. Mars Reconnaissance Orbiter, launched in 2005, aimed to find landing spots for future crewed missions, while the Curiosity rover, launched in 2011, assessed the habitability of Martian environments over time (May 2017). In recent decades, ideas of actual crewed missions, settlement, and the search for form of life have continued to shape the widespread public interest expressed in movies like *The Martian* (2015). Through the ages, Mars has had a significant impact on human culture and imagination (Rabkin, 2005), as a putative influencer on earthly life, as a potential habitable world, and as a neighbour planet to explore and settle. These imaginations and cultural preconceptions of crewed missions to Mars and of Martian settlements are not only a historical, obsolete background to contemporary efforts. They drive the motivation to go there and form further collective human expectancies and endeavours.

We can expect these cultural and imaginary conceptions to change if humans succeed in reaching Mars and settling there. Some of them will wither away—e.g., if a form of life on Mars is found to be non-existent, perhaps even impossible. Others will rise, but what cultural expressions emerge is hard to predict. One thing is certain: human culture and imagination will change, and crewed missions and settlements, successful or not, will affect life on Earth. As *human* missions they will not only be scientific and technological endeavours. They will also shape what it means to be human, and our sense of humanity's place in the Universe. Lastly,

should unexpected discoveries lead to a totally new understanding of life, they could have an enormous impact on human culture (Dunér et al., 2013).

4.2 Theological Aspects

From the outset, human space exploration has been marked by ritual and religious behaviour both on a political level and on an individual level by various astronauts. During the early space race, when the two superpowers (the United States and the Soviet Union) were competing against each other, religious arguments were also used to support this race. On the American side, the space race also became a race between Christians, who believed in God, and the God-denying communists in the Soviet Union (Weibel, 2017). On the individual level, different astronauts have engaged in different religious behaviours, for example, gestures performed by Yuri Gagarin and repeated by all the cosmonauts who have subsequently flown from the Baikonur base, the reading of verses from the Bible during the first crewed mission around the Moon, Buzz Aldrin's prayer before walking on the surface of the Moon, the blessing of the crews by an Orthodox priest, bringing other religious texts to the ISS, such as Bhagavad Gita, the Upanishads, the Mezuzah, the Bible, a written message by the catholic Pope, and so on.

When human beings realise that they have reached the limits of their usual human capacities, or when they realise the "seriousness" of what they are about to do, they may decide to make a symbolic gesture, a religious gesture. Perhaps the arrival of the first human crew on Mars will be the occasion for such a gesture. These gestures would mark the transportation of immaterial cultural heritage from Earth to Mars by representing different aspects of human culture from atheism to different religions and worldviews on Earth.

Once the first human steps have been taken on the surface of the red planet, and as human stays become longer and longer on Mars, the question of religion may also arise among some of the crews. Depending on their philosophical and religious convictions, and their attachment to their own traditions, the people on Mars will be able to respond to this question in a variety of ways: from religious indifference to a desire to construct new rituals or even a belief system in keeping with their Martian situation. The development of human populations on Mars could give rise to the emergence of new religious forms and, consequently, new theological discourses.

4.3 Anthropological Remarks

Until now, humans have been Earth-bound creatures. Numerous studies exist, with a specific focus on planetary exploration, such as the recent HI-SEAS Mars analogue mission. However, all simulations of planetary habitats have been tested on Earth. Apart from the stays on the ISS, the effects of extraterrestrial conditions on

the human mind and body have not yet been studied in other natural analogues such as the lunar surface on a long-term basis.

During the eventual expansion of humanity to Mars, future anthropologists will have an opportunity to observe the emergence and the formation of culture in real Earth-time and rethink the idea of Earth-boundness. That is, not only the evolutionary but also the cultural and emotional connections to Earth. An overview effect, experienced by astronauts when viewing the Earth from space, from orbit or on a lunar mission, has already been claimed and evidenced, with some dependence upon cultural background. It is regarded as an overwhelming, intense feeling and a cognitive shift, in thinking about the self and the whole (White, 1998). A sense of relationship to Earth can shift when it is viewed from space.

The question of how the extreme detachment will affect the emotional and mental health of individuals who set foot on Mars naturally emerges from this idea, and from astronauts' accounts of their stays in Earth's orbit. Will they feel the first signs of moral and psychological distancing or, on the contrary, Earth-sickness, of a broad consequence of gravity weaker than on Earth, one that no one has ever felt before? That would be the ultimate extraterrestrial experience. One that could not be properly replicated on Earth. Indeed, humanity could suffer from a kind of interplanetary space travel jet lag as we evolve into a multiplanetary civilisation and usher in a new era of great explorers. It is highly likely that Martian settlers will reevaluate their relationship with Earth and forge new relationships to our home planet (Capova, 2019).

4.4 Political Motivations and Factors for Mars Race

Getting to Mars first will be a major political victory. Even if the claimed reasons for going to Mars are often scientific and economic, and these reasons are shared by all parties, there is no doubt an underlying *political interest* in being the first to reach the red planet. We can certainly find plenty of political motivations for defending the massive effort of putting boots on Mars and eventually settling it but the following four mark important lines spanning interest groups, stakeholders, and politicians: national exceptionalists, libertarians, scientists and engineers, and communitarians (Schmidt & Bohacek, 2021). Schmidt and Bohacek argue that while national exceptionalism historically has been a strong driver for building monuments, and for ventures such as the Apollo program, the rhetoric of opening new frontiers has usually legitimised a destructive expansionist politics. This, in turn, could lead to a new imperialism. At the same time, megaprojects driven by a motivation to prove national greatness have served as an instrument for identity formation. This could be counterproductive vis-à-vis building cosmic consciousness of humanity to overcome wars, but it also helps to supply a political rationale and to defend project investments on a massive scale of the sort required for a crewed mission and actual settlement.

One could criticise libertarianism on the account that it inclines to ruleless governance. Applied to space, it treats the Solar System like a giant grocery store. It can also be claimed that libertarians ignore the fact that the actual possibility to embark on the massive mission to settle other planets is not a merit of a single person having the current opportunity to do so, but a result of centuries-long collective work of different experts. Libertarians have the potential to quickly create strong economic structures but may not pay as much attention to norms such as human rights and environmental issues. This driver inclines to the creation of monopolies as the most competitive end up controlling everything in the respective settlements—As with national exceptionalism, there is a risk that monopolies may become empires, thereby undermining liberties.

Maybe the most obvious driver emanates from scientists and engineers as without these people, no settlement can be built, survive, and thrive. However, technologies and practical solutions to problems cannot be developed without politics. Principally, science cannot claim that their results are apolitical. Instead, scientists working on specific topics which could be related, even not directly, to settling space programme, cannot ignore the ulterior motive. These intentions to do something, in the end, are political intentions. Matters could be different if science could instead provide clear results demonstrating that settling on Mars is not possible. Several groups of people are discussing to justify or to fight the idea to settle (beyond exploration) Mars. By the time being, both opposite groups find, in the scientific results of the Martian exploration and in the technical developments, arguments to support their claims.

The communitarian political driver is based on cosmopolitan thought but also on the principles found in the Outer Space Treaty (OST, see Chap. 5). These treat space as the province of all mankind, open to all nations. This communitarian view sees all of humanity belonging to the same, terrestrial community as well as other more localised communities. Their interpretation of the OST is that approaching space expansion in any other way would go against the principles of the OST. Here the worry is that non-communitarian interpretations could lead to conflicts. Waging wars would be extremely expensive and would immediately turn the settlement efforts into a shared disaster for everyone involved. Therefore, according to the communitarian view, if settling Mars is to be successful, the settlement governance would have to reflect strong redistributive obligations. These obligations can be captured in principles such as treating space as a global commons or as the common heritage of mankind, advocating against national identities to avoid international tensions, and advocating for global responsibility. That is, accepting a common Solar System responsibility for humanity as a whole.

In general terms, liberal democracies struggle to explain massive investments in Mars missions, especially if it is not clear what benefits it brings to the society (Billings, 2017). On the other hand, it is liberal democracies and the capitalist economic system that enable libertarian dreams of multibillionaires willing to fund missions far beyond their economic viability, while still returning profit from selected technological developments (Davenport, 2018). However, even liberal democracies can vote for nationalist-prone leaders who would consider settling

space as a way to revive the nationalist vibe in a society to keep themselves in power or simply to deepen the national pride emanating from the technological and scientific achievements, as could be claimed to be the case with the Apollo Program (Logsdon, 1976).

It should be noted that the national exceptionalist driver may be faltering under the impact of globalisation processes. Complex technological developments cannot depend on the national scientific and technological developments of a single country. Based on the negative associations of the national exceptionalist driver for space expansionism, the ensuing geopolitical consequences (Doboš, 2019), and the arguably cosmopolitan tone of the OST (Švec & Schmidt, 2022), some commentators argue for a model based instead on cosmopolitan thought (Deudney, 2020). Otherwise, the settling of space could become another domain of contest turned into an existential threat to humanity. The cosmopolitan model of space settlement governance could be achievable if the OST is genuinely reflected upon, the general interests are made vulnerable to geopolitical contestations, and the opportunities remain genuinely open to multiple nations. The Artemis Accords could be seen as an answer to the space treaty stalemate at the UN COPUOS. A stalemate which arises because achieving a consensus between more than a hundred states is understandably a challenge. However, the intentions behind the Artemis Accords are not to draft new international law but rather to tell interested parties in the Artemis Program, aiming to put humans on the Moon surface permanently, what rules will apply. Perhaps a more cynical view is that the intension of the Accords was simply to establish the US interpretations of some of the contested principles of OST. The defenders of the Accords claim that they do not go against the OST and other applicable laws, while some others think differently, especially because of the safety zones (for more on safety zones, see Sects. 8.4.1.2, 8.4.2.2, and 9.2.1.2). However, if China, Russia, or India decide to organise a mission on their own, we might get close to showing that the national exceptionalist driver prevailed. As USA is barred from cooperation with China in space by its own law, we can at least say that the cosmopolitan model requires imagination beyond the national security dogmas if it is to be achieved (Burke, 2013).

As we have seen, many of the political motivations in the Mars race are related to economic expansionism and often fuelled by ideas of exceptionalism. Extractivist attitudes can be present across different drivers for Mars missions. The leading idea is that the economy is driven primarily by the extraction of non-renewable resources and is often coupled with visions of exploiting resources on Mars or elsewhere beyond Earth. In the light of modern political history on Earth, starting to exploit resources beyond Earth may appear to be a tempting next step once globalisation coupled with capitalism has run its course and created a global, capitalistic market facing shortages of key resources for further expansion. However, in the book *Surviving 1000 Centuries: Can We Do It?*, the astronomers Bonnet and Woltjer (2008) convincingly argue that resource exploitation elsewhere in the Solar System would be very costly and that its potential is limited compared with achieving sustainable development on Earth. Such a sober assessment implies that there is little reason to think that settling and exploiting Mars would make much of a difference

with regard to humanity's access to material resources—at least in the foreseeable future. Though perhaps in the more distant future a period of abundance may be achieved. This could be achieved if humans can access the asteroid belt between Mars and Jupiter (using Mars as a stepping stone) to extract abundant resources that are there (Elvis & Milligan, 2019). Nonetheless, in the long run scarcity waits for us again, as argued by Elvis (2022), because "vast is not infinite". Moreover, economic and especially exponential growth may surprise us. To give an example, if 2% annual growth rate persist for another 10,000 years, the economic output would have to be ten million trillion times more than our current global economy produces for every atom within 10,000 lightyears from Earth (MacAskill, 2022).

Given the complexity of modern society, political motivations for settling space cannot ultimately fit into one category. The typology used here should rather serve the analysis of various stakeholders' interests that might drive and rationalise participation in the new space race efforts. It seems inevitable that participation will also become a driver for political divisions, struggles, and conflicts of a sort familiar on the Earth. On the other hand, settling space has the potential to open up new political alignments and struggles in the settled places where participants and stakeholders build new political ideologies and governing institutions tailor-made for the new era of humanity.

4.5 Planetary Protection

Planetary protection related to human missions to, and eventual settlements on, Mars, is very different from that in relation to lander and robotic missions, because humans cannot be sterilised to the same degree as machines. If we were, we would die since we cannot function without the microbes that live on and inside us. This means that the risk of contamination of the Martian environment is substantially higher for crewed missions.

Planetary protection is divided into protection against forward contamination, that is, against the contamination of extraterrestrial environments by Earth microbes, and protection against back contamination, that is, contamination of the Earth environment by extraterrestrial microbes (Persson et al., 2018). Forward contamination and back contamination present different practical challenges and are also partly based on different ethical assumptions (Persson, 2021; Persson et al., 2018).

Protection against forward contamination, the way it is defined and operationalised today, is essentially about protecting astrobiological science, that is, about avoiding false positives and/or destroying life forms that can contribute knowledge about the target body (in this case Mars), or about form of life on that body, or in general (Cockell, 2020; Crawford, 2005; Cypser, 1993; Persson et al., 2018). As such, this points towards a view that the Martian environment, as well as any Martian form of life, only matters to the extent it has value for science. This assumption has been criticised (Persson et al., 2018) [for a longer review, see Persson, 2012]. Some claim that Martian microbes are moral objects in their own rights, which means they

have their own interests that must be respected (e.g. Cockell, 2005, 2011). Others claim that microbes (Martian or others) cannot be moral objects, for instance, because they are not sentient, that is, they cannot feel or experience anything subjectively (Persson, 2012, 2019), or because they are not intelligent (Smith, 2009). Even so, they can have value to us that goes beyond their value for science. They can, for instance, have value as resources for bioengineering by human settlers (Cockell, 2005, 2011; Persson, 2019). They can also have value that goes beyond their practical usefulness in the same way as we value a unique landscape or an original painting on Earth. The idea that extraterrestrial microbial life can have end value, that is, they can have value beyond being a source of knowledge, or a resource, is sometimes put forth as a strong reason or even a moral obligation to take extra precautions against forward contamination (Persson, 2012, 2019, 2021).

In the same way, an uninhabited Martian landscape can need protection from being taken over by Earth life. That is because it can have value beyond it being a source of knowledge, resource, or a refuge for humanity, or as one author suggests, because we are required to value everything in the cosmos due to our physical relation and connectedness to the cosmos at large (Lupisella, 2016). Finally, some ethicists claim that species and landscapes (even uninhabited landscapes), and not just individual living beings, can have interests that need to be protected, and thus be moral objects in their own right (Lee, 1994; Rolston, 1986). For more on environmental protection, see Sect. 7.7.4.

In practice, these different theoretical standpoints result in discussions about how much resources need to be spent on decontamination (Debus, 2006; Fairén & Schulze-Makuch, 2013; Newcombe et al., 2005; Schon, 2009) and even whether humans with their high bioload should ever set foot on Mars because a full protection against forward contamination cannot be guaranteed. Another practical discussion regards the relative importance of protecting Mars form of life and pristine Mars environments relative to the expected benefits of sending humans to Mars, ranging from the idea of making humanity a multiplanetary species as a safety mechanism against human extinction (on existential risks, see Sect. 7.4.1), to seeing Mars as a tourist destination for the super-rich (Smith, 2009). Finally, even if we only value extraterrestrial form of life for its potential contribution to science, we still need to discuss how far we should go in terms of decontamination in light of the question of how much we owe to future generations of astrobiologists. That is, how meticulous we are in the decontamination process, and whether humans will be allowed to land and what restrictions we impose will determine whether or not or how long it will take before the planet will be contaminated to the degree that it will severely affect the search for and scientific study of its life (Greenberg, 2011; Persson, 2021).

The value basis for protection against backward contamination is different from that of protection against forward contamination. Contrary to the latter, the former is not only a matter of protecting science, but it is primarily about protecting Earth life (Cockell, 2020; Persson, 2021; Persson et al., 2018). The ethical basis for this is rarely discussed but assigning high importance to protecting life on Earth is compatible with many ethical theories. This does not mean the question of backward

contamination is void of ethical dilemmas, however. One important issue has to do with where to draw the line for what is safe enough. That is, how safe do we need to be to make sure that material from Mars does not contain viable material before we let it be brought back to Earth, and how much security do we need to implement at the storage facilities and laboratories on Earth where material from Mars is stored and handled? These are questions that are discussed already in connection with robotic missions that will bring samples of Martian materials back to Earth. If we send humans on return missions to Mars, these questions will have an additional dimension. When the returning material is not Martian regolith but human beings it will not be so easy to say "sorry, we cannot distinguish between your own biome and possible Martian biomaterial with sufficient certainty to pass the strict anti-contamination standards so we need to leave you on Mars or dump you in space".

4.6 Take-Home Message

While Mars may seem to promise a fresh start, plans for permanent settlements necessarily include expanding our terrestrial history to a new environment. If humans do go there, they will carry a part of their cultural and political diversity with them. The histories and futures of the people on the two planets will remain intertwined.

We must consider the political drivers for settling Mars and allow ethically informed discussion on these matters: the decisions made today will affect generations of the distant future. The introduction of humans to Mars will mark a radical intervention to Martian environments, and care must be taken to protect the planet from undesirable—and irreversible—consequences. The biological footprint of human activities could, for instance, affect indigenous ecosystems, if some exist.

Mars exploration may alter conditions on Earth. It will affect how humans perceive themselves, the Earth, and the Universe. It may also, if Martian life is brought back with us and contaminate our home planet, impact all terrestrial life. While the likelihood of such an occurrence is extremely low, its severity if proven would be so high that it must not be neglected.

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Chapter 5
Legal and International Context: Law and Disorder



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Any project to explore, exploit, and occupy the planet Mars, whatever the scenario or the scientific, technical, economic, political, or strategic objectives involved, raises fundamental legal questions about what might prevent, constrain or, on the contrary, facilitate it.

This chapter starts with an *introduction to the Martian Law* designed to take stock of the most basic features of this legal framework as it exists today: who created it, to whom does it apply, what does it say, who monitors its compliance, and which judge sanctions violations?

The challenges that need to be met to enable sustainable human settlement on Mars are then reviewed. A sustainable settlement could involve autonomy and quasi-independence (planet B). It would ideally exist within a peaceful, internationally recognisable framework, respecting the aspirations of the various public and private players, while preserving the terrestrial and extraterrestrial environments and the interests of future generations.

It is essential that all parties in this international endeavour are subjected to the same legitimate rights and obligations, and that each party's legitimate or exclusive rights, i.e., its investment, property, labour, security and peaceful occupation, etc.,

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are protected. They must not come at the expense of other equally legitimate rights and obligations, in the unavoidable context of large-scale international cooperation.

These other essential rights include freedom of movement, assistance and rescue of goods and people, environmental and planetary protection, free and non-discriminatory access to public markets and resources, free and undistorted competition, the sharing of scientific data, the exchange of data necessary for the safety and security of installations and activities, and the interoperability of different systems.

Solutions are already being discussed in several intergovernmental agreements, such as those drafted by the United States for the Artemis program to explore the Moon (the Artemis Accords), or, concerning Earth orbit, with a view to a future global Space Traffic Management *(STM)* system based on *Space* Surveillance and Tracking (SST) and Space Situational Awareness (SSA) capabilities. Following on from this, in Sect. 5.2.3, alternative sharing and redistribution solutions based on economic law, such as concessions, delegations, and mixed partnerships will be reviewed. What they all have in common is that they limit each party's right to protection and exploitation to the strictest possible limits in terms of content and duration.

5.1 Introduction to Martian Law

One might assume that going to Mars, a celestial body far from Earth, beyond the reach of its gravity, its traditional telecommunications links or real-time connections, far beyond any national borders and yet untouched by our species, could exempt us from the application of terrestrial laws and their judges.

This is not the case. Right at the start of the space era, a wide array of States' government whether or not they were involved in this endeavour, adopted the Declaration of the Legal Principles Governing the Activities of States in the Exploration and Use of Outer Space (United Nations, 1963). Under the aegis of the United Nations, this declaration defines the contours of an international law governing human activities in and towards outer space or celestial bodies (asteroids, moons, and other planets in the solar system). These principles were enshrined in the Outer Space Treaty (OST) adopted by the United Nations General Assembly, which came into force on 10 October 1967 (United Nations, 1967) and is commonly referred to as the "Space Treaty". The treaty has been ratified by almost all the nations of the world, making it an international legally binding text.

The Outer Space Treaty (Art. I, 2°, and 3° paragraphs) enshrines the principle of freedom of exploration and use of outer space and celestial bodies subject to certain conditions.

First and foremost, all space activities must comply with international law, including the Charter of the United Nations, in the interest of maintaining international peace and security and promoting international cooperation and understanding, with an absolute ban on the placement of weapons of mass destruction in orbit,

and on the surface of the Moon and other celestial bodies (Art. III and IV of the Space Treaty). Activity must also safeguard the interests of future generations and of humanity (cf. concept of "Province of all Mankind", 1967 Outer Space Treaty, Art I, 1st paragraph) (United Nations, 1967). This also entails duties to protect the terrestrial and planetary environments, and to ensure cooperation and mutual assistance between the various parties involved. Finally, the treaty prohibits any national appropriation of outer space, including the Moon and other celestial bodies by any means, including by claim of ownership and by means of use or occupation (Art. II of the Space Treaty).

5.1.1 Space Treaty

Technically, this treaty has created a public international space law. Primarily, this law binds states in their relations with each other, while obliging them to ensure that it is respected under their jurisdiction by the various government authorities, public administrations and agencies, nationals, companies, and private individuals concerned. This transposition results from Article IV of the treaty, which stipulates that each state must "authorise and continuously supervise" the space activities of its "non-governmental organisations", starting with launches from Earth into space.

From the 1980s onwards, this regime led governments to draw up national legislation or specific agreements for intergovernmental cooperation, to accompany the privatisation of these operations on a global scale.

Having already dealt with launch operations, satellite control, and the return of space objects, this legislation, in the contemporary context of the New Space era, will expand to cover private in-orbit services, i.e. docking, resupply, maintenance, repair, re-orbiting or de-orbiting of objects already in space. They should also include crewed flights and permanent installations of bases in orbit or on extraterrestrial soil managed by private companies.

Under the terms of the Convention on Registration of Objects Launched into Outer Space adopted on 12 November 1974 (Article VIII), each vehicle, whether crewed or not, launched and maintained in Earth orbit or any orbital trajectory beyond must be registered by the appropriate state, which must notify the Secretary General of the United Nations, who is the custodian of the international register (United Nations Office of Outer Space Affairs, 1974). Legally, this registration makes it possible to assign each private space object to a national jurisdiction. The state of registration also assumes international liability in the event of damage to third parties (U.S. Department of State, 1972). This system only provides for the registration of "space objects" as based on their stabilised orbital coordinates relative to the centre of the Earth. In this sense, it is not suited yet to the registration of stations located on extraterrestrial soil, in other words real assets.

On a practical level, it should also be noted that the launching and registration states transfer part of their international liability to the private operator concerned, via their national legislation. In this way, the amount of compensation payable by

the latter is capped, and the private operator is obliged to insure its share of the risk on the insurance market. For example, the private space launch company Arianespace operates from Kourou in French Guiana. This launch facility is based on French territory, under French jurisdiction and governed by the "CSG Agreement", a European treaty under the auspices of the ESA. Each launch of an Ariane rocket is protected by compulsory insurance taken out by the operator and covering damage up to a value of 60 million euros. Since 1980, a government guarantee has covered, without any time limitation, the portion of damage caused to third parties which exceeds this value.

Such intergovernmental or national systems of public coverage for third-party nonintentional damage caused by their private nationals, either by fault or not, are the concrete expression of the "responsibility" and "liability" commitments listed into in the 1967 treaty (art. VI and VII) and the 1972 "liability" convention. Such state coverage provides a solvent guarantee to any potential third-party victim, over a period and at a level of compensation that exceeds the capacity of most private industrial or commercial enterprise subject to the economic and cyclical hazards of its market.

This state guarantee also constitutes a form of support to the space industry. In this respect, it is legally considered as a public aid, which under international law comes under the jurisdiction of the World Trade Organisation (WTO). The granting of national subsidies to commercial enterprises is regulated and controlled on an international scale, and even regionally, as within the European Union, in order to avoid distortions of competition, protectionism, and discrimination in market access. As a result, a growing number of space-related activities are now governed by international economic law.

The State of launch or registration will nonetheless remain liable without time limit, under space law, to the third-party victim of the damage in the event of a gap in private coverage. Space-related activities must also deal with the law governing radio frequencies and telecommunications. Almost all spacecraft and on-board crew are connected by radio to control centres on Earth. All phases of the various types of space missions are concerned, i.e. from the Launch up to the end of the mission in a remote place of the Solar System or in orbit around the Earth. Any spacecraft or landed asset on a remote celestial body needs telecommunications to fulfil its mission: broadcasting, observing or sending meteorological data, etc. These communications are using bands within the radio frequency spectrum, the use of which is regulated internationally by the International Telecommunication Union, another body under the aegis of the United Nations but independent in its governance.

5.1.2 Legal Basis Needed for a Human Mission to Mars

Through the Outer Space Treaty, the United Nations has demonstrated its ability to promote peaceful and fruitful space exploration. A balance is achieved between the need for cooperation to pool risks, mobilise investment and skills between

governments, their space agencies and private companies, and the realities of competition and rivalry between these same players.

So far, however, this positive assessment has only applied to public–private activities in Earth orbit, or to intergovernmental programmes for crewed stations or scientific exploration of celestial bodies.

What's more, there is no supranational body with the power to enforce these laws directly at national level. Nor is there a permanent court of justice dedicated to space law, which would cover the entire spectrum of space activities, as we have seen in the case of economic issues. Typical of public international law, the Treaty is based on an implicit consensus between states. No one has an interest in working outside this framework. The party could ensue sanctions or retaliatory measures from others. It could therefore forgo to benefits to itself, such as freedom of exploration and use, the right to compensation in the event of damage, and legal certainty for all investments and activities.

This fragile balance has held up well to date, based on the legal principles forged within the United Nations until the relative failure of the 1979 Moon Agreement (the Agreement Governing the Activities of States on the Moon and Other Celestial Bodies; (United Nations Office of Outer Space Affairs, 1979)). This agreement has only been signed and ratified by only a few States that were not representative of the entire space community. The major space powers like USA, Russia, China, etc., neither signed or ratified it. The main cause of the disagreement, which persists to this day, concerns the proposal that the setting up of a dedicated international organisation should be a prerequisite for any form of appropriation or exploitation of resources from extraterrestrial soil or subsoil (under Article XI). Thus, principles of the 1967 Outer Space Treaty may be considered incomplete, in particular regarding condition of exploitation of in situ resources, but they have never been called into question as to their basic principles such as non-appropriation nor territorial jurisdiction on outer space orbit and land, nor have they been able to muster a consensual counter-proposal, or a solution, ruling or arbitration decision that has been seriously contested or challenged.

It is therefore on this basis that we propose to study the future law of human mission to Mars.

Additional measures will be needed to address the issue of resource exploitation for the needs of human mission and a new extraterrestrial economy, both in situ and to Earth in real time or on return from missions. It will also be necessary to redefine the sharing of responsibilities and risks between private and public players on an international scale, to ensure greater predictability and security of the respective investments, as well as a peaceful and propitious living environment for the humans who will work and live in these facilities on a daily basis. Finally, the conditions for the return to Earth of vehicles, goods, crews, and passengers from Mars will need to be addressed in their entirety, to avoid contamination, distortions of competition, or varying tax treatment.

5.2 Responsibilities of Public and Private Stakeholders

When talking about liability, the real question is who is going to be responsible for repairing or compensating for damage when it occurs. While under traditional conventional international law many entities can be held liable for damage, a system of derogations or exceptions has been established for space activities because of the risks inherent in the field, but also because of the rules laid down in international treaties governing space law. Only states—or certain international organisations meeting strict criteria—may be held liable for damage caused during space activities (Sect. 5.2.1). Specifically, an international organisation, i.e. the European Space Agency, has been granted launch authority status. This requires not only a declaration of acceptance of the 1967 Treaty and the 1968 Agreement, but also that most of the member states of the international organisation are party to both texts. Therefore, the European Space Agency will be considered as a state, within the meaning of the 1967 Space Treaty.

However, while at the international level only states are responsible for space activities and private companies enjoy a "*true state umbrella*", at the national level, private entities remain subject to specific rules if they want to be able to access space activities and obtain the authorisation of the state for that purpose. In certain defined cases, the state may, after having incurred its international liability, bring an action against the private entity responsible for the damage (Sect. 5.2.2).

In addition to this traditional liability linked to the occurrence of damage, more and more attention is paid to "space pollution" and rules have been implemented to limit space debris, which creates risks for Earth in particular (Sect. 5.2.3).

5.2.1 State Responsibility

Since Article 1 of the 1967 Outer Space Treaty allows freedom of space only for the benefit of states only such states may register objects sent into space and may then be launching authorities. It has been established in Article 8 of the same Treaty that "*The state party to the treaty on whose register an object launched into outer space is registered shall retain, under its jurisdiction and control, that object and all the personnel of that object, even though they are in outer space or on a celestial body"*. The state which registered the object is therefore responsible for it, its personnel, and the damage it may cause.

Thus, even if the space operation is organised by a private entity, the state which authorises this activity remains responsible since the space freedom of private entities is ancillary and conditional to the freedom of the state. Article 6 of the 1967 treaty clarified this point by stating that "*States party to the treaty have international responsibility for national activities in outer space, including the moon and other celestial bodies, whether undertaken by governmental bodies or non-governmental entities*". More practically, the launching state is then entrusted with two levels of responsibility:

- A general responsibility for authorisation and monitoring of space activities and
- Financial liability in the event of damage. The mechanism for this second responsibility is detailed in the 1972 Liability Convention (U.S. Department of State, 1972) and again provides for two types of liability:
  - Absolute liability, without capping, for damage caused to the air or ground and
  - Liability for fault in the event of damage caused in space, a liability for which the State may be exempted in the event of fault on the part of the requesting State or of an entity for which the latter is responsible

This responsibility of the state has a major political but also practical stake. It makes it possible to simplify the implementation of the system of liability in the event of damage since the victim state will have only one interlocutor, the state having caused the damage, and will have only one route of action, the diplomatic route. It should be noted, however, that the launching state cannot be held liable for damage caused to its own nationals or to foreign nationals who participated in the space operation which generated the damage (see below).

This system of liability based solely on launching authorities is particularly protective of all other "stakeholders" in space activities. They seem to be absolved of all responsibilities. But, if this is indeed the case at the international level, a system of shared responsibility could be established at the national level, allowing states to pass on to the other (private) stakeholders, at least in part, the burden that it must bear.

5.2.2 Operator Liability

In order not to bear sole responsibility for the space activities they authorise, some states have made the authorisation of the space activities of the various entities conditional on the subscription of insurance covering a certain amount for damages. Thus, the state will be financially liable only for damages exceeding the amount for damages covered by this insurance.

In addition, states have established specific principles for space contracts to reduce their liability. Thus, in many of those contracts, there is a clause stipulating the principle of non-recourse between participants in a space operation. Then it is possible to avoid any search for liability (cross-waiver of liability). Hold Harmless Agreement could also be signed making possible to attribute to one of the contractors the liability for damage which might be caused to third parties.

Thus, while the state is indeed the only entity responsible at international level, the system put in place at national level enables to place this responsibility, at least in part, on the entities that carried out the launching operation. However, only one operator will be covered by the terms of the contract, and once again, the liability will only be passed on to a single entity participating in the space operation, whereas several will intervene to carry it out. This system then replicates the same flaws as the international system and may have been the subject of criticism, particularly when liability clauses could have been transferred to subcontractors.

5.2.3 *Collective Responsibility for Combating Space Pollution*

The mass of objects in orbit has been increasing linearly for decades and is today estimated at nearly 10,000 tons. Importantly, about 1 million objects larger than 1 cm and more than 150 million objects larger than 1 mm are presently in orbit. Some authors, such as Christophe Bonnal, speak of the "dawn of space pollution" (Bonnal, 2019). Indeed, these numbers are expected to skyrocket in the years ahead.

Space debris poses a significant danger to current and future generations alike. An object in orbit is usually in orbit for 1 to several thousand years, and it travels at orbital speed at about 7 km/s. As the number of objects in orbit increases, so does the risk of collision, and any collision causes fragmentation, further increasing their number. Any object in low earth orbit will eventually fall back to Earth, and this could cause casualties, because big pieces of metal and some of the space debris—such as titanium and some types of steel—do not burned up when they re-enter the terrestrial atmosphere.

All objects in orbit also generate a risk either for the launching activities, and to various active satellites. Both numbers are also increasing, which in turn increases the risks of collision with space debris. This issue has not been ignored in space law. However, it is difficult to know the precise registration of several debris that would collide with an Earth asset or a satellite, so no defined liability regime has been put in place at this time. There is a system of accountability that emerged more philosophically than legally with the adoption of international recommendations to combat the development of space debris by the Inter-Agency Space Debris Coordination Committee (an international governmental forum of the 13 major space agencies) in 2002. This system also resonated in the European Code of Conduct for Space Debris Mitigation, with standards finalised in 2000 and approved in 2004 (United Nations Office of Outer Space Affairs, 2004). However, we stand today at the beginning of regulation; standards are not binding and therefore, as their non-compliance does not entail any penalty, they are not always respected.

5.2.4 *Responsibilities Towards the Rest of Humanity and the Future Generations*

5.2.4.1 The Rights of Future Generations on Crewed Missions to Mars

Considering both present and future generations in human missions to Mars is one of the new challenges facing the law. Future generations have been defined as "individuals who belong to the future in relation to a current person or humanity, with whom they share a genealogical connection" (Gaillard, 2011) or "human community in the making" (Le Bris, 2012). The concept of the rights of future generations has begun to take form within terrestrial legal frameworks, necessitating a forward-looking perspective. It has become a vector of a moral and then legal obligation

(Sands, 1995; Gaillard, 2011) to meet current needs without compromising those of tomorrow through preservation and transmission: "create such conditions as will ensure that the needs and interests of future generations are not jeopardized by the burden of the past, and to hand on a better world to future generations" (Declaration on the Responsibilities of the Present Generations Towards Future Generations, Unesco, 1997). It entails an obligation on the part of present generations toward future generations, notably principles 1 and 2 enshrined in the Declaration of Stockholm (United Nations Conference on the Human Environment, 1972). These concepts have recently been subjected to an attempt at clarification with the Maastricht Principles on the Human Rights of Future Generations in 2023.

The concept of the rights of future generations has found a favourable consideration within environmental and human rights law, addressing concerns primarily rooted on Earth. However, this doesn't mean it cannot manifest in space. Outer space represents the ultimate of spatiotemporal imagination, prompting thoughts of the boundless expanse of space and vast scales of time. For instance, the first photo of Earth from outer space has been seen as crucial in realising our interconnectedness through time and the need to protect humanity in the time to come (Gaillard, 2011). Current ambitions in Outer space encompass missions and projects over very extended periods. Aspirations for exploration can easily span generations. Certain concerns related to human missions to Mars inevitably lead us to think about the rights of future generations.

At first glance, the rights of future generations do not appear to interfere with crewed Mars missions. One might argue that the settlement of Mars may serve as a contingency plan for the long-term survival of humanity, particularly if Earth becomes unable to support life. Another perspective posits that it may eventually necessitate the exploitation of space's mineral resources to meet Earth's resource needs, if their preservation and transmission efforts have proven insufficient, notably in the face of a growing world population (Beurier & Kiss, 2017). However, the right of future generations focuses only on present needs, while respecting that even though the needs of the future are not perfectly discernible today, they will certainly be fundamental tomorrow. In other words, one could argue that this obligation cannot extend to mere hypothetical scenarios, which are sources of legal uncertainty, especially in the absence of specific regulations and a shared consensus on human Mars missions. Paradigm shifts cannot be ruled out, particularly when we link it to the declaration of the rights of future generations, which implies the preservation and perpetuation of humanity in the Art. 3 of the of Declaration on the Responsibilities of the Present Generations Towards Future Generations (UNESCO, 1997). On the other hand, there are immediate and long-term needs related to scientific research and the sustainable utilisation of new environments like the planet Mars. It has been argued that "to have meaning, it must impose consistent obligations not only on us but also on our children, grandchildren, and so forth, until the end of humanity" (Kiss, 1998), that implies a certain stability in trends—without being strictly rigid. In the realm of environmental issues, the rights of future generations have been founded on a distinct rationale rooted in conservationism, emphasising the safeguarding of natural and cultural resources. The scope is concretised by the notion of

legal irreversibility. Besides, these rights involve preventing irreversibility to preserve resources for the benefit of future generations, or, conversely, it entails implementing it to pursue the same objective, notably when an asset is designated as heritage, and its condition will remain unchanged (Kiss, 1998). Doubts also arise, notably, a more recent definition restricts the perception of future generations to those "who will inherit the Earth" (Maastricht Principles, 2023). We should consider these legal elements in space law and endeavour to clarify the responsibilities of stakeholders regarding the rights of future generations in the context of human missions to Mars.

The concept of future generations' rights is not foreign to the scope of space law, even if it is not always articulated in these precise terms. Its early manifestations are already enshrined in the foundational Outer Space Treaty of 1967. The development of space law is deeply rooted in the idea of humanity with space activities exclusively oriented towards "the benefit and in the interests of all countries". Multilateralism is already impactful because the nations of the world agreed to regulate legal situations that did not yet exist and were meant to serve future interests, resulting in several generations succeeding one another up to the present day. As a result, Art. 1 of Outer Space Treaty explicitly states that "there shall be free access to all areas of celestial bodies" (United Nations Office of Outer Space Affairs, 1967).

Space law has played a significant role in conceptualising the rights of future generations in its terrestrial applications and could even be considered as a special rights of future generations (Gaillard, 2011). Indeed, these rights of future generations have been founded upon and are deeply rooted in the extension of the concept of the common heritage of humanity (Kiss, 1998; Gaillard, 2011) and even more broadly, in the concept of humanity, as outlined in the Moon Agreement (United Nations Office of Outer Space Affairs, 1979). Its earliest and most extensive expressions shows explicitly in Art. 4 that "the interests of the present and future generations shall be duly taken into account" in the use and exploration of space. Its scope is broad, as it depends on the province of all mankind, extending beyond state parties and encompassing the "human community as a whole" (Le Bris, 2012). Its secondary manifestations are found in the common heritage of mankind. This encompasses the seabed, and celestial bodies along with their natural resources (Art. 11 of Moon Agreement, United Nations Office of Outer Space Affairs, 1979). The Moon Agreement, which confers this status, establishes an obligation towards future beneficiaries. Art. 11 of the Moon Treaty states that "States Parties to this Agreement hereby undertake to establish an international regime, including appropriate procedures, to govern the exploitation of the natural resources of the moon as such exploitation is about to become feasible" (United Nations Office of Outer Space Affairs, 1979). This status encompasses features that must be considered in all human lunar exploration projects, including the nonappropriation of resources, peaceful use, non-discrimination, rational use, and, particular the sharing of benefits and transmission to future generations (Beurier & Kiss, 2017).

Subsequently, the rights of future generations have evolved within terrestrial perspectives, particularly by intertwining with environmental law and human rights. It

has notably evolved through legal vector from principles of environmental law, such as the precautionary principle (Gaillard, 2011). This principle necessitates a high degree of caution in activities if the actual risks of contemplated actions are unknown (La Vieille et al., 2018). In this context, a parallel can be drawn between these principles and the Planetary Protection (Art. IX OST), especially the COSPAR Policy guidance which supports "a conservative approach consistent with a lack of knowledge of Martian environments and potential life" (9.3) (COSPAR Panel on Planetary Protection/COSPAR Bureau, 2021). One aspect of Planetary Protection with its distinctive aim of preserving science and scientific advancements, was conceived from the outset to address potential contamination. Further details are specified by the COSPAR guidelines to promote "scientific investigation during space exploration" (Coustenis et al., 2023). The guidelines were last updated in 2024, which demonstrates their evolution over time including for Mars. They address human missions to Mars, making it explicitly clear "the intention of this planetary protection policy is the same, whether the mission to Mars is conducted by robots or by human explorers", then "planetary protection objectives must not be relaxed to accommodate a human mission to Mars". Currently, Martian missions fall into Level III for flyby missions and Level IV for direct contacts (landers missions). Special regions can be delineated where "terrestrial organisms are likely to replicate" and "have a high potential for the existence of extant Martian life form" (category IV, c). So, human missions to Mars are restrictive, and even the ability for future explorers to contribute to exploration hinges on the condition that human-associated contamination is controlled and thoroughly understood" according to the COSPAR guidance (9.3). Planetary protection does not strictly prohibit missions, but it imposes a constraint that limits it in the immediate future.

5.2.4.2 New Environmental Considerations of Future Generations' Rights

In an environmental perspective, responsibility towards future generations is continuously evolving. How can this concept of future generations in its current concept and ongoing evolution be applied to the exploration of outer space? A more comprehensive understanding can be attained by observing what is happening on Earth, for example, in terms of the legacy of knowledge.

The space treaties accord paramount importance to the freedom of scientific research on celestial bodies (Art. I OST and Art. 6 of the Moon Treaty). By analogy, the Art. 2 of the Protocol on Environmental Protection to the Antarctic Treaty (Antarctic Treaty Secretariat, 1991) has established a "natural reserve, devoted to peace and science", ensuring environmental protection and excluding mineral resource exploitation "other than scientific research" (Art. 7). These provisions cannot be modified for a period of fifty years (Art. 25), excluding all other uses until 2048, after which revisions may be requested by a majority of the Antarctic Treaty Consultative Parties. A Mars framework could follow this model and impose such restrictions with modifiable durations.

The UNESCO World Heritage Convention also mentions the conservation of natural and cultural heritage for exclusive scientific purposes and for the "transmission to future generations" (Art. 4) (UNESCO, 1972). According to Article 2, this includes "natural features consisting of physical and biological formations or groups of such formations, which are of outstanding universal value from the aesthetic or scientific point of view; geological and physiographical formations and precisely delineated areas which constitute the habitat of threatened species of animals and plants of outstanding universal value from the point of view of science or conservation; and natural sites or precisely delineated natural areas of outstanding universal value from the point of view of science, conservation or natural beauty" as designated by the States (Art. 3). There is also a "List of World Heritage in Danger" which allows for the listing of properties threatened by "serious and specific dangers" such as any "large-scale public or private project or rapid urban or tourist development projects" (Art. 11). This model constitutes another approach to determining the forms that future generations are entitled to expect, as well as those that can be formalised to serve them.

So, in the spirit of the rights of future generations, we recognize the profound regard for science that must resonate in human missions in space. The legacy of knowledge is a crucial element, and it becomes even more so in a Martian context. Indeed, the challenge of future generations' rights is to identify the fundamental needs that can be presumed to endure for all eternity. Among these are "life, the transmission of life, food, water," but in the Martian climate and considering current scientific knowledge about the absence of life, the only "permanent data" to which one must "cling" (Kiss, 1998) are science and the future fascination that these natural spaces promise.

Further considerations can be explored, particularly by examining intersections with environmental law (Esslinger, 2023), and by encompassing all streams of thought related to the rights of future generations that we should attentively consider.

5.3 Sharing Responsibilities and Contributions Between Various Stakeholders

As we have outlined above in the "*Introduction to the Martian Law*", the governance models in force in the international order and in connection with space activities are shared between different types of actors. As the space activities changed from a purely competition between nations to a sector offering commercial opportunities, the governance evolved and diversified. It began with regulatory bodies within intergovernmental international organisation (mainly the Committee on the Peaceful Uses of Outer Space depending on the UN). Then some intergovernmental organisations have been charged by the states to organise a specific sector, a sector as the International Telecommunication Union (ITU) mixing the states representatives and in consultation with industry. Then several intergovernmental organisations have been privatised to provide a permanent service for some sectors which are able to provide a permanent service to customers (INTELSAT, EUTELSAT, etc.).

In short, in the space sector and related sectors (telecommunications, trade, etc.), the regulation of space activities is sometimes public, sometimes private, and does not allow "driving forces" to be involved on an equal footing nor to really work together. However the equal participation of all stakeholders is obviously essential for the proper conduct of space operations, the achievement of which is in the common interest of each of them, whether public or private. The difficulty of public and private actors to regulate space activities effectively on their own calls for a rethink of governance models. This is particularly true for missions to and on the red planet, whose exploration and use are, as with other celestial bodies, "the province of all mankind", as stated by the Outer Space Treaty (OST).

This is why it seems appropriate to draw inspiration from what exists in another sector which, like outer space, is one of the world's common goods/public goods: global health (Runavot, 2014). In this sector, original governance institutions have been set up and developed: public–private partnerships (PPP), whose structure and organisation appear to be particularly well suited to the Mars object. This could enable public and private actors to work together, without the former losing control over the activities of the latter. Above all, this structure provides a response to the growing financing demands of space activities. In fact, these PPP are based on a hybridisation of their structure as well as of their activities which blurs the line between the public and the private as much as that between the national and international legal orders. It is not simply a matter for States and traditional international organisations to let private actors invest the space sector and satisfy their commercial interests. The partnership structure of these institutions makes it possible to maintain public authority over private actors. At the same time, the extent to which non-governmental actors are involved in PPP is a qualitative leap forward in the institutionalisation of international relations, which have become global. In this way, these PPP supplant the institutional experiments mentioned above, while at the same time extending them (see Sect. 5.2.2). The partnership governance model proposed for the effective exploration and settlement of the planet Mars has two main features, inspired by existing PPP in the field of global health.

On the one hand, it would be *an institutionalised partnership*, i.e. endowed with its own organic structure that guarantees its autonomous operation to pursue the specific mission for which it was created (exploration and/or settlement of Mars). However, it would not necessarily be personified in the international order, which necessarily has an impact in terms of accountability and responsibility of its public and private partners.

On the other hand, this model of governance would entirely be based on a *partnership approach* that went beyond simple collaboration between public and private stakeholders. Consequently, the PPP for Mars (PPPM) would organise joint, if not common, management of its missions by its public and private partners. In other words, both public and private partners should be represented on the steering body with equivalent prerogatives. And, to ensure that the steering body works effectively, given the plurality of partners involved (particularly private partners), representation should be organised by "constituencies". These groups of organisations, institutions, or companies will name their representatives. With a few exceptions,

the multiple partners would thus renounce individual representation in favour of joint representation with those they share the same interests. There are many advantages to this.

Firstly, this avoids making a priori clear-cut choices between entrepreneurial, scientific, and regulatory visions (Clerc, 2021) of the mission entrusted to the PPPM.

Secondly and correlatively, such a PPPM should enable a coherent and coordinated approach by centralising functions: in the first place, it would produce the legal framework (normative function) and then, it would implement it at the appropriate level in accordance with the logic of subsidiarity (executive function). As far as the normative function is concerned, two additional advantages should be highlighted: (1) such as a PPPM could certainly be assimilated to an "international organisation" within the meaning of the OST, so that all its activities and the law produced within it should comply with this treaty. Besides, the partner States and international organisations would be held responsible for any breaches of the major principles that this treaty contains and affirms; (2) This would help to define how to exploit the natural resources of the planet Mars in the interests of *all* the partners and not just some of them. Indeed, while Mars' status as a "common good" means that its uses should not generate a profit, it does not prevent each partner in the PPPM from having an interest in it—a "return on investment"—in the broad sense of that expression and whatever its financial, scientific, or politico-diplomatic nature.

It is therefore necessary to specify the partners in this PPPM, to identify their contributions and their consequences.

Levels of Responsibilities and Contributions of the Various Stakeholders

The governance of missions to or on Mars might therefore combine public and private actors, but the nature and degree of involvement of each are not identical. The involvement of the various partners will depend on the interest—the "return on investment"—that each expects from the mission entrusted to the PPPM. At the same time, the contributions of the various partners might complement each other and not compete or be redundant.

Above all, the terms and conditions of involvement are subject to the OST. This text affirms general compliance with international law (including the United Nations Charter) and lays down the well-known principles of non-appropriation of celestial bodies (Article II) and peaceful use of outer space (Articles III and IV). It also requires the use of outer space to be non-discriminatory and therefore inclusive (Article I§2), i.e. for the benefit of all states and, beyond that, of humanity. It is in this sense that the PPPM has a mission of *common interest*. Finally, the OST establishes an essential distinction between *regulatory authorities*, which are necessarily public, and *other operators* (whatever their nature). All activities carried out in outer space and on celestial bodies—hence activities to and on Mars—must be authorised by an (inter)state partner and remain under its control and hence its responsibility. This raises the question: How do space-faring nations shield their international responsibility against the increasing "public liability for private activities"?

It is important to identify the partners and specify the terms and content of their involvement in the governance of the missions to and on Mars, making a distinction

each time between the authorities and other stakeholders *acting on Earth* and those *located on Mars*. In fact, the planet Earth will necessarily be the place where the initial impetus is provided, whether this be political, normative, or financial; on the other hand, implementation, as well as day-to-day and administrative management, would be carried out on the red planet.

Thus, the PPPM might bring together the following authorities and stakeholders, divided into constituencies: the group of space-faring nations; the group of other states (in line with Article I of the OST and Article 11§7.d of the Moon Agreement); the group of intergovernmental organisations (IGOs); the group of non-governmental organisations (NGOs); the group of private industry; and the group of voluntary donators.

Obviously, further details and distinctions are required as it relates to the contributions and responsibilities of each of these constituencies and the partners they include

- For the **group of space-faring nations**, the input would be above all political and legal, even if governments remain essential "investors" in the space sector. It is vital that sovereign states remain the regulatory authorities for space activities, whatever the evolution of their purposes. Given the origins and foundations of space law, it is up to the traditional space-faring nations (United States, Russia, Europe), the new ones (China, India, Japan), and the emerging ones (Argentina, Brazil, Israel, North Korea, South Korea, Iran…) to regulate space activities. This regulation can be done not only by laying down and reiterating the national and international rules to be respected, but above all by issuing the necessary licenses to private operators and monitoring the proper conduct of the licensed activities in compliance with the rules laid down. In addition to making public funds and existing infrastructures available (bases at Kourou for Europe, Baikonur for Russia, Cape Canaveral for the United States, or Jiuquan for China, etc.), the sovereign space-faring nations would therefore take responsibility for operations carried out under their control on or towards Mars. If Mars is to be explored or settled in the interest of humanity, this supervision and responsibility would have to be collective and joint. Thought would then have to be given to the relationship with the objective liability of the launching state under the Convention on Liability for Damage Caused by the Launch of Space Objects, which came into force on 1st September 1972. Obviously, the role of the national space agencies would be essential here and it would certainly be for them to represent their state in the PPPM. On this point, and in view of the sovereignty of states, it is not certain that it would be possible to waive individual representation of the space-faring nations, unless we could imagine a periodic rotation between the states of each of the sub-groups: traditional, new, and emerging powers. As to the "return of investment" for the states, it would be above all diplomatic and geostrategic, without forgetting the financial interest: the regulating states offload the bulk of part of the cost of operations to private actors, while reaping the dividends of industrial spin-offs.
- The **group of other states** should not be overlooked since activities towards and on Mars (as on other celestial bodies) must be carried out for the benefit of all,

without discrimination as stated by the OST and as an example, according to the principle of transparency recalled by the, USA led, Artemis Agreements.

- The **IGO group** seems essential: On the one hand, the IGOs already constitute an association of states wishing to pool their resources in the service of a collective interest; on the other hand, the specific purpose of each IGO makes it possible to cover the various challenges of a mission to and on Mars. Because of their purpose and their experience, this group would certainly include, at the universal level, not only the UN (via its COPUOS), INTELSAT, but also the WTO and even the WHO (since such missions certainly involve health issues). At regional level, we should mention EUTELSAT, ESA, and ARABSAT, and even certain regional economic integration organisations. Like sovereign states, IGOs involved in a mission to or on Mars should ensure control of the mission and thus be liable for damage caused not only by their agents, but also by private operators authorised by them or by one or more of their Member States (Article VI of the OST). They should, first and foremost, ensure compliance with the requirements of international law, whether these are enshrined in binding norms or in *soft law* secreted under the aegis of the United Nations or a group of two or more states (like the Artemis Accords).
- The **NGO group** should mainly comprise scientific NGOs, first and foremost the International Science Council (ISC) and its Committee on Space Research (COSPAR). But human rights and environmental NGOs would also have their place to ensure that the interests of the planets Earth and Mars, as well as those of present and future generations, are promoted and considered. The expertise of these NGOs is essential. As a consequence, these NGOs could strengthen their influence.
- The **group of private industries** is also heterogeneous in terms of the different professions involved (manufacture of launchers, electronic components, telecommunications companies, even service companies such as travel agencies, etc.). The various industries would bring their knowledge and their ability to innovate but would obviously only commit themselves if they were guaranteed to generate a profit commensurate with the industrial risk borne in the mission. At the same time, they would benefit from the liability umbrella provided by sovereign states and IGOs which, as is the case for ESA programmes, could agree to compensate damage exceeding a certain amount. Of course, this can only be considered if the space-faring nations and IGOs themselves consider that the benefits they derive are equivalent to or exceed the cost of this liability. It is all a question of balance and cost/benefit reciprocity between the public and private partners.
- A **final group** would be made up of **volunteers**, individuals, or charitable foundations, who would contribute to the funding of the missions to and on Mars, and whose sole interest would be the success of these missions.

This partnership governance model, which appears essential for small missions to and on Mars, must certainly be modulated according to the exploration and settlement scenarios, which must be distinguished (see Sects. 7.5, 8.4.1, 8.5.1, and 9.2) depending on the scenario envisaged. Depending on the strength of the link

maintained with planet Earth, the (partnership) governance model of a Martian settlement is subject to variations. From a legal point of view, the governance system to be conceived then moves from augmented reality (small missions) to a totally virtual reality where everything has to be imagined (Planet B).

5.4 Take-Home Message

Establishing an appropriate legal and institutional framework for crewed bases on Mars does not require any ground-breaking innovation. Currently, the legal framework for space activities is essentially intergovernmental at the highest level. It is extended to private players through national legislation, agreements, or the creation of dedicated organisations. The difficulty therefore lies at the political and strategic level, in the ability of governments and their representatives to build a consensus around relevant and sustainable solutions.

A solid foundation exists in the form of the 1967 Outer Space Treaty. This treaty enshrines the freedom of peaceful space exploration and the responsibility of participants in the event of damage to third parties. It grants protection of the terrestrial, orbital, and planetary environments, and the duty of assistance between players. It forbids the appropriation and national jurisdiction over any territories in outer space, including on Mars. These principles have been transposed into national legislations following the privatisation of space operations. They are fully transposable to the activities of future crews on Mars, at least in the absence of consensus on other solutions.

The main challenges will be to conceive a form of governance involving the various stakeholders, both public and private, and to supplement the Outer Space Treaty with a new international economic law. A fair balance will be needed between the need for cooperation and assistance, healthy competition between private players, protection of the environment, investment, and the interests of all stakeholders and future generations. There is nothing utopian about this.

Settling on a larger scale would mean establishing local law and governance to deal with all the administrative, civil, economic, and everyday life issues on Mars that can no longer be controlled from Earth.

Finally, in the hypothesis where a territory becomes independent of all Earth sovereignty, an interplanetary agreement between the two planets will have to be devised. Its purpose will be to manage the relations between the two entities peacefully and in their mutual interest, as well as to promote common principles on human rights and on the rights of future generations to their shared environments.

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Chapter 6
Perspectives for Crewed Missions to Mars: Exploration from Orbit and/or Short Stay

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6.1 Why Go There?[1]

The debate "humans versus robots", on Mars or anywhere else will not be engaged here. The decision has been made—by a single entity, a coalition, or a wide international agreement—to send astronauts to Mars. The focus is on what the astronauts could do, search for, or investigate while they are there.

The Science goals described in this chapter are based on published documents, such as the Decadal Survey (National Academies of Sciences, Engineering, and Medicine, 2023) and a NASA document describing a possible architecture for the first three missions to Mars (Drake et al., 2010)

Mars is the furthest frontier that human exploration can realistically envision implementing in the mid-term future. Flying to Mars, landing on Mars, and launching from Mars to rendezvous in orbit to travel back to Earth have not been all mastered, even for a robotic (i.e. Mars sample return) mission. For a human mission the

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challenges are much greater. Nevertheless, several programmes (see Chap. 3) aim to send humans to Mars in the next decades and return them safely.

Assuming that all technologies necessary will have been mastered, sending humans to Mars can have several motivations. The first is likely to be geopolitical as was the case with the Apollo Moon programme (Shelhamer, 2017). This endeavour could result from a competition between two or three groups of countries led either by the USA, People's Republic of China, Russia, or India. It could be also the result of a cooperative agreement between competing groups of nations to set a joint, highly visible goal in the frame of a change in international policy. This was the case for deciding to build the International Space Station (ISS) in the 1990s.

Interested groups and space agencies are developing scientific objectives that could be addressed by human exploration. These goals do not necessarily differ from those of robotic exploration, but in the case of human missions new tools, strategies, and priorities can be considered.

6.1.1 Advantages of Mars for Science

In this section, we describe reasons for exploring Mars to improve our understanding of planetary evolution and the origins of life.

6.1.1.1 Lack of Plate Tectonics

On Earth, tectonic activity has reprocessed most of the planet's early crust. The first billion years of planetary history is not well represented in the terrestrial geologic record. But it was during this period that several important events took place, including the origin of life. Conversely, the absence of Mars plate tectonics has preserved many instances of ancient terrains that are still available for study. Embedded impact craters with high cliffs make it possible to observe various geological layers. A large part of the geology of the planet has been preserved since its formation. While on Earth the tectonic activity scrubbed most of its early geological history, Mars has a well preserved geologic record covering a large fraction of this missing time interval (Beaty et al., 2019).

6.1.1.2 Past and Present Liquid Water

Orbital morphological and mineralogical observations plus lander and rover exploration results demonstrate that liquid water was available—at least episodically—early in the history of Mars. For liquid water to have flowed, the atmosphere had to be denser than today plus provide sufficient greenhouse forcing. The latter is required to compensate for the far distance to the Sun and for the fact that the early Sun shone with approximately 70% of today's brightness. Infant Mars may have

been wetter than today, but very likely remained globally cold. On the other hand, the heat flow from the interior (mantle cooling plus radioactive element decay) would have driven intense volcanic and hydrothermal activity, creating many local instances with some possibility for the development of a form of life, or at least interesting prebiotic chemistry (Vago et al., 2017). We do not know exactly when or how rapid the transition was; however, the geologic record signals a switch from Noachian phyllosilicate-rich minerals that had to form in the presence of water, to more sulphate dominated expressions in the Hesperian, once Mars started to dry up (Bibring et al., 2006; Loizeau et al., 2010).

6.1.2 Scientific Objectives of a Sustained Exploration of the Planet

A comparison of the US decadal survey (National Academies of Sciences, Engineering, and Medicine, 2023), the ESA exploration road map (Mey, 2022), the NASA astrobiology roadmap (Des Marais et al., 2008), and the MEPAG documents (MEPAG, 2020) regarding science objectives for the exploration of Mars, results in a list of science objectives. Their ranking may not always be the same and evolves with the discoveries, the ongoing missions, and the overarching strategy of the agencies. However, the objectives listed across documents remain in remarkable good agreement.

The last decadal survey defines three main goals: (1) determine if a form of life ever existed on Mars, (2) understand the processes controlling the weather and the climate, which are linked to the notion of habitability, and (3) decipher the evolution of the surface and the interior and determine the processes that control them. This encompasses most of the statements expressed through the publications of various institutions. In addition, several technological objectives (e.g. resource utilisation) are proposed to prepare for the human exploration of Mars.

6.1.2.1 Traces of a Form of Life

Discovering whether a form of life ever existed on Mars is one of the principal mission drivers. The search for signs of a past form of life requires a different approach than the search for extant forms of life.

Past Form of Life

If a form of life developed on Mars it must have started at the microscopic level (e.g. bacterial-like cells). However, most likely there was never much chance for more complex (i.e. multicellular) organisms to emerge.

The search for signs of life requires a progressive approach. The first step consists in the identification of past (or currently) “habitable” environments. The notion of habitability is assessed on the basis of evidence for the presence of liquid water

and its physical and chemical properties (temperature, pH, salinity, etc.). In other words, did an environment offer access to water that could be considered "suitable" for metabolic activities? It is also important to determine the duration, frequency, and location of this "habitability", for example, near the surface or in the shallow or deep subsurface. From a biological point of view, it is not the same to have permanent liquid water for millions of years or to have intermittent liquid water, especially if the wet instances are infrequent.

Another key aspect regards the availability of life-important elements such as carbon, phosphorus, nitrogen, sulphur, and organic molecules. This includes understanding their cycling between atmosphere, lithosphere, and hydrosphere. Finally, UV and galactic cosmic radiation are strong on the surface of Mars today. A denser atmosphere may have helped to reduce their levels in the distant past.

In situ investigations can search for morphological and chemical life clues in places with a high biosignature preservation potential. To support the eventual findings, it is also necessary to evaluate and characterise the evolution of the local environment and particularly the parameters which are susceptible to degrade or transform the morphological and chemical signatures. For example, the cosmic ionising radiation dose decreases with depth. Beyond chemical biosignatures, such as important bioorganic compounds, it is possible to look for physical structures or assemblages produced by microorganisms. They could be microscopic (biominerals, cell-like structures) or macroscopic, in the case of the imprint left behind by microbial colonies. On Earth, early life artefacts like stromatolites have been identified (Allwood et al., 2006; Westall, 2008). The most convincing signs of past life will be combined morphological and chemical signatures found in a previously habitable environment. It is important that the body of evidence be carefully constructed using several independent measurements. No one observation can be considered compelling on its own. It is a collection of results that, collectively, cannot be explained away by anything other than life that is required to establish sufficient proof (Vago et al., 2017).

Active or Dormant Form of Life

The presence of an active or dormant form of Martian life cannot be excluded. The first laboratories that landed on Mars, the Viking probes, were equipped to detect possible metabolic activity using active experiments meant to elicit a response from putative organisms. The results were intriguing, but ultimately no positive life detections could be confirmed. The signs that the Viking instruments observed were most likely due to a reaction with chemicals present in the Martian soil. Since then, other missions have attempted to focus on finding "habitable" areas. No other mission has tried to look for evidence of metabolic activity since Viking.

Based on observations of images taken from the orbit, there are some claims about an active life evidenced on some hills of polar regions (Gánti et al., 2003). This is characterised by dark spots appearing seasonally, often at the same location, on those slopes. For several authors these "Dune Dark Spots" could be the effect of seasonal growth and decay of an eventual form of life. They have been observed since the Mariner spacecrafts' time.

It is interesting to note that, in theory, the pressure of the geologic column at approximately 2 km depth should be enough to have subterranean liquid aquifers. If the temperature were to be high enough, subsurface water could exist in a state such that microorganisms could use it. For now, this must remain a hypothesis because we do not have the technology at present to drill that deep on Mars.

The search for a signature of a metabolic activity is the next logical step. This means detecting and quantifying organic molecules—or their remains—having a structure and complexity indicative of a biological function. Taking life on Earth as an example, significant compounds would be large carbon containing molecules like those used in terrestrial biochemistry (e.g. similar to amino acids, nucleic acids, lipids). If these organic molecules were to be different from ours, they could be hallmarks of a "foreign" or unknown form of life. Their biogenic origin could be established based on complexity, function, and for some molecules, enantiomeric expression.

These activities require in situ measurements using a rover equipped with a chemical laboratory (like ESA's ExoMars or NASA's Curiosity and Perseverance), plus further confirmation with analysis of samples on Earth.

A likely beneficial role of human exploration, versus plain robotic mission, is the human intuitive ability to focus on areas that portray distinct, even if unexpected, features, and to draw conclusions from patterns that may not be recognised by remote operators or (pre-programmed) machine intelligence (although the "learning robots", manoeuvred by artificial intelligence may soon be on some occasion smarter than humans in exploration).

6.1.2.2 Climate

Investigating atmospheric dynamics is essential understanding the current interactions between the surface and the lower atmosphere and the dust. This requires extensive and continuous study with appropriate instruments from the ground up to the top of the atmosphere. As on Earth, simultaneous observations from orbit and ground-based assets complement each other. Collecting climate data is also important for improving models, weather forecasts, and spacecraft landing precision—all useful for potential astronauts exploring the surface.

An important scientific goal is to understand the history of Martian climate in the "recent" past (250 Myr) and since early Mars (4.56 Gyr ago) including the thousands of large obliquity changes (Laskar et al., 2004; Salese et al., 2016; Ward, 1973).

6.1.2.3 History of the Surface

The early planetary history of Mars and the Earth have similar features which have mostly disappeared from the terrestrial geological record, while potentially being preserved in the Martian one. Many landforms and processes occurred on Mars that

can be considered as templates to understand what occurred on telluric planets during the early stage of their history.

Mars displays very ancient geological features, with more than 50% of its surface being older 3.5 Ga and some areas as old as 4.1 Ga (Tanaka et al., 2014). The earliest geological record may also contain traces of the chemistry, the biochemistry, and possibly biomorphological artefacts at various scales—although for the former it is important to source the material from areas protected from ionising radiation damage. The lack of metamorphism preserved the pristine state of most ancient rocks.

One of the main scientific goals is to identify current and past water and other volatiles reservoirs. This is important for understanding the evolution of the climate during the planet's history. To help us constrain the location, volume, and timing of volatile cycles that have shaped the surface, we can study surface morphology and the distribution of minerals and volatiles. Understanding the diagenesis processes that have modified sedimentary deposits is necessary to complete our understanding of how ancient formations may have been transformed into what we can observe today.

Another major objective is to determine the absolute and relative ages of geological units. Presently these ages are based on the crater distribution derived from knowledge acquired on the Moon (Hartmann et al., 1999). There are many sources of uncertainty and both models, lunar cratering chronology (Lagain et al., 2024) and Martian features age evaluations are both regularly revised incorporating newly available data (Hartmann & Daubar, 2017). A major step forward in this regard will be achieved once the material collected by the Perseverance rover will become available for study on Earth, following a Successful Mars Sample Return (MSR) delivery of samples.

6.1.2.4 History of the Interior

Mars is smaller than the Earth and Venus. Studying Mars' interior, its composition, as well as the evolution of crust, mantle, and core is key for understanding its formation and history. For example, we know that Mars had a dipolar magnetic field much like Earth's. It stopped some 4.0–3.9 billion years ago. We would like to understand what sustained Mars' magnetic field and how its demise was triggered. Could this happen on Earth? Then there is the issue of the relative frequent shifts in rotational axis tilt. How is this expressed in the planet's various rotating layers, which have different densities and moment of inertia. The planet's early interior dynamics played a fundamental role in shaping the surface environment. These aspects are useful for comparative planetology. Mars is the best-known planet after the Earth and the easiest to explore.

6.1.2.5 Preparing Human Exploration and Extensive Stay

For this section, it is assumed that the first crew is landing on the surface of Mars. If we follow the latest mission design (NASA, 2024b), the landing crew will include just a few astronauts who will visit the surface for a limited period of time. The mission will be a ground-breaking proof of concept for its many novel technologies. It will accomplish studies to prepare for a later, safe, long stay exploration mission.

This preparation will be also based on discoveries made through scientific activities. For example, we can envision the long-term study of the atmosphere from the surface, which will continue after the first landing. The characterisation of the vertical, horizontal, and seasonal distribution of aerosols is of major interest for ensuring a safe landing, stay, and exploration.

The recommendations from planetary protection policy will need to be reassessed when humans enter the Mars mission picture. In the current configuration, described in the "Design Reference Architecture" (DRA) (Drake et al., 2010; NASA, 2024b), responsible human exploration of Mars must not jeopardise further science activities and discoveries, particularly regarding astrobiology goals. The knowledge gained during the first and the following stays may necessitate defining possible special regions, or even no-go reserves, whose exploration would require extreme caution to fulfil COSPAR recommendations (Kminek et al., 2010). For example, to explore some regions, only ultra-clean rovers would be allowed, but no human presence.

6.1.2.6 Ancillary Science

Ancillary science are science activities which address research questions beyond the funded scope of the original study or mission. We could take as example the recording of acceleration data with a dedicated instrument (atomic clocks, accelerometer…s) while swinging by Venus (as a hypothesis) to test some principle of the gravitation. Throughout the cruise phase, in orbit and from the surface it would be possible to study the deep space environment and the radiations. Observations using radio telescopes have been performed during the transit phase on board several Soviet Martian Probes (Mars3, Mars5) (Basharinov et al., 1976). In a prospective workshop, the possibility to extend the baseline of radioastronomy using a radiotelescope deployed during these different phases has been suggested with some preliminary calculations (Duke & Keaton, 1986). The latter possibility is also mentioned in an early report on crewed Mars exploration (Duke & Keaton, 1986)

6.2 What to Do There?[2]

The search for signs of life and the study of the early Mars and its subsequent evolution remain the driving streams for science objectives. The tools to undertake scientific studies have improved in performance and shrunk in terms of mass and volume requirements, not so much for optics, but yes in terms of electronics.

Exploration and scientific activities are not yet fully defined. New avenues for research will open and be made possible by progress in instrumentation and availability of technical resources (mass, energy, heat management, data transmission, and more).

The human exploration scenario is based on a careful, gradual approach. First, a demonstration accomplished with two uncrewed cargo flights transporting the landers and the infrastructure that will be needed by the forthcoming crew on the surface. Later, a crewed mission that may just remain in orbit to perform test operations (Drake et al., 2010), or, according to a later design, land astronauts for a 30-day stay on the surface (NASA, 2024b). These steps follow a similar strategy as that envisaged for Moon exploration, either for the past Apollo programme (Compton, 1989) or for the ongoing Artemis programme (Witze, 2022).

6.2.1 Human Crew in Orbit Controlling a Surface Rover

NASA has gained much experience controlling landers and rovers from Earth (from the Viking landers to the Perseverance rover, see details for various Mars robotic missions in Chap. 2). China has also conducted a successful Mars mission (Tianwen programme). Similar knowledge was acquired also on the Moon by the Soviet Union for the Luna programme (Moon sample returns and Lunokhod) (Slyuta, 2021, 3), India (Chandrayaan programme), and China (Chang'E programme).

The hypothesis of an inhabited mission to Mars without a landing is not mentioned in the DRA (Drake et al., 2010). However, there exist a few publications contemplating the possibility to place a human mission in orbit around Mars and, from there, teleoperate rovers exploring the surface—something called Human Exploration using Real-Time Robotic Operations (HERRO). The concept is not limited to Mars exploration and could be applicable to other targets, such as Venus, the Martian moons, the Moon, and near-Earth objects.

For the Human Exploration using Real-time Robotic Operations (HERRO) mission, the idea is as follows: 26 months before the crew departs for Mars, three sets of rovers are sent to explore three different regions. Each set is composed of one Truck and two Rockhounds. The Truck is a big rover equipped with the telecommunication system, tasked with transporting the Rockhounds from place to place,

[2]This section is authored by Michel Viso, Jean-Pierre de Vera, Emmanuelle Javaux, Sandra Siljeström, and Jorge L. Vago.

supplying them with energy for operations and for heating. The Rockhounds are small agile vehicles to explore around each Truck to analyse and or sample places of interest.

Once these elements are in place, a spacecraft with six astronauts would be launched and placed in a large elliptical orbit (12 h Molniya type), rotating on itself to ensure a Mars gravity equivalent for the astronauts. The astronauts could teleoperate the rovers from a short distance, avoiding the Earth-Mars radio signal delay (can be up to 30 min). However, it is not obvious that this would result in a significant gain in productivity.

Presently NASA rovers are operated through a cooperation of scientists who gather remotely every day to define sol-to-sol operations and elaborate mid- and long-term activity plans. The programme proposed by the science community is then reviewed by the engineers in charge of rover operations to integrate all the parameters (energy, distance to be travelled, slopes, boulders, memory capacity available, data do be download, etc.). After a thorough review, the activity plan for the next sol is uploaded to a data relay satellite, which communicates it to the rover when in view. Even with astronauts near the rovers, defining activity plans requires inputs from many skilled scientists and engineers based on Earth. Even if inputs from Earth were to be used just for establishing plans for long traverses, it is not clear whether the required operational and scientific expertise could be made available in real time by a crew of six, who would need to be familiar not just with the required science disciplines, but also with all surface elements' parameters, software, and resource management tools.

The advantage of this design is that it allows preparing for a future "full" mission landing astronauts. It can test the 500-day stay in orbit, the back-and-forth travel, as well as the organisation of a long-lasting programme with several launch windows specific constraints (launch energy needed versus mass to be landed with geographic limitations) (Fig. 6.1).

The rovers could be supplemented with a sample collection and a Mars ascent vehicle. Considering the technical success of Ingenuity (NASA's small helicopter operated with Perseverance which performed 72 flights over 3 years), it is also likely that robotic drones may be part of the surface exploration assets.

This HERRO option has been considered by several space agencies (Zhang, 2001). Some preliminary tests have been performed by ESA to control terrestrial rovers from orbit (Taubert et al., 2017).

A more advanced version of HERRO has been presented by Edwards et al. (2023) as a follow-up of the latest nuclear-propulsion mission design included in the Artemis programme (NASA, 2024b). The interplanetary vehicle stays in orbit for 30 days with a crew of four persons on board to establish a Mars Base Camp (MBC). From there, the crew can pursue remote robotic observations of the surface, as described above. The mission would also carry a "small" Mars Ascent/Descent Vehicle (MADV), which could be used for short-term landings and stay on the surface.

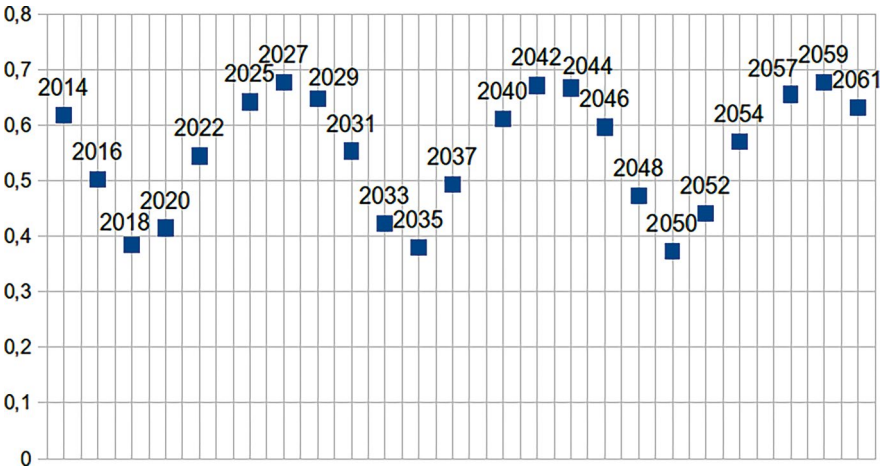


Fig. 6.1 Minimal distance between Earth and Mars from 2014 up to 2061 (in Astronomical Unit). By Sandegud—Own work, CC0, https://commons.wikimedia.org/w/index.php?curid=29792263

6.2.2 Early Human Missions

There are many hypotheses presented in human mission papers. In general, they provide few details and are very optimistic regarding logistics, travel, self-sufficiency for food and other resources, ISRU (in situ resource utilisation) and technical capabilities. In 1985, there existed already several hypotheses gathered in a compilation of papers (Duke & Keaton, 1986; Keaton & Duke, 1986). Almost 40 years thereafter, the same hypotheses are being revisited and reproposed as scenario for a NASA-led crewed mission to Mars (Drake et al., 2010).

6.2.2.1 Mission Concept and Mission Duration

All robotic missions to Mars so far have been accomplished using the Hohmann transfer orbit (or Hohmann-like), requiring the least energy consumption for travelling between Earth and Mars. The Hohmann transfer relies on the conjunction of the two planets and minimises the energy requirement for launch and Mars orbit insertion. Launch windows for this trajectory open regularly at 26-month intervals. The complete return mission from Earth to Mars lasts around 1000 terrestrial days with about 500 sols at Mars. Due to its energy conserving features, this method will continue to be favoured for future robotic missions, and possibly either for the forward or return transfer of crewed missions. However, the main challenge of the "Hohmann trajectory to Mars"—relative to the present crewed mission around the Earth or even to the Moon—is that the launch window is short. Finally, because of space mechanics, there is a very narrow window for the launch of the return mission. The

launch of the crew hinges on the successful execution of the cargo missions launched during the previous window. Due to the long flight time, and particularly, the long waiting times at Mars other, faster trajectories for interplanetary travel are being considered.

Another possibility is to prepare a so-called Opposition Mission that requires a lot more energy and a Venus flyby either on the forward or on the return leg. In this case, the mission duration is reduced to approximately 700 days with a stay on the Martian surface between 30 and 60 sols. The feasibility of a Venus swing-by for astronauts has not been demonstrated. For opposition missions, each launch requires a large delta V which, most likely, can only be achieved with nuclear propulsion (either thermal or electric or electric and chemical).

In the most recent designs (DRA 6.0) and later designs (see Drake et al., 2010; Kludze et al., 2023; NASA, 2024b) the programme for the first crewed mission would be accomplished by making launches at three consecutive launch windows, first sending two uncrewed cargo missions, and then a crewed "short duration" mission, using different quasi-Hohmann or opposition transfer orbit.

6.2.2.2 The Crew

According to these mission designs, the first crew would be composed of a small number (four or six) of astronauts. The first mission will land on a predesigned site on the surface, pre-equipped with necessary infrastructure by the previous cargo flights. The small size of the crew seems to be the most effective encompassing the required skills, the workload, and the complexity of such a mission.

6.2.2.3 Surface Assets

Any landing of a crew on the surface of Mars requires the presence in advance of several functional and tested assets. The first one is the ascent vehicle to reach orbit and to rejoin the Earth-return vehicle. The second is the habitat, mobile or not, in which the crew must live and work for at least 30 sols (minimal hypothesis), but perhaps up to several months. The third is a reliable source of energy to support the presence and the activities of the crew.

Several design options are under study for the first mission sending humans to visit the Martian surface. Beyond their political significance, all of them have, as a declared goal, exploration and science. The plan described in the DRA 6.0 mission configuration is called the "commuter reference architecture". The crew lives for 30 days in a monolithic habitat centrally located in the area of interest. Energy is delivered by a static nuclear power plant, sent on an earlier cargo vehicle, that is operational before the crew lands. The crew uses two large, pressurised rovers and two smaller unpressurised rovers for mobility, each can carry or tow equipment. Pressurised rovers can accommodate two astronauts, have an autonomy of about 100 km and 1–2 weeks of sortie duration. Traverses are planned on Earth, but the

crew, in conjunction with Earth ground control can adapt activities depending on the day-to-day findings. The walking range for the crew with his or her portable life-support system is around 20 km.

The rovers are equipped with only a few scientific analytical instruments. One of the main goals of the astronauts after the selection of interesting sites and the preparation of the operations is to identify and collect properly the samples (without contaminating them with terrestrial microbes or chemicals). These operations are performed having in mind the recommendations for planetary protection policy and the safety of the Earth.

A more recent mission architecture (Kludze et al., 2023; NASA, 2024b) plans a landing crew of only two persons, living and moving around for 30 days in a small pressurised rover, a size similar to a small trailer home.

6.2.2.4 Surface Operations

Beyond the required activities for acclimatation upon arrival, the commissioning of the various assets, the maintenance operations, the tests of the Mars Ascent Vehicle (MAV), and the preparation to shut down the habitat, most of the crew's time will be devoted to exploration and science. The crew will have to recognise the sites of interest, perform analyses using the available instruments and sample those sites, access and sample the subsurface by drilling from metres to tens or hundreds of metre depth, with a sterile and ultraclean system (Palmowski et al., 2023). The crew will probably use field systems for preliminary analyses during the traverse and to prepare the samples. It is planned to have a laboratory in a habitat on the surface of Mars to perform further measurements on the samples and to prepare selected samples to be returned to Earth with the crew. A first estimate is that each mission could bring back to Earth up to 250 kg of samples (if compatible with the MAV and Orion spacecraft landing capabilities). This amount must be compared to the 500 g of sample mass planned within the ongoing NASA-ESA Mars Sample Return mission.

In parallel the crew will deploy stations in selected locations for long-duration monitoring of seismic activity and climate.

6.2.3 From Long-Term Robotic Investigations to Crewed Scientific Activities

One can easily recognise some practical advantages of having a human investigator rather than a robotic one. For example, it is easier to dig into the surface or to seal a tube when you have hands. However, it is less obvious to what extent a human mission can accelerate the timeline of scientific analyses needed to achieve a mission's science objectives.

Since 2012, the Curiosity rover has been analysing the Martian surface and shallow subsurface with its ten instruments. The mission's main objective is to study the past and present habitability at Gale Crater. Onboard Curiosity operates an analytical laboratory to study in situ organic molecules and potential biomolecules: SAM, the Sample Analysis at Mars (Mahaffy et al., 2012). To date, SAM has investigated 42 scooped or drilled locations, driven over 31 km, and negotiated 700 m of positive elevation. SAM, scientists have discovered Martian organic molecules (Freissinet et al., 2015). The first detection was obtained from the Cumberland mudstone sample, the second sample ever drilled by Curiosity, in 2013. Following the chlorohydrocarbons evolving from the sample at low temperature (<500 °C) (Freissinet et al., 2015), sulphur-bearing compounds were found at higher temperature (> 500 °C) on the same set of data, in 2018 (Eigenbrode et al., 2018). An additional 2020 directed search for organics on Cumberland material resulted in new discoveries (Szopa et al., 2020). More than 10 years after the drill, the highest molecular weight compounds, long chain hydrocarbons, were detected on the same data set from 2013.

It takes a whole team of various scientists, some highly specialised with extensive experience in chromatography to understand SAM results. Mars has unique characteristics (and often surprises) that defy a straightforward interpretation. Figure 6.2 shows a SAM data set. It is easy to appreciate why data analysis is long and complex, often requiring a directed search for specific compounds. This was particularly obvious when specific chlorohydrocarbons were found in 2018 on the Viking 1976 data (Guzman et al., 2018). In addition, to understand one set of data received from Mars, scientists must use numerous laboratory instruments and

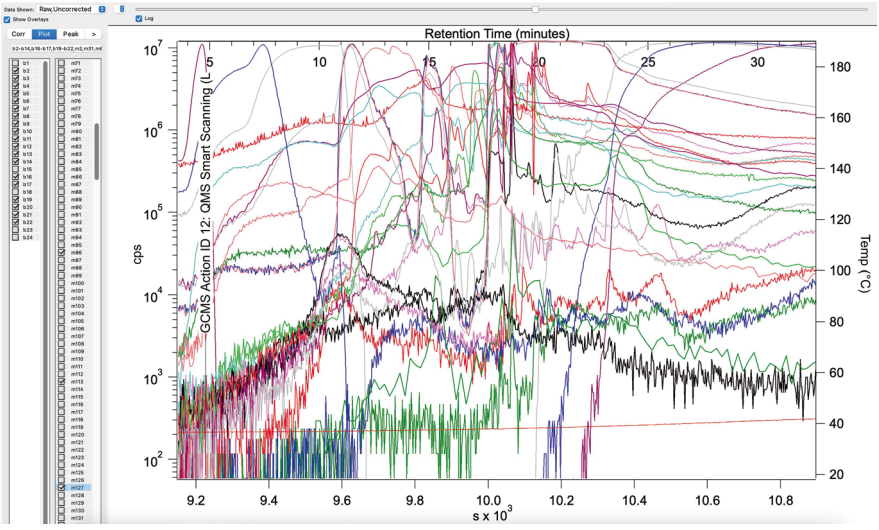


Fig. 6.2 Typical SAM Chromatogram (GCMS analysis) showing the extent of complexity for analysing one Mars data for its content in organic molecules (credit Caroline Freissinet)

mixtures to reproduce what is observed on Mars and gain confidence that the interpretation of the results is correct. The timeline of analysis is often longer when it becomes necessary to find Earth analogue samples representative of the specific Martian sample. The team need to collect and analyse them as well. Throughout this work, the conclusions need to be discussed within the community to receive feedback and sometimes re-interpretations that we must consider carefully. This may lead to parameters changes in the Mars run. They could take years to redo on Mars.

Eleven years after the Cumberland drilling operation, Curiosity still holds a Cumberland "doggy-bag" in its carousel. It is still possible to request a SAM run with optimised parameter and compare the outcome to the previous data. Thus, the limiting factor is not the amount of data obtained on Mars but the time of the team of scientists available to interpret the data with all the required tools on Earth. An astronaut holding a rock on the red planet would face the same incompressible challenges. It is very difficult to choose a sample that can contain the molecular information we are interested in to study. An astronaut may be able to collect several kg of samples, but it will be difficult to ascertain if any of them is organics-rich.

To resolve fundamental questions regarding Martian samples, such as "is there or was there life on Mars", one cannot pick a sample expecting it to be the "right" type. We first must understand if the context of this particular sample is consistent with the objective. Is the geology favourable for a long-term preservation of any form of life remnants? For example, clays can accumulate and preserve organic molecules. Has the sample been protected sufficiently from the harsh surface environment during geologic times? Here, a major concern is the exposure of organics to ionising radiation effects. A possible way to deal with this is to collect material at depth, or to select samples that have been exhumed relatively recently by wind erosion.

The second step is to understand local habitability: were appropriate geochemical conditions present at the same place and time for life to emerge? A positive answer to both context and habitability, obtained with multiple space probes (orbiters and rovers), several independent instruments, and numerous local analyses, would allow to consider a sample "of interest" for further investigation and possible return to Earth for more thorough work. Typically, with the whole Curiosity payload after multiple years of relevant investigations on Gale crater, preceded by orbital studies with other probes, thorough inspection of Cumberland (15 subsamples analysed to understand its organic content, sulphur and carbon isotopes, exposure time to the surface environment, nitrates abundance, etc.), and worldwide teams supporting experiments in laboratories, we would consider Cumberland as a high potential sample location.

The current and future state of knowledge of simple and complex organics preservation, as revealed by robotic investigations, provides a critical source of information for understanding returned samples. This information has been distilled over decades with a dedicated programme and will continue to accrue as we send more robotic detectives to Mars. The European-led ExoMars 2028 rover will investigate the chemistry and potential biochemistry of Mars in a new environment: in the subsurface, down to two metres depth. This may be a game-changer. Those

investigations could pave the way for astronauts and help them to select the most promising samples to return back to Earth for further thorough analyses.

6.2.4 Perspectives

In the USA, the decision to send humans to Mars is likely to depend on complex geopolitical considerations. The cost of even the simplest of human missions will be very significant and will extend over several government administrations. The science goals presented here are like those proposed by MEPAG (Mars Exploration Program Analysis Group).

The presence of astronauts on the surface of Mars can provide a unique opportunity to perform in-depth exploration and intelligent sampling. Initially, a 30-day surface mission scenario is preferred to the 500-day-stay. Both have technical implications which can affect or simplify the choice. Scientific activities will benefit from the presence of humans, their ability to move, to react to the environment, to take initiative, and to conduct complex tasks faster than remotely controlled robots.

Having astronauts on the surface will not change the communications delay between the Earth and Mars. Compared to the real experiment conducted by the Instrument SAM (Sample Analysis at Mars) (see Sect. 6.2.3), some steps could be shortened by automatisation of preliminary tasks or analysis. However, data handling, measurements, time series must be thoroughly checked, compared to data obtained on the ground and during the calibration of the instrument itself. Certain processing times are incompressible. In most space experiments, the time lapse between execution, receiving the data, elaborating the results, and publishing a paper can take several years. This is likely to remain the case.

Finally, the first steps of a crew on Mars could prepare for a further decision to maintain a sustained presence of humans in a more permanent base.

6.3 Visiting Mars: Current Knowledge and Requirements[3]

Several space agencies and other institutions are claiming their desire to send humans to the surface of the Moon, and then to Mars. This section is based on the most advanced descriptions of the plans, technologies, and preparation for the flights to both destinations that have been published and advertised.

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6.3.1 From the Moon to Mars

A crewed mission to Mars involves transporting human crews to the Martian orbit, landing them safely onto the Martian surface, supporting them there for the mission's duration, and finally launching them back into orbit, from where spacecraft which had been waiting can transport them safely back to Earth. The realisation of such an endeavour will require the development of a large variety of new space infrastructure and technologies for travelling to, landing, and staying on Mars. Later on, further developments will be needed to enable the extensive in situ resource utilisation required for repeated or longer duration visits to the Martian surface. In addition to technical issues, also numerous concerns related to human endurance, as well as economical and legal issues, and ethical considerations pertaining, e.g., to planetary protection will arise (see Sects. 4.5 and 5.2.4.1).

The preparation for such missions, however, does not start from scratch. It will build upon the experience gained from many space missions and technologies that have been developed since the 1960s. Much of that experience has been accumulated through robotic missions. Most crewed missions have been restricted to flights into low Earth orbit (LEO; between 160 and 1,000 km above the surface of the Earth) taking passengers and cargo to and from space stations, such as the Soviet Union MIR station (1986–2001), the International Space Station [ISS; continuously inhabited since November 2, 2000 (NASA, 2023b)], and most recently, the Chinese Tiangong station (in orbit since 2021). Extensive experience has been also gained with the long-time residence of crews on these space stations, especially on the ISS that has now completed 25 years of successful operation and has served as a habitat and laboratory for hundreds of astronauts. Many technologies have been developed and tested in all aspects of science and technology, which will be of fundamental importance for a crewed mission to Mars. There is also the valuable experience from the Apollo programmes, which between the years 1969 and 1972 transported six small crews in orbit around the Moon, and successfully landed a total of 12 crew members (two at a time) on the lunar surface (NASA, 2024a).

6.3.1.1 Establishing a Permanent Base on the Lunar Surface

The memory of the Apollo programme stimulates today's preparation of crewed missions to the Moon. Currently, NASA, ESA, and other space agencies, jointly with some commercial enterprises, are collaborating on the Artemis programme, which aims to land crews on the lunar surface and to establish a permanent base both on the lunar surface and a station (the Gateway) in the Moon's near-rectilinear halo orbit (NRHO). One of the goals of this infrastructure lies in the development and testing of tools for human survival in space, especially some that pertain to the monitoring of solar radiation issues. It is planned to support both short- and long-duration crewed missions to the Lunar surface. It may also, farther in the future, be used for logistical support to Mars missions.

One aim of the Artemis programme is to investigate and exploit the in situ lunar resources, such as water, minerals, energy resources, and oxygen, to allow a sustainable human presence on the Moon. Meanwhile, frequent cargo missions will be deployed on the lunar surface to enable these first steps of exploitation. Many commercial enterprises are already preparing their procedures and infrastructure. Heavy-duty rockets and other hardware have been already constructed and tested to launch this large cargo into orbit around Earth. These include NASA's Space Launch System (SLS) rocket, and the Orion spacecraft for space transport. The private company SpaceX is developing the reusable Starship rocket and the Falcon Heavy boosters which, at the very moment this sentence is being written, are being launched for a test mission which includes an orbit around the Earth. Other systems, such as the Human Landing System (HLS), which is planned to be used in the forthcoming 1-week stays on the lunar surface (the first of which, mission Artemis III, is tentatively scheduled for 2027), are still pending. The date when these early missions take place depends on the progress and maturity of further technologies. The equipment planned for the Base Camp includes a Lunar Terrain Vehicle (LTV, an unpressurised rover), a Habitable Mobility Platform (a pressurised rover), a habitation module, power systems, and an in situ resource utilisation system to extract water from the Lunar regolith, or from the deposits in the South-pole craters. The foreseen uses of the extracted water include fuel production and human consumption. New types of spacesuits, such as the Exploration Extravehicular Mobility Unit (xEMU), are also being developed for the landing crew, that will directly interact with the lunar environment. More than two dozen essential science instruments have already been chosen to be sent to the Moon, for example the Volatiles Investigating Polar Exploration Rover (VIPER) and the Heliophysics Environmental and Radiation Measurement Experiment Suite (HERMES) (Howley & Johnson, 2022; NASA, 2020). All these technologies are intended to later be adapted for Mars missions.

The plans to return human crews to the Moon and to establish a permanent human presence on its surface and/or in its orbit are causing vivid international competition on spacefaring capabilities and leadership. Nations which are not involved in the Artemis programme have recently announced their plans to send their first crewed mission to the lunar surface. The Russian space agency Roskosmos, for example, is planning to send the first cosmonauts to the Moon and to start building a lunar base in 2031–2040 (Reuters, 2023). The China Manned Space Agency (CMSA), after successfully sending several uncrewed missions to the Lunar surface (Chang'e 3 and 5), is now planning its first crewed mission before 2030 (Yeung & Zhu, 2023). Finally, the Indian Space Research Organisation (ISRO) is planning its first crewed landing by 2040 and has successfully landed its first vehicle, Chandrayaan-3, on the Lunar surface in August 2023 (The Economic Times, 2023). Within this very competitive environment, the Artemis programme has political objectives and aims of establishing a US leadership in international space programmes.

6.3.1.2 Envisioning the First Crewed Mission to Mars: Mission Design

Among the goals of the Artemis programme is also that of enabling the first crewed missions either in orbit around, or on the surface of, Mars. Both the Moon and Mars are hostile environments. Undoubtedly, the exploration of the Moon will teach spacefaring countries a lot about living beyond Earth and about the exploitation and utilisation of in situ resources to support a sustainable interplanetary presence. As Mars is much more distant from Earth than is the Moon, the latter will provide a valuable ground for developing technologies intended for Mars mission.

Over the last decades, multiple mission designs and architectures have been studied by NASA and its international collaborators and private industrial contractors (e.g. SpaceX, Lockheed Martin, Blue Origin) for the first crewed mission to Mars (Rapp, 2023). They have considered multiple options for each of the various elements of a Mars mission architecture. Major questions are technical ones, e.g., what kind of interplanetary travel and propulsion technology would be used? What would be their optimal flight trajectories, timing and duration? Would humans stay in the Martian orbit or land, and in the latter case, where on the surface and for how long? Further questions to answer are, e.g., how many crew members are included? How many of them are destined to land on the surface and how many are to stay in orbit? Others include how the landing and launching technologies can be accomplished in a safe way? How the safety and wellbeing of the crew can be assured through all stages of the mission? And—last but not least—how this all can be accomplished with a minimal amount of cargo? And how much the mission will cost? No mission design is best in all aspects. Each poses major challenges and requires technological developments (Rapp, 2023).

In its recent 2023 Moon to Mars Architecture Definition Document (NASA, 2024b), NASA describes its commitment to pursue human landings and scientific missions first on the Moon, then on Mars. However, defining the exact architecture in precise details for these missions will require extensive development, involving the definition of concepts, operations, functions, and technologies whose development schedules are long and often interdependent. Therefore, the document states that it is yet not possible to "pick up" an entire architecture of that sort as a "single pass through", particularly as many of the considered concepts or technologies are still not mature. Such "full architecture design" has previously been tried several times over, with limited success.

Rather than giving a single definition of the mission design, the Architecture Definition Document mentioned above is describing how the first crewed missions to the Moon, and then to Mars, are to be approached. Mission plans are first to be evaluated through the basic questions that are driving these endeavours: where are the missions flown and for what purposes; what are the expected and accepted safety and risk levels for the crews; what are the mass, volume, and costs; who are the stakeholders; and what are the mission strategies and policies? Various parameters have different priorities (e.g. safety is considered a very high priority, as are the costs and achievable maturity of the technologies) and will have different emphasis on the choices to be made among the different options.

The approach to manage the multitude of technical challenges is to first divide them into two types of categories, which can be developed as separate mission entities. The first category is formed by groups of tightly coupled systems, needs, and capabilities as sub-architectures, or as system-to-sub-system relationships. These include, e.g., Transportation Systems; Power Systems; In Situ Resource Utilisation Systems; Habitation Systems; Data Systems and Management; Communication, Positioning, Navigation, and Timing Systems; Human Systems; Infrastructure Support; Logistics Systems; Mobility System; Autonomous and Robotic Systems; and Utilisation Systems. The second category is formed by established segments. These, as defined in the 2023 Architecture Definition Document are the Human Lunar Return, Foundational Exploration (on the Moon and in its vicinity), Sustained Lunar Evolution, and Human to Mars. The mission architecture would proceed through these segments, allowing the later ones to benefit from the technologies developed in the previous ones, and allowing the Mars mission to heavily rely on the progress made in the lunar return programme.

The Moon to Mars Architecture Definition Document also describes optional plans and technologies, drawn from the mission architectures that have been constructed in previous years. It refers, e.g., to the Human Exploration of Mars Design Reference Architecture 5.0 (DRA 5.0), conceived by the NASA Mars Architecture Working Group (MAWG) between 2005 and 2009, and published in 2009 (Drake, 2009).

Currently there is no experience of human flights beyond the cis-lunar orbit. All previous uncrewed missions to the Martian system have been achieved with small spacecraft relying on either chemical (e.g. hydrazine) or electric/ion propulsion, flying to their destination using the Hohmann transfer orbit following the conjunction-class trajectory (see Fig. 6.3) requiring the minimal amount of energy for the interplanetary transit, and taking typically about 8 months of flight time between Earth and Mars. Using this Hohmann transfer in the crewed mission would require a waiting time of 500 days in the Martian system to access the next launch window for the return trip. The long interplanetary travel time and the long stay in the Martian system (either surface or orbit) would expose the crews for a total of nearly 3 years to the (partly unknown) dangers of the deep space and Martian surface conditions (see Chap. 2 and Sect. 2.3 and 2.5). Thus, a safer option would be to rely on faster travel technologies and a shorter stay (about 30 days) in the Martian system, achievable with higher-energy (nuclear) propulsions systems and shorter flight trajectories. Depending on the opportunity, most of them require a flyby of Venus on one leg and the acceleration (ΔV) required is highly variable (up to 2.5 times more that the Hohmann-like transfer). The rocket equation physics makes this more challenging.

The DRA 5.0 Mars architecture specifically compares two optional propulsion systems, namely, a chemical combustion engine using liquid hydrogen (LH_2) and liquid oxygen (LOX), and a nuclear thermal propulsion (NTP) engine, for the interplanetary trip. It concludes that a NTP rocket engine is chosen due to its better performance (higher thrust and impulse), allowing higher acceleration (ΔV) and velocities. This propulsion would allow the spaceship to take faster transit

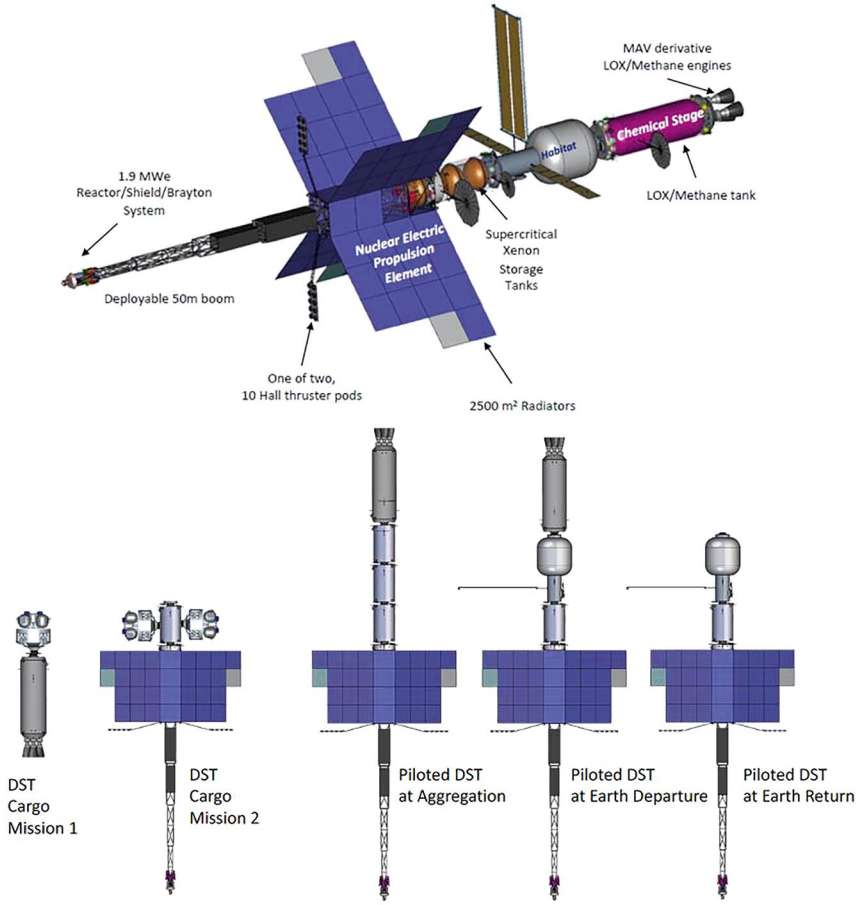


Fig. 6.3 Schematic picture of the NEC/CCP Reference Vehicle concept, as presented in NASA (2024b) (@NASA)

trajectories from Earth orbit to the Martian system—and likewise to return faster from Mars to Earth. The minimal length of these interplanetary travels would be 160 days, or even as low as 140 days, compared to the circa 200 days achieved with a chemical combustion engine along the Hohmann orbit (Drake, 2009).

Considering the very high total cost of Mars mission design and preparation, the NASA DRA 5.0 architecture suggests a strategy where the first missions are to be prepared in triplicate, with replicates being launched in three subsequent launch windows, each 26 months apart (and using the previous missions as testbeds for the next ones). Each of the missions would feature six crew members, four of whom would be destined to land on the surface, and two to stay on the mothership that would stay in the Martian orbit, waiting to serve again as the interplanetary ship for the crew to return home. Each of the crewed missions would require two preceding

cargo flights carrying a total of three landers and the infrastructure and supplies needed for the 30-day visit of four crew members on the Martian surface.

All of the interplanetary vehicles (for both the cargo and crewed flights) would be composed of different components including the NTP core propulsion stage, the in-line propellant tanks, additional thrust tank and payload units including the human interplanetary travel habitat (containing also the life-support supplies, i.e. food, oxygen and water, and recycling systems for water and oxygen), and auxillary units, such as the propellant tank Zero Boil-Off cryo coolant system to prevent the evaporation of the H_2 fuel, solar panels for electricity, systems for the communication with Earth, a module containing the contingency consumables, and the crew exploration/Earth-return vehicle (Orion capsule) and service module. The heavy weight components would be launched separately and placed to wait in low Earth orbit until they are assembled there into the final Mars transfer vehicle. A total of nine heavy launch vehicle flights would be needed to accomplish each of these crewed missions, i.e., five flights to assemble each of the two preparatory cargo flights, and four flights to assemble the final crewed vehicle in Earth orbit.

A detailed further analysis of the putative nuclear propulsion options for the first crewed mission has been made and described by NASA's *Mars Transportation Assessment Study* (MTAS) team, composed of 95 experts (Kludze et al., 2023). This committee was primarily tasked to establish the feasibility of transportation systems for a circa 2-year human Mars mission in the 2030s with acceptable risk and minimal development. It aimed particularly to compare two optional nuclear propulsion systems, the NTP and NEP (Nuclear Electric Propulsion) to seek for maximal efficient propulsion for fast interplanetary travel, and to benefit from synergies with the technologies that are being developed in the Artemis programme. In this study, NEP propulsion was found preferable to NTP, particularly when combined with Chemical Combustion Propulsion (CCP) that uses liquid oxygen and methane (LOX-LCH_4) (Kludze et al., 2023) as fuel. The high-power CCP propulsion is to be used for docking manoeuvres, and when leaving or entering planetary orbits. The NEP engine is used for interplanetary travel. It uses supercritical xenon as the thrust propellant, and a sodium heat pipe system for reactor cooling (Hu et al., 2021), and its concept is based on the technology of the 10 kWe Kilopower nuclear fission reactor (Gibson et al., 2017; Space Nuclear Propulsion Technologies Committee et al., 2021). According to this design, the different modules of the vehicle (the Propulsion Module, the Chemical Propulsion Module, the Xenon Interstage Modules, the LOX-LC H_4 propellant and transfer element, and the Deep Space Habitat element) would first be launched separately to LEO, where they would be aggregated and refuelled, and then lifted by the CCP rocket to a higher Earth orbit at 1100 km altitude, i.e. at a distance from Earth that is safe for operating the nuclear reactor. From there, this stack would be lifted by the NEP rocket engine to a near-rectilinear halo orbit (NRHO) around the Moon, where it is aggregated with the Deep Space Habitat, equipped, and tested. This assembled Deep Space Transport (DST) vehicle would then be returned to the high (1100 km) Earth orbit for the boarding of the crew, and then launched from there towards Mars. These transport manoeuvres are to be performed with a number of consecutive launches by several different rockets [e.g. the

Space Launch System (SLS), the Heavy Commercial Launch Vehicles (H-CLVs), and the Super Heavy Commercial Launch Vehicles (SH-CLVs)]. Together with the cargo transport, methane-LOX-propellant refuelling operation, and transport of the crew to the DST vehicle, this mission will take a total of 13 launches (Kludze et al., 2023).

The NEP/CCP technology is favoured over NTP because its technical principles are derived from previously known or explored technologies and are thus of higher maturity and of lower development cost, and more robust. The NEP/CCP propulsion system also benefits from synergies with the ongoing development of the LOX-LCH_4 propulsion systems for other spaceships/rockets, of the Kilopower nuclear fission reactor (Mohon, 2017; NASA, 2023a) for the lunar surface, and of the solar power and electric propulsion systems designed for the Gateway.

The faster option that has been considered for the interplanetary travel is the use of the opposition-class trajectory, achievable with the high ΔV obtained with the nuclear propulsion systems. With this trajectory, the return launch window from the Martian system could be accessed within 3 months of arrival, and thus the stay of the crew on the surface of Mars and in orbit could be accomplished in about 2 years, or even less. This would significantly reduce the total duration of the trip, when compared to conjunction-class trajectories using the Hohmann orbit, which require approximately a 3-year roundtrip with a 500-day stay in the Martian system. Depending on mission design, the time spent by the crew in Martian system could vary from 30 days to 1 year (Drake, 2009; Edwards et al. 2023; NASA, 2024b). The opposition trajectory thus allows more flexible travelling schedule, reduces the total duration of the crew in the space radiation environment, but at the same time it adds major new challenges: it takes the ship transiently closer to the Sun (inside the orbit of Venus), increasing radiation exposure and thermal challenges for the crew (NASA, 2024b; Space Nuclear Propulsion Technologies Committee et al., 2021) (Fig. 6.4).

Also this designed crewed mission must be preceded by two preparatory missions to the Martian orbit, to deploy three 65,000 kg Mars Descent Systems (MDS)

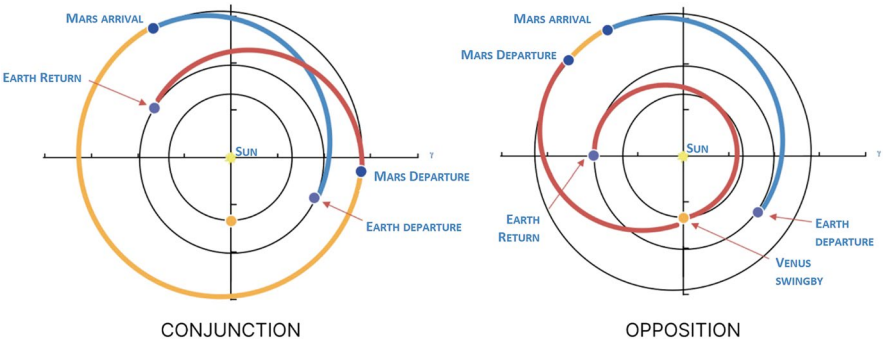


Fig. 6.4 Illustration of the conjunction- and opposition-class trajectories to Mars (NASA, 2024b) (@NASA)

there. These missions would be timed so that the first lander will land on Mars before the second lander is launched, to provide a proof of the Entry, Descent, and Landing (EDL) system for this size-class of payloads. To do this before commissioning of the NEP propulsion technology, this mission would be done by the SLS vehicle using the Chemical Propulsion Module, and by refuelling the spaceship on the lunar NRHO. The remaining two landers would be transported to the Martian orbit by the vehicle driven by the NEP and Xenon Interstage Modules, testing these elements prior to the crewed flight. These mission elements would be stacked in the NRHO prior to their journey to Mars and arrive in Martian orbit 18 months prior to the departure of the crew. Each of the three MDSs would be capable of landing about 25 metric tons of useful cargo on the surface of the planet (a total of 75 tons of infrastructure would be required for a crew of 2 persons, for 30 days). Two of them would deliver a partially fuelled Mars Ascent Vehicle (MAV), a nuclear fission power system (NASA, 2023a), and additional propellant for the MAV. The third MDS would transport to the surface a pressurised rover (the size of a large mobile home), and this would be used both for the housing and for short distance movement of the crew on the surface (Hall, 2020). Altogether, the transport and refuelling of the modules of these two preparatory missions to the NRHO would require a total of 17 launches by the SLS, and the Heavy or Super heavy commercial launch system, bringing the total count to 30 heavy space launches for the accomplishment of the first crewed mission by the NEP+CCP propulsion system. Technologies for refuelling the spaceships in space with the cryogenic liquid fuels are among those that are not available as yet (Kludze et al., 2023).

Once the interplanetary transport vehicle would have been assembled in space, it would remain functional for the next mission(s); thus, it needs to be developed to a reusable level. The specific technical challenges of this system include the sodium heat pipes for the reactor cooling, which are difficult to replace in space and consequently, require long-life alloy materials for the pipes, and reliability in their performance (Hu et al., 2021; Rosenfeld et al., 2004). It is also worth mentioning that launching nuclear energy supply materials is made quite difficult by legislation: the launch of the nuclear fuel-containing NEP or NTP Modules poses an environmental risk to the launch site and beyond, due to the potential explosion or loss of control; therefore, such propulsion modules cannot be used, or deployed, below the "nuclear-safe height" orbit at 1100 km. Further complications related to the nuclear reactors are the strict safety and security guidelines applied to the handling of the enriched-uranium fuel during rocket construction and launch. A further challenge is that the crew needs to be shielded from emitted radiation during operation (Kludze et al., 2023; NASA, 2024b; Space Nuclear Propulsion Technologies Committee et al., 2021).

The described mission design includes a crew of four persons, of which two would land on Mars and stay for 30 Martian days (sols) on the surface. After the two astronauts have explored the Martian surface for the planned time, they would use the MAV to return to the DST vehicle in Martian orbit, to join the other two crew members for the return trip to Earth (Kludze et al., 2023).

Another mission architecture and design, derived from the MTAS team plan, has been published by the private company Lockheed Martin (Edwards et al. 2023). In this scenario, the flights to Mars (cargo or crewed) will start and return to the Lunar

Gateway station in the NRHO, but in this case by using the NTP propulsion, using hydrogen (H_2) as the propellant fuel. This fuel would be a very attractive choice as it could be produced on the Moon: as the product of a lunar ISRU economy, it would significantly reduce the launch and operational costs. Again, one of the challenges in this NTP propulsion system is that the propellant storage and handling system should constitute a long-term, zero-leak cryogenic fluid management (CFM) system. This mission scenario includes a crew of four astronauts to be transported and positioned in Martian orbit, with short visits to the surface by using a small descent/ascent vehicle (see Sect. 6.3.2.2); the interplanetary transport vehicle will then act as a space station around the planet, named Mars Base Camp (MBC).

The SpaceX Company aims for again another mission architecture, where the chemical rocket, i.e., the Starship vehicle, is to be used for interplanetary travel (Heldmann et al., 2022). The vehicle would initially be launched into LEO, where its CCP (methane-LOX chemical combustion) engine would be refuelled for the interplanetary trip. The fuel initially needed for the operations in the Martian system (landing and launching), as well as the initial life-support consumables and infrastructure would be transported to Mars, but plans do heavily rely on using local water resources for the production of the fuel for the return trip, and of oxygen and water for human consumption (Heldmann et al., 2022). Again, multiple heavy-duty launches from Earth are required to take up all the units of the transport vehicle(s), and the infrastructure in cargo. According to the 2023 NASA Moon to Mars Architecture Definition document, the CCP combustion propulsion (as well as the solar energy propulsion) options would be suitable for slower interplanetary transport along the Hohmann trajectory, larger cargos and longer duration mission designs, e.g. for missions including a 500-day stay on the surface. These could be pursued once the adequate infrastructure and life-support systems, some of which could rely on local resources, have been established on the surface (Fig. 6.5).

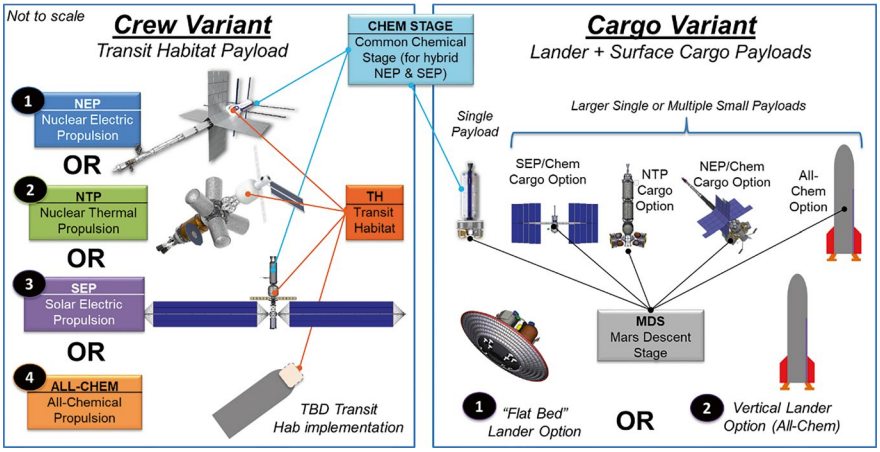


Fig. 6.5 Selection of optional propulsion systems considered for various missions to Mars. From the NASA Moon to Mars Architecture Definition document, p. 223 (NASA, 2024b) (@NASA)

6.3.2 Interplanetary Travel and Landing on Mars

In deep space, the interplanetary vehicle will be exposed to continuous high radiation, namely galactic cosmic radiation (GCR) and solar energetic particles (SEP). These must be blocked from the passenger compartment as much as possible. Radiation shielding could be made of low-Z materials such as aluminium, titanium, and magnesium (Zeitlin, 2021), but preferably should include even lower-Z-containing composite materials such as high-density polyethylene, carbon fibre, and polyether ketone, due to their more efficient shielding against high-energy particles (Naito et al., 2021; Thibeault et al., 2012). Such materials could be installed in an inflatable structure. Other materials carried in the payload—e.g., the water or fuel reservoirs—could be placed in positions where they provide additional shielding against radiation (Edwards et al. 2023). Radiation conditions encountered in the Martian orbit are similarly severe as they are on the surface, and about 2.5 times higher than what is encountered on LEO, onboard the ISS. They also vary, notably in case of solar particle events (NASA JPL and Laboratory for Atmospheric and Space Physics, Uni. Colorado, 2017; Williams, 2016); these need to be considered in the technical design of the vehicle.

All food materials need to be transported from Earth with the crew in the interplanetary transport vehicle, at least for the travel to and from Mars. During space travel, other life-support supplies (notably, oxygen and water) for the crew may be provided by the physicochemical revitalisation and purification of the gases and the water in a nearly-closed loop system, using similar but more advanced versions of technologies currently used on the ISS (Amini et al., 2022; NASA, 2024b). The food and other life-support supplies needed on the Martian surface may be transported with preparatory cargo flights prior to the crew's arrival.

Likewise, all combustible or nuclear fuels needed on the surface and for the return flight must be transported from the Earth with the earlier cargo flights. In the design of SpaceX, where the mission is to be accomplished by using the Starship vehicle and methane-LOX propulsion, fuel would be produced from water at the Martian surface. The water (a total of about 600 metric tons) needed for this purpose should be either mined from the proximity of the landing site or transported from the Earth (or from the Moon) by an additional Starship cargo vehicle.

6.3.2.1 Landing on Mars

The multiple failures in the history of robotic Martian missions underline the difficulty of the soft landing of even the small robotic landers, caused by Martian atmosphere, which is too dense to ignore but also so thin that it limits the possibilities of the aerobraking. The methods used so far are only suitable for landing small payloads, no larger than a small car, weighing up to about one metric ton, which is the heaviest lander that has been sent to Mars so far. The NASA-designed Mars Descent Vehicle (MDV) is planned to have a weight of 65,000 kg, and to be able to land a payload of 25 metric tons (Kludze et al., 2023). Deploying this lander-vehicle on the

surface of Mars is certainly a challenge of a much higher order than is the landing of small robotic rovers (Cain, 2019). Thus, completely new landing and launch technologies will be needed for the crewed missions. The experience gained in the Moon landings will be useful even in the landings on Mars, even though the latter will take place under higher gravity and will rely on different principles. The designed landing technology will be tested with several cargo missions prior to the landing of the first crew.

Different landing site facilities would be needed for different types of landing vehicles and technologies. According to current NASA mission designs, the first MDV would land directly on the Martian surface (Kludze et al., 2023; Kruyer et al., 2021; NASA, 2024b). The SpaceX mission plans also include a direct landing of the Starship vehicles on the surface, as the Starship design includes the capability for vertical landing, as well as of vertical launch from the surface back to orbit (Heldmann et al., 2022). In both cases, the first crewed mission would be preceded by several uncrewed cargo flights that would test the landing technologies. These robotic preparatory flights would install the necessary infrastructure on the landing site, e.g., a nuclear power reactor, a rover (or several) for the crew, and in the SpaceX architecture, robots for water prospecting, excavation and extraction, for fuel production and for shelter construction. If the preparatory missions fail, the crewed missions would be postponed until the problems have been solved and the technology developed to adequate maturity (Kludze et al., 2023).

While several assets have to land several years apart for a single crewed missions, new constraints appear for the selected landing site which must be able to welcome within a "travelling distance" three landers with deployable assets. Consequently, all the landing phases, e.g., entry, deceleration, parachute deployment if any, final precision landing adjustments, must be conducted with a very high accuracy and precision. Using the recently achieved landing accuracy of around 10 m by Perseverance, these needs seem to be fulfilled within a few years.

6.3.2.2 Selection and Preparation of the Mission Site

The selection of the first mission site(s) depends on the whole mission design architecture that is chosen. In any case, if the crew is to land for a 30- or 500-day surface mission, the site needs to be equipped with infrastructure (power source, fuel, ascend vehicle, habitat and life-support supplies, at least one mobility vehicle, and research gear) that is adequate to last for the whole duration of the stay.

The DRA 5.0 design (Drake, 2009) plans for three consecutive crewed missions, all of the same design but landed in different predesigned sites for 30 days, each site considered as a potential location for a future base. This allows hands-on investigation of these sites. Each site needs to be prepared by previous cargo flights, to bring and install the necessary infrastructure on the surface.

Several parameters must be considered in the selection of the landing sites, based on knowledge about the geological history of the terrains, and on the suitability of the local terrain for the landing and mobility manoeuvres. Technical restrictions

confine landing sites in the low-altitude areas, due to the slightly thicker atmospheric layer.

Most importantly, the selected location has to offer interesting features to be explored, since one of the most important aims of a Mars exploration programme is to increase our scientific knowledge of the planet, notably with the hope of finding evidence for extra-terrestrial life, extinct or extant.

A different site selection design is described by Edwards et al. (2023): here, the crew would mostly stay in the "Mars Base" space station in orbit and would explore the surface by remote observations and, if suitable robots are available nearby, by robotic manoeuvring. Still, the Mars Base orbiter would contain a small Mars Ascent/Descent Vehicle (MADV), powered by LH_2 and LOX, which could be used for landing and short-term stays on the surface. In this plan, the landing sites could be selected by an appropriate committee on Earth in almost real time among the previously short-listed few potentials, as the situation calls for them.

6.3.2.3 Information and Communication Technologies

As on Earth, a communication infrastructure will be necessary on Mars. The hardware infrastructure will not only be composed of vehicles and other static instruments deployed on the surface of Mars, but also of orbiters around Mars to provide the communication interlinks between distant infrastructure and of course, with Earth. However, live communication with Earth is not possible. The signal travel time between Mars and Earth varies between circa 3 and 21 min, depending on the distance between the two planets. Therefore, a crew on Mars will be much more isolated and should act more independently than on the Moon or in LEO. Thus, interlinks and the time delay of communication between Mars and Earth don't allow to control or even monitor the critical phases of the missions in real time.

The local communication infrastructure will continuously monitor and control all activities on the planet, while being able to issue alerts when risks are detected, especially those that are related to environmental issues or to operational issues of robotic systems and instruments. A substantial number of sensors will be employed to continuously monitor every technical device installed in the environment and in the infrastructure, such as air quality in habitats and mechanical stability of the structures, human presence and their exact locations, human health, and almost every aspect of human activity. This requires a highly demanding informational infrastructure (Heldmann et al., 2022). High-power and fast communication will be established locally, and between Mars and Earth by using relay laser satellite systems (Hall, 2020). This requires areostationary communication satellites, placed at an altitude of about 17,000 km, staying in the same position over the surface of Mars, as are the geostationary satellites on Earth orbit. This communication system would be also useful for broadcasting any events that would be of high interest to the international audience on Earth. Other satellites are also needed for monitoring the surrounding radiation environment and the solar wind, e.g., by using tools such

as the HERMES (Heliophysics Environmental and Radiation Measurement Experiment Suite) instrument.

The first visit(s) to the Martian system are expected to be much more demanding than the later ones, because all hardware infrastructure must be assembled and tested for their operation on site; afterwards, in the more permanent base, it can operate to a high degree automatically. Highly modular structures with multiple sensors have to be designed, allowing automated assembly into integrated functional systems. The role of new informational technologies is expected to be significant; technologies such as Digital Twins and the Machine-to-Machine (M2M) Framework may allow an initial simulation of the base infrastructure. This system would be able to identify and mitigate risks during its operation and could support the continuous management in every level and detail. These technologies are still to mature on Earth, and this requires the involvement of many businesses and attracts many investments from the private sector. The drive to go to Mars can be expected to push this sector to proceed faster in communication technologies to achieve higher precision in the localisation infrastructure, and to increase the speeds in data processing and handling, in storing big-data or retrieving information from advanced cloud systems. Such operational examples from Earth may already exist, but they are still fragmented without unified protocols and interfaces. New methods should be developed to support Machine-to-Machine (M2M) and Machine-to-Human (M2H) technologies, in a way that communication is rapid and immediately understandable by any device and by humans, for reducing the response times, which could introduce risks in cases of a delay. Similarly critical is the development of security and authentication technologies, based on advanced cryptography systems, because any security issue will affect the lives of several people, if not of the whole mission itself. The evolving Artificial Intelligence (AI) systems can enable great steps in this direction, though ethical issues must be resolved, while trusted results should be ensured as outcomes of such systems. Consequently, trained systems that respond to human requests should be thoroughly tested, reducing the human factor as a critical parameter, at least for the next two decades.

6.3.2.4 The First Habitats

According to NASA's Moon to Mars Architecture Definition Document (NASA, 2024b), "*Habitation (…) provides controlled environments (…) and functions including environmental control and life support (ECLS), power, communications, thermal control, command and data handling, extravehicular activity (EVA) support (e.g., ingress/egress, suit services, worksite accommodations), crew habitability (e.g., hygiene, food and nutrition, waste management, sleep, crew exercise), crew health (e.g., health and medical care, human performance, psychological support), and crew survival (e.g. pressurized suits, safe haven), among others*". According to the same document, the first habitats on the Martian surface should resemble, as much as possible, the crew habitat module during the interplanetary travel in the Deep Space Transport (DST) vehicle, thus taking use of redundant technical

solutions, and to allow the crew to occupy an environment similar to one they are used to.

In the past 30 years, NASA has produced multiple studies and designs of habitat infrastructure for the arriving crews, as reviewed by Rapp (2023) and Amini et al. (2022). An essential feature is that these containment facilities are shielded against the hard cosmic and particle radiation and are isolated from the Martian atmosphere to allow the accurate maintenance and regulation of the internal atmosphere, i.e., the breathable air. Temperature insulation is needed against the extreme temperatures and large daily temperature variations (see Chap. 1), but this may be achieved with fairly modest insulating structures due to the low heat conductivity of the thin local atmosphere and of the regolith, that serve as a great insulator.

The previously landed vehicles and landing module(s), or other protective modules transported from Earth, may be used as transient habitats for the first, small landing crews. The NASA mission architecture drawn by the Mars Architecture Team in 2021 (SAC21) suggests that the first landing crew will consist of two persons and will be housed for a duration of 30 days in a pressurised rover (Rucker et al., 2022).

The habitats also need to provide the necessary and vital life-support systems, initially by using consumables (notably oxygen, water, and food) transported from Earth and recycling them as much as possible. Current technologies used on the ISS, and to be constructed during the Artemis mission on the Moon, will form the basis for the life-support systems (LSS) on Mars. These should be capable of recycling most of the water, and to re-extract the oxygen from the carbon dioxide produced by the astronauts, e.g., by using processes based on absorbent beds (Fig. 6.6).



Fig. 6.6 An artistic view of the landing module and the rover habitat (@NASA)

6.3.2.5 Maturity of the Infrastructure

Many of the technologies and infrastructure mentioned above are still in their development or testing stages. For instance, by 2024, the Starship and Super Heavy Commercial Launch Vehicles (SH-CLVs, the Starship with heavy Falcon boosters) launch system are still being tested. At the time of writing the heavy launcher Space Launch System (SLS) has only flown once and its operations are quite costly. The whole NEP propulsion is composed of six subsystems which all seem feasible on a conceptual level, but the whole system still requires aggressive development and testing, both on the ground and within uncrewed missions. The NTB propulsion system is even farther from maturity. Technologies for the in-orbit refuelling of the cryocooled liquid fuels, or for the cryocooling system of the H_2 fuel, are not available yet (Kludze et al., 2023; NASA, 2024b).

The Moon to Mars Architecture Definition Document (NASA, 2024b) describes the maturity stages of the various technical function systems and example concepts (e.g. Mars Entry, Descent, Landing, and Ascent Functions, Mars Surface System Functions, Mars Transportation System Functions), with a total of 30 system functions described. Of these, most have the status "concepts development is ongoing", "conceptual design in development, or available", or "to be derived from corresponding Lunar habitation and mobility concepts" (for details, see NASA, 2024b).

Most of the hypotheses listed in this chapter have been thoroughly studied by the relevant committees and commissions for "analysis purpose". In our knowledge, for NASA no option has been definitely chosen or preferred. The projects to explore Mars with crewed vehicle from other countries, e.g. China, are not publicly advertised. In any case they will face the same challenges.

6.4 Physiology, Psychology, and Medicine for Astronauts on a Short-Term Mission[4]

Journeys into outer space are in popular culture often compared to earlier human adventures. To humanity venturing out of the African rift valleys. To sailors circumnavigating the planet. To Roald Amundsen going to South Pole, to the voyage of the Mayflower. These journeys were without doubt perilous. People endured enormous hardships, and many died on the way to new lands. Some made it to their destination and started a new life. Others travelled back home to tell tales of wonders they had encountered. Motivations to venture into the unknown were manyfold: to gain new land, to gather new knowledge and sometimes advance science, to get rich, or powerful, the possibility to lead a freer life elsewhere, a new start. Certainly, there are many similarities between then and now. And yet we should keep in mind that this time, important details will differ. Space is an environment not made for human survival. Early human explorers on Earth, crossing oceans in handmade canoes, still

[4] This section is authored by Carmen Possnig and Natuschka Lee.

had an infinite amount of perfectly breathable air at their disposal. Creatures lived in the waters they crossed. They did not rely solely on technology for survival. Their surrounding environment, however freezingly cold or high in altitude it may have been, was still one humans are in basics adapted to. It did not meddle with homeostasis inside their brains or destroy their muscles. No sudden bout of radiation would damage their DNA, no fluid shifts would elevate pressure in their heads to the point of inducing vision problems. Once these travellers reached their destination, they got off the boat and were able to walk. The probability was high they would find food and water not far off. Exploring space, daring to go beyond the Moon, will add challenges we were never meant to take. The risks and sacrifices the astronauts on the first Mars missions will face are a giant leap away from any past adventures we took. One of the reasons for this is that we simply do not yet know enough.

Why Don't We Know More?

Humans have spent time in space for more than 60 years, but most of the missions were relatively short-termed. Valery Polyakov currently holds the record for the longest continuous time spent in space: 437 days on Mir in the 1990s. The time spent on the surface of another celestial body is certainly shorter, with a total accumulation of just under 2 weeks. Looking at these numbers, it becomes evident how little we actually know about whether we can stay alive and healthy—and able to perform mission-relevant tasks—on a journey that would span years.

With only a little over 600 people ever having launched into space, and a lot of them for short-term missions, possibilities to perform experiments on how humans adapt to the spaceflight environment have not been abundant. Earth-based studies simulating microgravity are a possibility to collect more data. A simulation of microgravity can be achieved via bed rest studies, where the participants lie in a horizontal or head-down tilt position for days to months at a time. Bed rest-induced changes in cardiovascular or musculoskeletal systems are comparable to those happening in space. Body weight is of course not lost during bed rest, but the gravitational vectors shift from the typical head-to-foot one when upright on Earth to a much smaller chest-to-back input. Dry immersion studies, where participants lie immersed in water (though not in direct contact with it) and underneath a water-filled blanket, have even greater effects than a typical bed rest. While these experiments are useful for evaluations of potential countermeasures, they cannot give us true microgravity conditions. Tissue pressures will be different compared to a true spaceflight situation, and hydrostatic pressure columns cannot be abandoned. True microgravity conditions can be achieved with parabolic flights, but as they can only provide us with 22 s of microgravity at a time, they can give insights solely into fast adaptations to microgravity which are not necessarily translatable to long-term adaptations. All of these factors lead to our current lack of knowledge on long-term effects of space, especially outside low Earth orbit.

As of our current understanding, we have only two data points regarding gravitational effects on the body: one and zero. On Earth, we of course live in the constant environment of 1G, which is the acceleration we feel due to gravity at the surface of the Earth, equalling 9.8 m/s^2. The human body has been, through thousands of years of evolution, perfectly adapted to this 1G environment. On the International Space

Station (ISS), astronauts experience 0G (or microgravity) due to the station's free fall around our planet. With the experience we have today, we can safely say that microgravity has various and sometimes unpredictable detrimental effects on the human body. A challenge for Mars missions is that we have almost no knowledge about life in *partial* gravity (0.38G, in the case of Mars). The best we have is twelve men who walked on the Moon, experiencing 0.16G. These astronauts spent a few hours to up to 3 days on the lunar surface. If partial gravity has any detrimental effects, they might simply take longer to show up.

While studies on astronauts have demonstrated negative effects of microgravity on both human physiology and psychology, we have also found and implemented countermeasures to the most urgent ones. Several new fields of research have emerged as a consequence of studying health issues of humans and other organisms sent to space. In the early space age, these were mostly comprised of physiological changes elicited by the space environment (space physiology), as well as medical care for space travellers (space medicine). Today, preserving physical and mental health for astronauts is a multidisciplinary task, additionally involving preventive medicine, emergency medicine, bioastronautics, toxicology, telemedicine, space nutrition, space psychology, and space architecture.

This kind of research has not only revolutionised our understanding of various diseases on both Earth and in space, but has also led to the development of a whole new category of remote monitoring systems used on Earth as well as on space missions, providing life support and environmental control, identifying dangers and enabling an early identification of suitable medical treatments (Hodkinson et al., 2017).

6.4.1 Final Preparations and Lift-Off

Sending the first humans to Mars will in many ways be a different challenge from previous robotic missions. NASA identifies five main spaceflight-related hazards for human missions: space radiation, isolation and confinement, distance from Earth, altered gravity, and closed or hostile environments.

On a human mission, the passengers' health and safety will be the number one priority. While medical facilities to treat injuries and illnesses and perform certain kinds of surgeries will have to be included into the ship, spaces for relaxation and social activities are just as important. Both the spacecraft and the habitat on Mars, as well as the daily work schedules, should be adjusted to promote mental health and wellbeing and therefore support mission success.

Today's medical strategy for space missions is prevention. During a typical astronaut selection, a whole week is dedicated for health check-ups, ensuring not only that the healthiest people are selected, but also the ones that are most likely to stay healthy within the following decades, and with the lowest risk for developing any space-induced illness. Ensuring perfect health of the astronauts on the first Mars missions will be especially crucial, as the possibility for medical care will probably

be limited. Ideally, the crew will be selected as an entity, ensuring that not only are they all in perfect physical and psychological health, but also, on the long run, match in terms of personality.

Before lift-off, the interior and the exterior of the spacecraft will be extensively sterilised (as far as possible considering the capability of current standard detection techniques of microbes) to minimise the concentrations of unwanted microbes or parasites. Countermeasures against deconditioning will be on board, medications stored and nutrition optimised for optimal diet, and radiation sheltering in place for emergencies.

Before the space vehicle can enter the steady flight mode to Mars, it must pass the Kármán line (the boundary separating Earth's atmosphere and outer space, at an altitude of 100 km above mean sea level), and low Earth orbit (LEO, between 160 and 1000 km). The ascent from Earth to the Kármán line takes on average about 3 min, depending on the launch vehicle. After this, it takes generally 5–7 min to enter LEO, and another couple of hours to pass the International Space Station at around 400 km height. Even though short-timed, the ascent will have a first stressful impact on the human body as astronauts get exposed to up to three times normal gravity. As astronauts undergo special g-force training beforehand and modern spacecraft are designed to keep g-forces within a comfortable range, detrimental effects of a launch are rare these days.

Once in space, the flight from Earth to Mars may take about 6–9 months, depending on the type of spacecraft, and where Mars and Earth are on their respective elliptic orbits (the closest distance between these happens only every 26 months (see Sects. 3.1.2 and 6.3.2.1)). In total, anyone travelling from Earth to Mars with a return ticket and using a so-called Hohmann-like transfer (Sects. 3.1.2 and 6.3.2.1) must foresee this trip to last at least 3 years. Even though the length of the travel may not appear impossibly long, the travellers must not only face the various space stressors, but also live in a confined space with a constant lack of privacy. A rigorous diet, daily training sessions, sleeping issues, and the necessity to perform high-risk tasks (e.g. space walks) will inevitably result in elevated stress levels.

6.4.2 Microgravity and the Human Body

Gravity is a fundamental force in the universe and sets the course for how life may evolve on a planet. Human bodies have evolved over millennia to perfectly fit Earth's 1G. The shape of our heart, the thickness of our bones, and the architecture of our vessels are all adapted to this scenario. If we move to a different gravitational environment, everything changes. Mostly, not for the better.

For the crew of astronauts having just left Earth for their mission to Mars, the most immediately noticeable physiological reaction on entering microgravity will be the so-called Space Adaptation Syndrome. It occurs when signals from the vestibular system, tactile receptors, and the visual sense do not correspond anymore. 70% of ISS astronauts experience this syndrome, with symptoms usually lasting for

3–5 days and ranging from nausea, dizziness, vertigo, fatigue, headaches, to vomiting. Depending on the severity, the syndrome can cause minor discomfort, but in extreme cases also lead to incapacitation (Heer & Paloski, 2006). Who will be affected cannot be predicted on Earth, even having been on a previous space flight does not seem to be an advantage. The strategy to prevent onset of symptoms consists in avoiding abrupt head movements and delaying critical activities to a later mission stage. Importantly, similar symptoms reappear for up to 10 days after landing on Earth, as the astronaut is now adapted to space and returning to Earth initiates a new adaptation process (Freeman, 2000). It can therefore be expected that upon landing on Mars a similar Planetary Adaptation Syndrome will occur, as the astronauts get used to the new gravitational environment, and that this will possibly impair performance and wellbeing for up to 3 days.

6.4.2.1 The Cardiovascular System Leads the Way

Another imminent reaction to microgravity is the adaptation of the cardiovascular system. The anatomy of most mammals is configured such that the heart is at about the same level as the brain when awake. In contrast, the human brain is in the worst possible position: above the heart, which needs to pump blood against gravity to supply it with oxygen and nutrients. As an additional challenge, the human brain has a very high need for oxygen—consuming about 20% of anything available—but almost no capacity for storage (Lassen, 1959). Heart and blood vessels are so well adapted to Earth's gravity that quick changes in position (e.g. from lying supine to standing upright) can usually be executed without problems (Garrett et al., 2017). However, everything is dependent on gravitational vectors. When humans stand upright on Earth, blood pools in the legs as gravity pulls it downwards. Leg veins are equipped with valves to avoid blood flowing backwards, and surrounding muscle pumps help guide blood flow back towards the heart. In the upper body, blood pressure needs to be maintained in order to "shoot" blood upwards into the brain. In the jugular vein, the largest venous outflow of the brain, valves are often absent or incompetent, as they are not needed in most situations: gravity is used to guide blood from the brain towards the heart (Valecchi et al., 2010). In space, with hydrostatic pressure gradients abolished, weightlessness leads to a headward shift of blood and body fluids. This results in 1–2 l of venous blood from the legs to centre around the upper torso and head. With blood volume thus increased in the upper body, volume receptors signal an overload and the body starts decreasing fluid volume. 15–20% of plasma volume is lost in the first few weeks of spaceflight. In one study looking at shuttle astronauts, 17% of plasma volume was lost within the first 17 h (Alfrey et al., 1996). Blood thickens only marginally, as this loss in fluid is followed by a decrease in red cell mass (Johnson, 1979).

In addition, the headward fluid shift may lead to a congestion of blood in the neck veins. An unexpected consequence could be dangerous on long-duration flights: a recent investigation onboard the ISS discovered six out of eleven astronauts to have stagnant or reverse flow in the jugular vein after 2 months of

spaceflight. In two of those subjects, thrombi had formed in the vein, one of which occluded the vessel. The mechanism for this stasis is not known at present, but it might have been caused by a combination of fluid shifts, anatomical compression of veins inside the thorax (as larger vessels and the lungs shift upwards), and pressure changes inside the upper torso (Marshall-Goebel et al., 2019). While no related clinical consequences have emerged, venous stasis and coagulation are a potential threat. On Earth, complications include difficulty to swallow, difficulty to breathe, and secondary infection of the thrombus, often leading to sepsis. As a worst-case scenario, the thrombus could dislodge into lung vessels and cause pulmonary embolism (Boedeker et al., 2004). For long-duration spaceflights, a screening method should be available (e.g. ultrasonography), as well as a therapy option, e.g. blood thinners as well as antibiotics. Lower-body negative pressure suits were tested as a countermeasure and seem to work well in improving flow, but their application is not without risks in itself and a system applicable for long-distance spaceflights has yet to be invented. These suits also only make sense if there is no prior issue—if a thrombus has already been formed, negative pressure could dislodge it and cause complications.

A lower-body negative pressure suit is a sort of chunky trouser, or, for the version used in terrestrial studies, a very chunky sleeping bag, which gets fixed around the waist. Negative pressure is applied (on Earth, by sucking air out with the help of a vacuum cleaner hose), which pulls bodily fluids downwards into the legs and basically simulates being upright. It decreases fluid shifts and provides efficient training for the heart, blood pressure regulation, and blood flow in general. As an additive benefit, it lowers intracranial pressure and may therefore work as a countermeasure against vision problems (see Sect. 6.4.2.3 below) (Petersen et al., 2019).

As mentioned earlier, human bodies are well adapted to handle changes in position on Earth. Nevertheless, a balance in blood pressure, heart rate, blood flow, and several other mechanisms is needed to ensure steady blood supply to the brain during these stunts. The ability to maintain this homeostasis is often lost in space. About 50% of astronauts returning to Earth experience orthostatic intolerance, i.e. they cannot stand upright for a prolonged amount of time (Aubert et al., 2005). The reasons for orthostatic intolerance to occur are probably a combination of plasma volume loss, leg muscle loss, and diminished blood pressure regulation, induced by the headward fluid shifts (Charles et al., 1994). Upon returning to Earth, these adaptations result in an insufficient perfusion of the brain. This being a possibly life-threatening situation, the body reacts with fainting, which in itself is protective as it shifts the body into a supine position and therefore the brain and the heart onto the same level: blood can now flow easier between the two. The consequences of orthostatic intolerance after return to Earth are usually not of a serious risk for health, due to countermeasures applied during spaceflight, and due to the astronauts being welcomed by a support crew and their flight surgeons after landing. Recovery is therefore usually fast.

A combination of orthostatic intolerance and reduced exercise capacity results in postflight cardiovascular deconditioning, effects which are usually reversed within

3–4 days (if countermeasures are applied), but whether the degree and duration are correlated to the time spent in space is unknown.

6.4.2.2 Risk of Cardiovascular Disease

Apollo astronauts are to date the only humans having left Earth's protective magnetosphere and were exposed to higher doses of radiation than any other astronauts. While several of these men reported "seeing" radiation, mostly in the form of flashes of light which were visible even when their eyes were closed (Fuglesang et al., 2006), no radiation-induced symptoms have been reported (although a lot of personal data has not been made public). A retrospective study reported that lunar astronauts exhibit a 4–5 times higher cardiovascular mortality compared to astronauts who remained in lower Earth orbit during their missions. No differences were found between astronauts who participated in Low Earth Orbit missions compared to astronauts that never flew (Delp et al., 2016). The lunar astronauts' higher mortality could be related to the direct effects of space radiation and microgravity-induced changes to blood vessels. However, the sample size in the above study was small, as only seven of the Apollo astronauts had passed away at that point, and the methodology has been subsequently questioned (Cucinotta et al., 2016).

Microgravity exposure also changes heart anatomy: the size of the left atrium is increased after 6 months in space, possibly a result of headward fluid shifts distending the chamber. This is supported by findings of a higher stroke volume and higher cardiac preload (i.e. more blood going into and out of the heart). The main concern regarding the cardiovascular system is whether the combination of these effects will be dangerous in the long term. In addition, both microgravity and radiation accelerate inflammation in the arteries. Astronauts on missions to Mars would need to perform regular screens for precursors of arteriosclerosis, cardiac ischaemia, or arrhythmias (Norsk, 2020).

6.4.2.3 The Eyes and the Brain

Astronauts have repeatedly reported vision impairments during ISS missions. Mostly, these were refractory changes (i.e. far-sightedness) and could easily be corrected with adjustable glasses. As the phenomenon was investigated more profoundly, several anatomical changes inside the eye were observed: retinal thickness is increased in these astronauts, alongside a swelling of the optical disk, a flattening of the globe and several other factors. These symptoms are summarised as the spaceflight-associated neuro-ocular syndrome (SANS) and occur currently in half of all ISS astronauts. SANS is considered one of the top three health-related risks for future long-distance flights (alongside radiation and human behaviour) (Patel et al., 2020), because the changes in the tissue at the back of the eye (the retina and choroid) might lead to permanent vision defects. In some astronauts, changes in eye anatomy persisted on the ground, and whether these changes would continue to

worsen after 6 months of spaceflight is not known (Lee et al., 2018; Mader et al., 2017). There are several theories as to what causes SANS. Fluids, as discussed, shift upwards in space, which poses quite a problem for the brain: essentially, the brain is a lot of tissue surrounded by fluid in an already tight container (the skull). Adding more fluid is not a good idea, as the brain is very sensitive to pressure. Indeed, elevated intracranial pressure (elicited by fluid shifts) disrupting the balance of pressure inside the skull and pressure inside the eyeballs is one of the hypotheses for how SANS develops. Microgravity does not seem to elevate intracranial pressure by a lot, as a study on a parabolic flight has demonstrated (Lawley et al., 2017), but small changes may be enough to cause havoc. On Earth, with every change in position, pressure inside the brain changes. It is higher when we are lying down compared to when standing up—pressure inside blood vessels plays a role here, as well as fluids shifting with changes in gravitational vectors. This means regular small changes in intracranial pressure are normal throughout a typical day. In space, in the absence of gravity, intracranial pressure stays constant most of the time—and it seems like its level is just a little higher than the 24-h mean value on Earth (Lawley et al., 2017). This may just be enough to cause anatomical changes in the eye (and possibly the brain) and therefore SANS. It also means that if we can lower pressure in the brain for a few hours a day, we could alleviate the risk for SANS. Countermeasures such as lower-body negative pressure are currently being tested for efficiency.

Anatomically, our eyes are part of our brains. If the eyes are affected by spaceflight, odds are, the brain is as well. Indeed we see changes in the brain occurring at the structural and functional level. MRI studies show that the brain shifts upward, while being slightly compressed. Grey matter volume decreases while the ventricles engorge (Lee et al., 2019; Roberts et al., 2019). Alterations in connectivity inside brain tissues have been reported for motor and cerebellar regions, alongside a decrease in vestibular connectivity (Demertzi et al., 2016). This in turn may evoke sensory conflicts between visual and tactile inputs and the vestibular organs, and may be a mechanism of the Space Adaptation Syndrome (Moore et al., 2019; Van Ombergen et al., 2017). It is difficult to say whether microgravity is directly responsible for these changes, as there are various other stressors on space stations that could lead to or exacerbate problems, e.g., high concentration of CO_2, radiation, psychological stress, sleep deprivation, amongst various others, all of which can influence cognitive and neural functions.

6.4.2.4 Bones and Muscles: A Gradual Decline

The musculoskeletal system takes some time to adapt to spaceflight. Bones, muscles, tendons, and ligaments are all subject to the "use it or lose it" principle, meaning that if they are not exposed to a certain level of biomechanical loading, they will atrophy. In space, there is no need to support the body against gravity and without countermeasures, loss of bone and muscle would commence rapidly. Postural muscles as well as the big leg muscles are the first to atrophy, resulting in a decreased lean muscle mass and increased fat deposition, and an overall loss of muscle

strength. This can impact the ability of astronauts to conduct routine mission tasks or perform strenuous extravehicular activities. Even though astronauts participate in daily exercise regimes during ISS missions, they suffer from decreases in lower-body flexibility, agility, and strength. At the same time, upper-body and core muscular endurance and strength remain relatively stable (Laughlin et al., 2015), as these are still being used regularly. Muscle loss in postural muscles in particular may have an impact on stability and performance upon landing on Mars, or once returned to Earth.

Astronauts on current ISS missions are required to perform 2-h exercise regime 6 days a week. The time is split between endurance exercise to preserve aerobic capacity, performed on either a bicycle or a treadmill, and resistance exercises with, for instance, the *Advanced Resistive Exercise Device* (ARED), to preserve musculoskeletal mass and strength. The exact type and amount of exercise needed to preserve fitness and muscle and bone health are unknown. Muscle loss during long-term missions has been greatly reduced due to the newly installed ARED. However, equipment such as ARED can only be fitted into a rather grand space such as is available onboard the ISS. It is questionable whether a spaceship en route to Mars, or even early lunar habitats, will have the luxury of this much room being allocated to exercise. Fitness equipment will therefore have to be optimised for more confined spaces. It is important to note that while a bicycle would require a lot less space, running is the best countermeasure for bone health. Bones, especially in legs and hips, need regular biomechanical impacts to preserve their density, which only running can provide (Rector et al., 2008).

Even with today's training schedule on the ISS, workout is focused on some big muscle groups. Yet there are hundreds of small muscles (and tendons, and ligaments), which, on Earth, get their exercise from gravity, and which cannot be trained in space. Astronauts also get taller in space as the spine lengthens (growing about 6% in seated height), which can cause back pain, and, in the worst case, can result in the astronaut being too tall to fit in their space suit or return vehicle. In this case, a special suit is worn before the return trip, in an effort to "shorten" said astronaut's spine into a more reasonable range. Additional high-load resistance training may also be of help.

Similar to the muscles, bone loss is seen mostly in the lower extremities, pelvis and the spine, indicating that these are more dependent on ground reaction forces and thus more sensitive to their loss. The loss of bone is quite variable within astronauts, with some losing up to 2% per month, while others lose considerably less (~0.1%). Bone loss is also related to preflight bone density: astronauts with higher density lose substance more rapidly. The risk of fractures however does not appear to increase, as up to date there has never been a recorded bone fracture in space (although missions have been relatively short so far). One of the largest bones in our body is the femur, located in the upper thigh. As this is a weightbearing bone that is not used much when floating in microgravity, it is also one which typically loses a lot of density—on average, about 1.58% per month. Using this to roughly evaluate the effect of a 1000 day mission to Mars and back, loss in bone density could be as

much as 50%—greatly surpassing the established threshold for significant risk of fracture, which is a gross bone loss of 15% (Horneck et al., 2006).

A secondary consequence of loss of bone density is that all those minerals (mostly calcium) liberated from the bone need to go somewhere. As a first step, they get released into blood vessels. Calcium however is an important regulator of many biochemical pathways, notably in the heart and brain, and its blood level is tightly regulated. The liberated calcium is therefore eliminated from the body via the urinary tract, passing the kidneys. This poses a problem as an excess of calcium in the urinary tract is a risk for development of kidney stones (whose main ingredient is very often this mineral). Depending on their size, kidney stones can cause havoc inside the kidney itself, obstructing the ureter or urethra or irritating the bladder, and causing excruciating pain. If they are not small enough to get washed out with urine, they need to be removed, as they pose a risk for infection of the urinary tract, which by itself is threatening but can also spread and lead to sepsis. Astronauts at risk for developing gout are also likely to suffer from the high levels of calcium. Chronic hypercalcaemia might additionally affect other physiological systems, such as the cardiovascular system or the brain, which are dependent on calcium signalling. Currently unknown consequences of bone loss might therefore exacerbate risks for secondary and tertiary diseases (Hart, 2023). While individual variability in bone loss is rather big, no difference has been seen between female and male astronauts (Smith et al., 2014).

One way to avoid a lot of these effects would be to build a rotating spaceship, thus creating artificial gravity. Spacecrafts like these are costly and to our knowledge, not considered as a real possibility at the moment. Of note, one would probably need all of the living quarters to be in artificial gravity. As mentioned before, Space Adaptation Syndrome occurs because our bodies need to adapt to the new environment. If crewmembers would constantly change between gravity and microgravity sections of the ship, it is likely that adaptation would never take place, and every change in gravity might bring waves of nausea, vertigo, and vomiting spells. On the other hand, the brain is adaptable in amazing ways, and may find ways to cope with regular changes in gravity. Theoretically, rotating a spacecraft at Mars gravity levels might make landing and the first days thereafter easier for the crew. Orthostatic intolerance might be avoided, and any kind of physical training done during the trip be more efficient than if performed in microgravity.

6.4.3 Radiation

As with gravity, the human body has evolved with certain types and amount of radiation. Our skin's layer of dead cells protects us from radiation, as do several internal mechanisms that repair or destroy damaged cells. On Earth, we are fairly well protected by the magnetic field and the atmosphere of our planet. Problems arise once we leave these two behind. Once outside their protection, two types of

radiation will be dangerous to our astronauts: solar radiation and galactic cosmic radiation.

6.4.3.1 Deadly Sun

Solar radiation is basically energy from the sun. It is mainly ionising radiation that we must be concerned about—a type of radiation with so much energy that it can knock an electron out of an atom (thus ionising it). The atom becomes more reactive: chemical bonds can break, DNA mutations emerge. Most of the time, the sun emits energy, mostly protons, electrons, and heavy ions, at a constant level, and this is manageable for space travellers. Two different kinds of events however are dangerous. First, a solar flare is a sudden increase in brightness that can last for hours and emit higher doses of radiation. Second, these solar flares can be accompanied by an even bigger problem: a coronal mass ejection, or solar particle event, which is a tremendous release of energy, a cannonball of protons moving in one direction like the beam of the Death Star. Coronal mass ejections are the cause of Northern and Southern lights—but we do not want them interacting with astronauts. If a spacecraft with its inhabitants happens to be caught in that beam, acute radiation sickness would occur—that means (depending on dosage) heart, brain, and lung damage, skin burns, vomiting, compromised immune systems, and in the worst case, a painful death. The good news is that we do get a warning. Coronal mass ejections need up to 3 days to reach Earth, enough time to tell astronauts to take shelter. Solar flares travel near the speed of light, and therefore take eight minutes to reach Earth—taking shelter until they have passed (usually about an hour) is still a good idea.

The sun has a cycle of magnetic activity, with a peak in activity around every 11 years. In order to avoid solar flares and mass ejections, a mission to Mars could be scheduled in a low-activity phase. The trouble is that solar winds protect us from the second radiation-related problem: cosmic background radiation. We are faced with a dilemma: in high level periods of the sun, there is less cosmic background radiation, but low-level sun periods are accompanied by higher cosmic background radiation.

6.4.3.2 Deadly Cosmos

Cosmic background radiation originates from stars exploding somewhere in deep space. Unlike the attacks of our sun, cosmic radiation is constant, low-level destruction. Apollo astronauts have reported "seeing" this type of radiation: they saw flashes of light in front of their eyes, when they were closed, about every three to seven minutes (Fuglesang et al., 2006). Astronauts onboard Mir, space shuttle missions and the ISS have also reported seeing these flashes. Their frequency seems to increase the greater the distance from Earth, and they are mostly noticed when trying to fall asleep (and can provoke sleep disturbances). The flashes might be caused

by particles colliding with the astronauts' optical nerves or crossing their eyeballs (and interacting with photoreceptors). The eyes are of course a small part of the body—if incoming radiation is noticed there, likelihood is high that other parts of these astronauts' bodies were also affected, perhaps thousands of particles passing through them every second. According to physicist Eugene Parker, for every year spent in outer space, a third of a human's DNA would be sliced by cosmic rays (Parker, 2005). This would greatly overpower their own DNA repair mechanisms. We must also consider that we are not alone: our microbiome consists of billions of microbes that support our bodily functions in many ways, and that are themselves susceptible to DNA damage.

There are indications that excess radiation causes declines in cognitive function, mainly in memory, attention, and quick thinking, and may also increase the risk for diseases such as Alzheimer's (Cherry et al., 2012; Meyers, 2006). But these studies are from patients undergoing brain radiation treatment therapy and may not directly translate to the constant low-dose radiation in space.

Indeed, we cannot say for certain whether radiation is a total showstopper. Once again, we are faced with a lack of data. We do know that sudden high dosages of radiation, such as caused by atomic bombs or radiation treatment, have detrimental effects and can lead to long-term consequences such as cancer. During space missions, a solar flare or coronal mass ejection may have these exact effects and in the worst-case lead to radiation sickness or even death, if appropriate shielding is not available. However, astronauts on their way to Mars are not only subjected to the high-dosage lethal version of radiation. They will also face the consequences of the constant low-dose radiation by cosmic background rays. We know little to nothing about long-term effects elicited by cosmic background radiation, especially if exposure is spread over a mission that lasts several years.

The only humans ever having left Earth's magnetosphere were the Apollo astronauts. And they were lucky: Solar events did happen during the mission years, but none while astronauts were in space. The solar storm of 1972 happened exactly in between the Apollo 16 and 17 missions. It has been calculated that, had an astronaut been on the lunar surface at the moment, he would have been exposed to a level of radiation that would have ensured him a 50% chance of dying over a short amount of time. He would have needed a bone marrow transplant to survive. Admittedly, had the astronaut been inside the lunar lander instead of outside in his suit, exposure would have been decreased by an order of magnitude thanks to the lander acting as a shield (Wanjek, 2022).

Shielding is the key word here: against solar flares, a place with extra protection inside the spaceship will be needed. Protection of course means more material, which means more mass and therefore more fuel and thus more expensive ships. But as we will be able to warn the astronauts of any big solar events, a small space in which they can hide for a few hours might be sufficient for the first missions. The trouble is, for cosmic background radiation, a small amount of shielding can be worse than no shield at all: When these fast, heavy ions collide with the ship's hull, they can generate cascades of secondary particles, which are even more destructive than the original ones. The ship will need a thick shield, a few centimetres of metal,

or perhaps (a lot of) water, stored food, or even trash. Other solutions—such as magnetic force fields that deflect cosmic rays, something researchers at CERN work on—are still far in the future (Wanjek, 2022). At the moment, we do not have a solution for the cosmic background radiation problem, other than simply hoping that effects will not be too detrimental.

While Mars is much further from the sun than Earth or the Moon, on its surface, solar radiation can still be deadly. Mars, after all, has neither a thick enough atmosphere, nor a magnetic field to protect from radiation. Radiation levels, according to the Mars Odyssey probe, can be more than an order of magnitude higher on Mars' surface compared to Earth. Settlers will therefore need to be protected, ideally on a constant level, e.g. by designing habitats to include shielding, or by erecting them underground, or inside lava tubes. About ten times a year, a coronal mass ejection happens that can seriously endanger life on Mars. A special storm shelter will certainly be useful for these events (Wanjek, 2022).

6.4.4 Space and Psychology

Human behaviour is cited by NASA as the number three red risk on a journey to Mars (Patel et al., 2020). Living and working in a home away from Earth for years will expose astronauts to unprecedented neurocognitive and behavioural stressors. Predominantly, sources of stress can be divided into four interacting categories:

- Physical factors, including microgravity, radiation, and light/dark cycles
- Habitability factors, including confinement, vibration, noise, temperature, light and air quality
- Psychological factors, including isolation, danger, monotony, workload, sensory deprivation, and constant risk
- Social or interpersonal factors, including lack of privacy, gender issues, cultural effects, crew size, leadership and social dominance issues, communication, and personality conflicts (De la Torre, 2014; Horneck et al., 2006; Manzey et al. 1998)

A mission to Mars will involve continuous exposure to all these challenges for up to 3 years. The duration and distance from Earth will far exceed any prior space mission, subjecting our astronauts to unprecedented levels of exposure to any spaceflight hazards. In addition, these humans will be farther away from Earth than anyone before. The effects of seeing Earth disappear as a small spot in the distance are unknown. Some researchers suggest that this so-called Earth-out-of-view phenomenon might bring as a consequence a deep feeling of loneliness and isolation. Effects could range anywhere from a restructuration of humanity's place in the cosmos, to no impact at all (Kanas, 2005).

Exposure to spaceflight stressors will affect each individual crew member and each crew differently. Notably, psychological stressors and their severity may change from mission to mission. Being among the first humans to venture to Mars will surely create a different experience compared to being part of one of the

following crews, who perhaps will experience less novelty in the eyes of the public. Composition of the crew and crew support will have effects as well.

It has been suggested that individual responses to these psychological stressors can vary. Impairment of cognitive performance and motor skills is possible, as are maladaptive behavioural reactions and disturbances of interpersonal relationships within the space crew and between space crew and ground personnel (Horneck et al., 2006).

In addition, care for astronaut's health and wellbeing should not stop after the mission is complete. Post mission stressors are manyfold and it can be difficult to readjust to normal life after a long time away. Problems can be physical, such as lingering effects of microgravity or radiation, but also psychological. Long periods of separation can be difficult for families and couples, and finally, personality changes can occur. While these can be positive, such as "new insights into the meaning of life and the unity of mankind", they can also be of negative nature and range from substance abuse to anxiety and major depressive disorder, with the necessity for psychotherapy and psychoactive medications (Kanas et al., 2009).

6.4.4.1 Cognitive Performance and Motor Skills

As described above, spaceflight can alter brain structures and connectivity and thus directly affect mental performance. As a consequence, the astronauts' cognitive and motor skills can be affected (Bock et al., 2001). In addition, psychological stress can indirectly impair neurocognitive performance (Newberg, 1994). A decrease in mental performance may also be related to the physiological stress of adaptation to microgravity (Space Adaptation Syndrome), or combined effects of other stressors (e.g. confinement, isolation, workload, elevated levels of CO_2).

Results from recent studies differ from those performed at the end of the last century. Earlier studies reported elementary cognitive functions (e.g. memory, logical reasoning, object recognition) to remain largely unchanged by spaceflight, while motor skills and the ability to focus attention are significantly disturbed (Bock, 1998; Manzey & Lorenz, 1998). More recent studies found additional decreases in executive functions (Flynn, 2005), with decreases in problem-solving abilities, memory, learning, and attention as well as reaction times (Moore et al., 2019; Roberts et al., 2019). Whether these factors reflect detrimental effects on the central nervous system, or effects of unspecific stress, is unclear, although sleep deficits and circadian desynchronisation are likely culprits. However, it must be noted that a wide range of cognitive tests exists, and they vary quite a lot. Other studies, albeit done during short-term missions, noted that although some Low Earth Orbit travellers have reported a subjective decline in cognitive performance, only minor changes are measurable with objective tests (Flynn, 2005). These tests also usually have a learning effect and might not display the most realistic picture.

Two long-term studies stand out among the shorter missions: Cognitive abilities of Valery Polyakov were investigated by Manzey et al. (1998) during his record 437 days on Mir, while during the NASA twin study, Scott Kelly's cognitive abilities

were observed over a year (Garrett-Bakelman, 2019). The results of the Mir study show a surprising resilience of cognitive and perceptual-motor abilities over this remarkably long time spent in orbit. Decreases in performance, alertness, and well-being were found, but only during the first 2 weeks in space and after landing back on Earth, suggesting a reaction to altered gravity as well as high workload. After the cosmonaut had successfully adapted to microgravity, performance and mood returned to preflight levels and remained stable throughout more than 400 days spent in space. For Scott Kelly, minor attenuations in some but not all cognitive functions were found. Long-term exposure to microgravity and space-related stressors therefore seem not to automatically impair cognitive performance. Nevertheless, indirect stressors such as high workload, circadian disruption, and psychosomatic discomfort have impaired performance in several other space and isolation studies (Nechaev, 2001). Whether we can compare the situation on Mir and ISS to a future journey to Mars is questionable as well: Polyakov and Kelly never experienced phases of boredom and social monotony lasting more than a few months, as crews were changing throughout their missions, regular care packages arrived from Earth, and communication was as easy as possible. On a rather monotonous month-long journey to Mars, isolation, confinement, and either low or high workload can lead to cognitive fatigue, which in turn can result in impairments of performance (Stuster, 1996). Resupply from Earth will not be possible and communications will be delayed by up to 22 min each way. As a consequence, the Earth-based support currently given to astronauts will be unavailable for exploration missions.

This also sheds light on a general problem for research of psychological effects on future exploration missions: we do not have the perfect analogue situation to perform this research.

6.4.4.2 Earth-Based Missions

On Earth, psychological effects of spaceflight are often studied in the so-called ICE environments (isolation, confinement, extreme environment). An ICE environment is a setting that combines extraordinary physical, psychological, and interpersonal demands, necessitating significant human adaptation for survival and performance. These environments share several characteristics—notably constant danger, the need for a high-tech life-support system, a lack of space, isolation, discomfort, lack of external visibility, a need for protective clothing, unusual photoperiodicity, a lack of intimacy, and the possibility of sudden disaster. Previous exploration missions from the “heroic age”, Antarctic research bases, and submarines are examples for scenarios similar to space missions. Antarctica mirrors the extreme environment, the isolation and confinement and the inability of rescue should an emergency occur. Crews however are not on site to be participants for space exploration studies, but perform their specific job while perhaps also participating as research subjects, mostly during their free time. Among other results, research in Antarctic bases has highlighted the occurrence of sensory deprivation as a result of the monotony of the landscape, which in combination with social monotony and boredom due to

repetitive and restricted tasks can be a precursor for problems in individual performance, but also for interpersonal interactions and cooperation within the crew (Bachman et al., 2012).

Observations from analogue scenarios are complemented by simulation studies such as the ESA's and IBMP's (Russian Institute for Biomedical Problems) Mars500 or NASA's HiSEAS missions. Simulation studies typically select crews for their astronaut-likeness, which then perform tasks similar to those of crews in space. However, the fact that there is no real risk involved and rescue is possible within a few hours renders their setting different from an actual mission into space. Furthermore, while some factors of spaceflight can be simulated, others, such as the impact of radiation or the Earth-out-of-view phenomenon, cannot be accurately represented.

A similar problem exists for studies in low Earth orbit. While still physically isolated from home, the close proximity of the ISS to our planet facilitates psychological support. Private psychological conferences are offered to astronauts, who benefit from services from a robust ground behavioural health and performance support team. Astronauts also receive delivery of care packages, letters and surprises from home. Combined with the relatively large volume of the ISS, the possibility to communicate in real time, the possibility to evacuate within hours in case of emergency, new crewmembers rotating periodically, and relatively low levels of radiation, the overall mission structure is quite different from a journey to Mars. Behavioural challenges experienced today are expected to not entirely reflect those that future crews will face during exploration missions.

For Mars missions, different ways will have to be found to support psychological wellbeing, improve crew morale, and preserve mental and behavioural health. In addition, new psychological issues may emerge as a result from the constant danger, high-risk environment, the dependence on automated life-support systems, and the distance form Earth.

It's Not All Bad

Literature repeatedly reports the negative effects of ICE environments while omitting to consider the positive consequences. Sojourns in ICEs can have beneficial effects on crewmembers, proving that humans are capable to adapt to these extremes. Something about these missions makes people strive for a second round: Space travellers work hard to be able to return to space, Antarctic winteroverers dream of spending another long night in the south, and submariners go on multiple missions. History tells a similar story. Shortly before his death in a tent on the way back from the race to South Pole, Robert Falcon Scott professed not to regret to have returned to the ice desert—"how much better it has been than lounging in too great comfort at home" (Scott, 2008)—and of his surviving crew, Cherry-Garrard (1922) later confirmed this ambiguity, writing that "an Antarctic expedition is the worst way to have the best time of your life". Since the first space missions, space travellers have reported feelings of adventure and accomplishment, pleasure, fulfilment, humility, humanity, and a restructuration of their values (Kanas, 1987; Suedfeld & Weiszbeck, 2004). While the Earth-out-of-view phenomenon might have an effect on future

Mars explorers, we may be better equipped to handle them than past literature suggests (Kanas, 2005).

6.4.4.3 Gender Issues

Gender issues will have to be carefully considered when choosing a crew for a Mars mission. Literature is divided on whether a mixed-gender crew would perform better than same gender crews (Horneck et al., 2006). Possible formation of couples and sexual activity are likely to arise during a 3-year mission, whatever the composition of the crew, and may come with several risks, such as interpersonal tensions due to jealousy, sexual harassment and violation, disturbance of crew cohesiveness and unintentional pregnancies.

In the scope of the first Mars missions, contraceptive measures for either male or female crewmembers will be paramount to prevent a potentially dangerous pregnancy from occurring, alongside providing options for termination as an emergency solution. Thought will have to be put into the How, as a 3-year journey would require about 1 100 contraceptive pills per female astronaut. Pills are certainly not the most reliable way of handling this issue, as radiation might affect efficiency of drugs and drug metabolisation might be changed due to changes in the digestive system (e.g. stomach content floating instead of settling down). In addition, every pill has a weight and must be stored. Furthermore, space toilets are, as of now, not made for processing menstrual blood. While an improvement in toilet hardware certainly is needed, contraceptive measures could be combined with suppressing menstruation, perhaps making female astronauts' lives easier. Contraceptive implants or injections can be a way of handling both, but these usually have to be removed after about 3 years. Intrauterine devices can stay in place for 5 years and are perhaps the better option, although requiring regular check-ups.

6.4.4.4 Sleeping on Mars

Sleep loss and fatigue are a common occurrence during spaceflight missions. Sleep quality is often deteriorated, as evidenced by a reduction in both REM and slow-wave (deep) sleep—a balance of which is needed for recovery, performance, and wellbeing—and increased movement arousals. The reasons are most likely work/rest schedules, workload, noise, light exposure and physical discomfort, nocturnal alarms, and a shift in circadian rhythms. A disruption of sleep is directly linked to a decrease of cognitive and operational performance, as well as mood disturbances. Sleep loss also leads to increased intake of sleep medication, whose side effects, similar to medication against motion sickness, include decreased alertness and deterioration of cognitive skills (Mallis & DeRoshia, 2005).

The circadian clock is a finely tuned system playing a critical role in control of physiology, sleep, cognition, and performance. A stable alignment of circadian rhythm and sleep is crucial for optimal function of the nervous system, hormonal

balance, cardiovascular system, core temperature management, and many others. A misalignment can be a health risk but also once more decrease performance and cognitive skills. Usually, *zeitgebers* determine the length of the human circadian rhythm. These can be day/night cycles, changes in temperature, but also social clues such as working schedules and mealtimes. Luckily for Mars explorers, the rhythm is not necessarily bound to Earth's 24-h days, but is adaptable to a certain extent. A day on Mars would be 37 min longer than an Earth day, amounting to 24.65 h. Studies done in Antarctica show that, in the absence of a "normal" day/night cycle, circadian rhythms can free run even with people having knowledge of time, getting closer to a 25 h day (Kennaway & Van Dorp, 1991). During the robotic Phoenix Mars lander mission, support personnel were expected to adjust to Martian day length while controlling the robot. Most people were able to adjust their rhythms to a 24.65-h day. Blue light was used at their work place to maintain alertness (Barger et al., 2012). Light in general is the most prominent pacemaker of the circadian clock, a factor also important for the design of both spacecraft and Martian habitat. Exposure to sufficiently bright light can therefore alter the circadian clock within a certain timeframe (e.g. days around 23.5–25 h are feasible, whereas trials to introduce 21- or 27-h rhythms seem doomed to fail) and will be a prominent tool in keeping astronauts alert during transfer and on the surface (Guo et al., 2014).

6.4.5 A Year in Orbit: The NASA Twin Study

Having a pair of identical twins in their astronaut corps was an opportunity NASA did not let pass by. Marc and Scott Kelly were both experienced astronauts, having flown several missions, when they were selected for a year-long mission to look at physiological changes during long-term spaceflight. While Scott spent 340 days on the ISS, Marc was retired by then and spent the year on Earth as his genetically matched control. Although this gives us just one subject, such perfect controls are hard to find and the results rather interesting (Garrett-Bakelman, 2019). Data was collected over 25 months, including preflight, inflight, and postflight testing, and span over ten different research fields. Some physiological functions were significantly affected by spaceflight and while others did not undergo changes, a majority eventually returned to a preflight baseline. NASA has since identified the major spaceflight-induced changes the space-twin underwent and categorised these:

- Body mass and nutrition
- Telomere length regulation
- Maintenance of genome stability
- Vascular health
- Ocular structural adaptations
- Transcriptional and metabolic changes
- Epigenetic shifts
- Lipid level changes

- Microbiome responses
- Cognitive function

Effects that persisted for 6 months after landing included an increased number of short telomeres (a biomarker of ageing and a determinant of age-related diseases such as cardiovascular disease and cancer), some genes' expression levels, increased DNA damage, and attenuated cognitive function (although these were limited to a few domains only).

Investigations of Scott's eyes revealed symptoms of SANS, some of which existed already preflight (a remnant from earlier missions) and worsened during his year in space. This underlines the need for countermeasures to be found to avoid SANS, especially for a flight to Mars. Symptoms might evolve during the 6–9 months of travelling there without the astronaut noticing, then worsen during the journey back to Earth and endangering health. Interestingly Mark, the twin who remained on Earth, had no symptoms related to SANS; despite having participated in several previous space missions (although Scott previously had spent a total of 180 days in space, while Marc had only participated in short-term missions, with a total of 54 space-days over four missions).

The diversity of the gut microbiome is often considered to be an indicator for microbiome health. Changes in gut microbiome diversity were surprisingly small in Scott and can be attributed to a change in diet and isolation with a small number of people. However, changes in microbiome function and composition were found. Depending on the nature of the change, this may have different effects on health. If the diversity of microbes in the gut is reduced, this may lead to a higher risk of health issues affecting the digestion, immune system, skin health or even the mental state (Gilbert et al., 2018) (see also Sect. 6.4.8).

Upon return to Earth, Scott's immune response was consistent with an inflammatory process, likely due to the stress of landing. The first test of a vaccination applied in microgravity was also made during this study. The immune response (T cell receptor repertoire) was not significantly affected by spaceflight.

Given the results of the twin study, astronauts on a trip to Mars can expect risks from their immune system being under stress, impaired function of mitochondria, changes in the cardiovascular system that worsen over time, a slight decline in certain cognitive functions, and the genetic side: alterations in telomere length, gene regulation, and genome integrity.

In addition, upon landing on Earth after 340 days, Scott was barely able to walk and stand steadily. His muscles had become weak, especially postural ones needed for stability. He had lost bone mass and suffered from nausea. But he got better day by day. His coordination was off, although he was able to perform routine tasks. This Planetary Adaptation Syndrome is not such a big problem on Earth, where astronauts have a support crew awaiting them, carrying them away in a comfortable seat, and giving infusions to replace any lost plasma volume. On Mars, no welcome committee awaits the pioneers. Mission critical tasks will need to be performed. After 6 months spent in weightlessness, muscles will be weakened, the cardiovascular system deconditioned, plasma volume decreased, bones will be brittle, and on

top of this it is likely that Mars Adaptation Syndrome will occur. Mars Adaptation Syndrome will stem from both the fact that the vestibular system needs to adapt, as well as the orthostatic intolerance (due to cardiovascular changes, see above) and the loss of postural muscle mass and strength. This combination might be very dangerous for mission success, especially if critical tasks need to be performed immediately after landing. Countermeasures such as exercise and adapted nutrition during the flight will be crucial to ensure the astronauts are as prepared as possible for landing. As it does on Earth, postural stability after landing will probably initially improve rapidly, followed by a gradual recovery. Therefore, mission tasks within the first days should be kept light and critical tasks should be avoided. In combination with weakened muscles, bones and cardiovascular deconditioning, caution is warranted to prevent accidents and injuries (Horneck et al., 2006). On the bright side, it might not be as bad as landing on Earth. Mars' 0.38G will be an advantage at least in this perspective.

6.4.6 Medical Care in Space

The best medical strategy for spaceflight will always be prevention. Astronauts are thoroughly screened during the selection process. Screening is done for any underlying medical problems, but also to ensure (as far as is possible) they have as low a risk as possible of contracting space-related illnesses. They then have annual checkups, more often if they are assigned to a mission. However, we cannot screen for the likelihood of accidents. Bones can break, appendixes can burst, kidney stones develop—not to mention any space-related illness we have not yet thought of and which might occur on long-duration flights.

Should anything worrisome happen onboard the ISS, astronauts can be evacuated within 6–24 h. For a severe medical emergency, delaying treatment for such a span of time may have severe consequences, especially considering that the injured astronaut still has to endure the landing process, subjecting them to about 4G for a few minutes. In addition, depending on when the undocking occurs, the landing site could be out of immediate reach by the terrestrial support crew, making the waiting time inside the capsule a possibly rather long one. Nevertheless, this is still quite a comforting scenario.

What happens if there is a medical emergency en route to Mars? Hopefully, there is a medical doctor on board—and hopefully, they are not the one with the problem. With evacuation impossible, the crew will have to be autonomous. Help and guidance from Earth might be available, but with communication delays somewhere between three and 22 min each way, this might not be of much use.

Some medical issues will need surgery for resolution—but surgery in microgravity is no minor feat. Without gravity, blood aerosolises and forms a fog (Wanjek, 2022). Blood flow, tissue pressure, and the efficacy of any medication (especially anaesthesia and other vasoactive drugs) are so different that even routine procedures

would not be comparable to the same situation occurring on Earth (Norfleet, 2000; Panesar & Ashkan, 2018).

While minimally invasive (laparoscopic) surgery might be an option, it is a solution only for certain surgeries. Even then, microgravity tends to make organs float also inside humans, which would likely turn the experienced surgeon into a novice. The image they see on their screen will hardly correlate to the same procedure done on Earth. Administering anaesthesia is another challenge. Since spaceships as well as habitats are sealed environments, we cannot administer the Earth-common inhaled anaesthetics, because if there is a leak, the patient will not be the only one asleep. Oxygen leakage into the cabin would increase the risk of fire. Spinal anaesthesia might work for some problems, but with fluid shifts and in the absence of gravity, one cannot be certain where the medication will end up. Local injection is another option. This is an attractive technique because the patient is conscious and needs less support and equipment. However, local techniques are not suitable for any kind of surgery and if applied, require significant skill and training in order to be efficient. In addition, research shows medications are absorbed at different rates in space, likely once more due to fluid shifts, and the fact that the content of stomachs is floating.

Even if surgery is successful, wound healing is the next issue on the list of factors affected by microgravity. The immune system itself seems to not perfectly adapt to space. Dormant viruses such as herpes tend to awaken and cause illness. Living in an almost sterile environment such as a spaceship for months or years is a further challenge for the immune system, which needs constant inputs of agents in order to stay alert (Horneck et al., 2006) (see also Sect. 7.4.1).

There is a good reason to worry about accidents. After 6 months in weightlessness, astronauts will have several of the effects described above: brittle bones, weak muscles, worse coordination, bad eyesight, nausea, dizziness, and clumsiness. After having endured the hypergravity conditions of landing, they then have to walk and work in a completely unfamiliar environment, deal with psychological stress and possibly with a high work schedule and several critical tasks to perform.

Space medicine's soon-to-be sibling, Mars medicine, will need to be a specialisation developing before any long-term settlements are set in motion. While today's astronauts, and surely the first ones going to Mars, are heavily screened and as healthy as possible, this will change once space travel gets more accessible. If creating permanent settlements on Mars turns into reality one day, thousands of people will try their luck at this new final frontier. The space doctor's strategy will have to change from prevention to managing pre-existing and space-induced conditions in more "normal" humans. On a positive note, surgery under Martian gravity should at least be a lot easier and similar to terrestrial situations than when performed in microgravity.

For now, what we have is a little data on how astonishingly healthy people cope with microgravity for some months. We lack data on anything exceeding 437 days continuously spent in space. We completely lack data on partial gravity. And we certainly lack data on how microgravity affects people who are not in perfect health,

are either very young or above retirement age, and have not had years of training on how to cope with spaceflight-related stressors.

6.4.7 Staying Healthy on Mars

Microgravity, we can safely say, is detrimental to our health—at least, without application of countermeasures, and if we plan to return to gravity at some point. But how much gravity do we need? Is 1G paramount for keeping a healthy body and mind? Once again, we can safely say that we do not know—because no one has ever had the chance to test it. Some parabolic flights have been flown with lunar or Martian gravity levels, but due to their methodology and the fact that a parabolic flight can provide us with only a few seconds of altered gravity, neither can they tell us about long-term adaptations nor answer the most important question: can humans flourish while living on Mars for years?

It is often assumed that the effects of lunar and Martian gravity levels on human health will be distributed on a linear line between 1G (optimal health) and 0G (detrimental for health). But is it really a linear connection? Is 0.5G exactly in the middle between good and bad? We do feel gravity more with age. Spines bend towards the Earth, muscles get tired more easily, bones weaken. Ageing might in fact be easier with less than Earth gravity. What if 0.8G were actually the optimal level for human health? On the one hand, Moon and Mars gravity might be neglectable and their effect almost as detrimental as microgravity. But on the other hand, Martian gravity might also just be enough to keep us healthy, and even take some load off our bodies.

Apart from gravity, Mars's environment does have some rather comforting features: Temperature, for instance, will not be of greatest concern for Martian explorers. By day at the equator, temperatures can rise to a cosy 21 °C, while at night (due to the absence of an atmosphere) they can drop to around –100 °C. The average temperature is about –63 °C. However, there is no windchill on Mars, and since the atmosphere is very thin, it does not carry much heat away. It is possible therefore that the felt temperature would be even higher. Incidentally, –60 °C is also the average temperature of a polar winter in the Antarctic Concordia Station, where the crew regularly ventures outside with an adapted suit. Another positive factor: The Martian day conveniently is 24.7 h long and therefore circadian rhythms should be able to adapt, which will be a relieve after the disruptive effect of space travel.

6.4.7.1 Can We Venture Outside Without a Suit?

The absence of an atmosphere suitable for human survival is a bigger concern. The average air pressure on Mars is 6 millibars (at altitude 0) and much less on mountains or high plateaus. On Earth, air pressure at sea level is around 1000 millibars. On Mount Everest, it still ranges around survivable 340 millibars. There is no need

for excessive worry: At 6 millibars, human blood would neither boil, nor would the body freeze. The pressure inside our vessels ("blood pressure") protects blood from boiling. A typical blood pressure of a standing person on Earth is around 120/75 mmHg. This means that the lowest pressure in the (arterial) vascular system does not fall below 75 mmHg (depending a little on the position as, standing up, the pressure in the feet is higher than in the head (gravity!), but in space—weightless—the pressure is the same throughout the body). The temperature at which water starts to boil depends on the ambient pressure. On Mount Everest (340 millibars), for example, water boils at 71 °C. In blood vessels, at 75 mmHg (equal to about 100 millibars), the threshold is 46 °C. Fortunately, this is far above a typical humans' core body temperature, which is 37 °C. Therefore, blood will not boil because the pressure within blood vessels keeps the body temperature below boiling point. As long as the heart keeps beating and maintaining the pressure, there is no need to worry about that. There is need to worry about the lack of oxygen and decompression sickness. Oxygen is needed to keep organs—first and foremost the brain—up and running. On Earth, the atmosphere consists mostly of 78% nitrogen (N_2) and 20.8% oxygen (O_2). Pressure is needed to prevent gases such as nitrogen to form gas bubbles inside the body. Now, if astronauts breathe a 78% N_2 + 20.8% O_2 air mixture from a gas bottle while on an EVA on Mars, they still need a pressure suit: Similar to divers' decompression sickness when they surface too quickly, gas bubbles form when the pressure difference between the environment and the body is too high. Most of these bubbles will consist of nitrogen (as nitrogen is usually not bound to other molecules), but they can include oxygen (and also water). These gas bubbles form in tissues, but also inside blood vessels. A dangerous situation, as the bubbles can block arteries and veins and cut off blood flow from organs, exacerbating the lack of oxygen and leading to tissue damage, cell death and irreversibly injuries in the heart, lungs, and the brain.

Nitrogen bubbles might be prevented by simply providing a 100% oxygen environment. 100% oxygen is what ISS astronauts currently breathe inside spacesuits when on an EVA. However, a two-hour pre-breathing protocol to remove nitrogen from their tissues is needed beforehand, as the air inside the ISS still contains nitrogen. Not ideal, in case a fast EVA is needed for urgent repairs. Opting for a higher oxygen, lower nitrogen (and lower pressure) atmosphere inside the habitat could be an option (Norcross et al., 2013). The fire hazard must be balanced with possible symptoms and effects of hypoxia. Up to date, no studies have looked at the combined effects of hypoxia and partial or microgravity.

Interestingly, the lowest pressure before blood does begin to boil (the "Armstrong limit") is 63 millibars. This is equivalent to the pressure at an altitude of about eighteen kilometres on Earth. To survive in an environment with a pressure lower than 63 millibars, an adapted suit is needed. However, 63 millibars is still not a pleasant environment to live in. Any fluids outside the astronauts' bodies—tears, sweat, etc.—would evaporate immediately. Breathing must be controlled to avoid an excessive pressure difference between the lungs and the surrounding atmosphere (pulmonary alveoli would rupture). Oxygen would have a hard time transferring from the lungs into the bloodstream and binding to haemoglobin. For our bodies to

function normally, humans would need an air pressure of at least 150 millibars (while breathing 100% oxygen). However, this is still far from the situation on Mars, and as long as we lack atmosphere there, Martian settlers will not be able to venture outside without a pressurised suit (see Chaps. 8 and 9).

6.4.7.2 Storm Season

If anyone were there to listen, Martian rovers might sing songs about dust storms. Mars is famous for its desert-like environments and massive storms, some of which dramatic enough to be viewed by telescopes from Earth. Similar to the lunar version, Martian dust (containing, e.g., particular fine-grained silicate minerals and gypsum) may be hazardous to humans in various ways. Particles can be tiny, down to 20 μm, and are often abrasive, sharp or even electrostatic. They can cause severe damage to mechanisms, limit the travel possibilities, but also be detrimental to sensitive communication constructions. The dust may irritate eyes and skin, and when inhaled, damage the lungs and cause similar symptoms as coal dust in miners. Martian regolith may even be toxic due to the presence of perchlorates (see Sect. 7.4.1). Even though some of these problems can be overcome with adequate space suits and a sophisticated airlock system between the outer and inner spaces, problems can still arise as the dust may stick to the space suits, and, if these are brought inside the habitat, will come along.

The Apollo missions showed that lunar dust can damage the spacecraft, the space suits (including scratching the helmet visors), and other equipment such as cameras, and last but not least, the lungs when inhaled by the astronauts. When astronauts returned from their moon walk into the lunar lander, the dust clogged mechanisms, interfered with instruments, caused radiators to overheat, and ironically, it even destroyed the vacuum cleaner NASA had designed to clean the dust off space suits (Krisanova et al., 2013; Miranda et al., 2023).

6.4.8 Microbial Infections and Microbial Ecology in Space

Any of the microbes travelling within the spacecraft and the astronauts themselves may have an influence on human health. Different types of microbial species live inside and outside of the human body, constituting the "human microbiome" as well as the "human virome". The amount of microbes (in particular bacteria) in a body is about equal to the amount of human cells, with the majority of the microbes residing in the gastrointestinal tract, the mouth, and the skin (Sender et al., 2016). These microbes play a pivotal role for human physiology in both health and disease, as they can enhance or impair a multitude of different metabolic and immune functions (Marco, 2020). As the amount of their genes is considerably higher than those found in humans, it is often assumed that the microbiome offers humans more diversity and flexibility to respond to environmental stressors. Consequently, an alteration in the microbial community in the body can have a significant impact on human health,

disease pathogenesis, immunological reactions and potentially development of allergies and cancer.

Prevention of Microbial Infections

Wherever humans travel, microbes will be along for the ride. Avoiding infections from occurring will be crucial in especially the first missions, as treatment will likely not be abundant and epidemics must be prevented.

Screening studies on the ISS have repeatedly shown different species of microbes and viruses are found all over the place, and that even biofilms form on various surfaces. In fact, several hundred different species of opportunistic pathogens have been detected inside the ISS (Perrin et al., 2018). Biofilms pose a severe threat as they may facilitate the development of resistance of microbes against antibiotics, drugs or even cleaning and sterilisation procedures. Not surprisingly, astronauts on the ISS have reported skin rashes, ocular infections, or upper respiratory infections (Barrila et al., 2021; Crucian et al., 2016; Taylor, 2015); see also Sect. 7.4.1.

These observations must be taken seriously to combat possible dangers to human health on space crafts and in habitats on Mars. Considering that we know little about the microbial diversity and influences on our bodies, research on relevant microbes is needed.

An array of different technologies for cleaning and sterilisation procedures will need to be taken on a flight to Mars, along with a growing understanding on which microbes can be found on space missions, and which ones might become dangerous to humans. Technology should be safe and sustainable to use (e.g. not damaging materials and equipment, not requiring cancer-causing substances, not producing toxic waste, or cost lot of space and energy). Different regulations and standards have been developed to prevent microbial infections during a space mission. The most generally accepted standards have been established by the Committee on Space Research (COSPAR).

Measures to prevent microbial infections can be divided into at least three categories:

1. Sterilisation of the spacecraft itself (interior parts). The two most common and accepted methods are based on dry heat, or using hydrogen peroxide (Flax et al., 2022; Pottage et al., 2012). However, alternative technologies based on plasma are under consideration (Fuchs et al., 2017).
2. Sterilisation inside the spacecraft or space base where humans live—for this, there are a number of different measures:

   (a) Clean surfaces: Some disease-causing microbes or parasites may survive for months on a surface or in water. It is therefore crucial to disinfect surfaces which are prone to support the growth of biofilms, e.g. computer keyboards, light switches, handles, and other often-used instruments. If not done properly, microbes may become resistant to cleaning or sterilisation. A solution to this is to produce antimicrobial surfaces, which can be based either on antimicrobial substances, such as copper, silver, or nanoparticles, or on various smart technologies (Paton et al., 2020). These are currently tested onboard the ISS.

(b) Clean air via air purifiers and electronic noses that may detect early non-healthy substances in the air (NASA, 2022).

3. Preventive measures for the occupants

(a) Quarantine: It is usually custom that every astronaut that is about to go on a space mission must spend 2 weeks in quarantine in order to prevent infections prior to launch.
(b) Personal hygiene: Hand-washing, face masks in case of infection, etc.
(c) Toilet hygiene—Although special devices have been developed and are constantly improved, they cannot guarantee against leakage or other miss-happenings, which may spread particles of human waste to the surroundings.
(d) Vaccination—Astronauts are fully vaccinated against an array of foreseeable infections prior to a spaceflight. However, there are a number of issues that may arise. Microbes may react differently under space conditions—thus it is hard to predict whether they will become more or less pathogenic, and whether the so far developed vaccines will be efficient. A possible scenario is also the emergence of a new epidemic on Earth, for which vaccines are newly developed after the astronauts took off. Under such circumstances returning astronauts must be vaccinated upon return and be kept in quarantine for an adequate duration.
(e) Nutrition: A well-balanced food with all the essential components (proteins, carbohydrates, vitamins, trace elements, etc.) is needed to support a well-functioning and healthy human body. However, food is more than just fuel for the body, it is also associated with mental wellbeing, home, and culture. Space conditions mean we cannot take everything along, and a whole new science has developed around Space Food; providing suitable packaging, safe storage, suitable processing, and providing probiotics (Bharindwal et al., 2023; Kumar & Gaikwad, 2023; Pandith et al., 2023).

6.5 Cost of Mars Science Missions[5]

6.5.1 Cost of Spaceflight

In discussing the plans for Martian exploration and ultimately settlement it is necessary to address the inevitable question of cost. How will such a programme be funded? In terms of budgets joining the "space club" comes at a high cost. The largest previous space programme was the USA Apollo programme in the 1960s. The cost of Apollo programme is hard to determine but Table 6.1 provides some

[5]This section is authored by Nigel J. Mason. The author thanks Ms. Stella Tkatchova for her contribution.

Table 6.1 Estimated cost the of Apollo project (the bold numbers are sum of previous numbers)

Project Apollo, 1960–1973	Actual	Inflation adjusted
Spacecraft	$8.1 billion	$81 billion
Launch Vehicles	$9.4 billion	$96 billion
Development & Operations	$3.1 billion	$26 billion
Direct Project Costs	**$20.6 billion**	**$204 billion**
Ground Facilities, Salaries, & Overhead	$5.2 billion	$53 billion
Total Project Apollo	**$25.8 billion**	**$257 billion**
Robotic Lunar Program	$907 million	$10 billion
Project Gemini	$1.3 billion	$14 billion
Total Lunar Effort	**$28 billion**	**$280 billion**

numbers presented by the Planetary Society assembled by Dreier (2022), compiled from original budget justification documents provided by the NASA Historical Reference Collection at NASA Headquarters in Washington, D.C. As Dreier commented, Apollo was primarily funded from the NASA R&D account but also involved significant infrastructure investments, notably the establishment of the Manned Spacecraft Center and the Mississippi Test Facility, and major expansion of the Kennedy Space Center. The Apollo programme utilised a large amount of NASA's staff time which is not included in the costs outlined in Table 6.1. Thus, proper accounting of the Apollo programme (and any future Mars programme) must take into account such "indirect" costs along with the "direct" R&D costs.

Such numbers must be placed in context. The total NASA budget during this period was $49.4 billion ($482 billion adjusted to today's equivalent) or almost 4 billion a year (about 40 billion adjusted today) which should be compared with NASA's budget in the 2023 Financial Year (FY) of $32.41 billion (excluding Artemis). This is 0.2% of the FY 2023 U.S. federal budget.

https://www.usaspending.gov/agency/national-aeronautics-and-space-administration?fy=2023

In contrast, on December 23 2022, President Joe Biden signed the Fiscal 2023 National Defense Authorization Act into law, allotting $816.7 billion to the Defense Department.

Another major cost to the USA during the period of the Apollo programme was the prosecution of the Vietnam War which is estimated to have cost $168 billion or $1.7 trillion adjusted, which included $111 billion in military operations and $28.5 billion in aid to South Vietnam. Compensation benefits for Vietnam veterans and families still cost $22 billion per year (Baker, 2023). In a more modern context in February 2024, it was estimated that damage to Ukraine's infrastructure in the first 24 months of the Russo-Ukraine conflict was $155 billion with the World Bank estimating that Ukraine would need $486 billion for overall recovery and reconstruction. Ukraine's military spending was $44 billion in 2022, which was 34% of the country's Gross Domestic Product (GDP), while the cost to Russia has been estimated at $67 billion a year, with more than $107 billion excess spending in its GDP due to war costs. Direct support to Ukraine from its allies was about $200

billion in a single year (2022–2023) and is expected to continue at a rate of $17 billion or more per month. These sums are more than other recent international initiatives being equal to the total of global Overseas Develop Agency (ODA) and humanitarian aid combined. These figures should be used to place in context the costs of any Mars exploration and settlement.

The next major step in human spaceflight will be the return of humans to the Moon. What is this expected to cost? The Artemis project is the best indicator of a modern Apollo programme and the cost of astronaut missions. The Artemis project draws upon the legacy and infrastructures of several US spacecraft programmes including the Orion space capsule, the Lunar Gateway space station, and Commercial Lunar Payload Services but also requires entirely new programmes such as the Human Landing System. Its costs have steadily escalated (as is typical of large-scale projects and such an overspend must be anticipated in any Martian programme) until, on 15 November 2021, an audit of NASA's Office of Inspector General estimated the true cost of the Artemis programme at about $93 billion between 2012 and 2025, with each SLS/Orion launch being about $4.1 billion.

"To account for all Artemis costs for FYs 2021 through 2025, including Phase 2 projects like the SLS Block 1B, Mobile Launcher 2, and Gateway, we found that $25 billion should be added to the Artemis Plan's estimated costs, increasing the total costs over this 5-year period to $53 billion. Furthermore, when considering the $40 billion already spent on the Artemis mission from FYs 2012 to 2020, the total projected cost through FY 2025 becomes $93 billion" (Office of Inspector General, 2021).

However, even these costs are being questioned by Jim Free, former Deputy Associate Administrator for Technical in the Human Exploration and Operations Mission Directorate in a meeting of NASA's Advisory Committee for Human Spaceflight. Jim Free discussed the budget from fiscal year 2024 through fiscal year 2028. "During this 5-year period, the space agency will spend at least $41.5 billion on the Artemis programme, including $13.1 billion over 5 years for the Space Launch System rocket (more than $6 billion over the original budget). Thus, we might expect the Artemis lunar programme to eventually require a budget in excess of $100 billion". Nevertheless, this is less than the projected cost of Apollo, which was estimated to be $280 billion at today's prices (Table 6.1).

The next stage of humanity's engagement with the Moon will be to establish a lunar base, first by robotic manoeuvring, and later establishing the first permanent human habitat on an extra-terrestrial body. Costs for such an endeavour have been debated for more than two decades with estimates, (McKay, 2013), ranging from $10 billion to around $38 billion, based on the successful operation of an infrastructure built for Artemis lunar landings. A major factor in the construction of the lunar base is the transport of materials needed to build and sustain the structures, estimated to be up to about 10,000 $/kg, based on the Falcon Heavy cost of 1400 $/kg. However, construction and operation costs could be significantly reduced if the base was to make widescale use of in situ resources, this depending on the current research into the use of lunar regolith as a structural material (Kim et al., 2021; Lim

et al., 2021), and extraction of water (Liu et al., 2023) and oxygen from the regolith (Schlüter & Cowley, 2020; Schlüter et al., 2021).

6.5.2 Cost of Lunar Science Missions

Using the example of lunar exploration and settlement lets us project the cost of the first stage of a Mars exploration and settlement programme. The cost of robotic missions to Mars including the use of rovers has been established through the highly successful NASA missions. The Mars Exploration Rover (MER) mission cost $1.08 billion or half the sum allocated for prize money payouts in the 2022/23 European Champions League football (2.032 billion €). Of that amount, $744 million was spent on spacecraft development and launch and $335.8 million was spent on 15 years of mission operations, a modest operating cost of $22 million a year or less than the transfer fee of many footballers in the European leagues. The Perseverance rover is projected to cost $2.7 billion dollars, of which $2.2 billion was for spacecraft development, $243 million for launch services, and approximately $300 million for operations and scientific analysis for its 2-year primary mission. The Ingenuity helicopter cost an additional $80 million to build and $5 million to operate. The European-led ESA ExoMars programme is budgeted at 1.3 billion € ($1.35 billion). Thus, robotic missions come at a cost of around $1 billion over a decadal timescale, a large sum but well within space agency budgets. What is required now is the political will and scientific desire to construct and operate such missions.

However, the recent success of the Indian Chandrayaan-3 lunar missions at a reported cost of $74 million (cheaper than the production of 2023 Hollywood film projects such as “Barbie”, “Oppenheimer”, “Avengers: Endgame”, or “Avatar: The Way of Water” and half the cost of Christopher Nolan’s epic Interstellar ($165 million)) demonstrates that space missions can be operated at lower cost. Indeed the idea of a lower-cost Mars mission is not new with Pillinger et al producing Beagle 2 for $50 million, a mission that we now know came tantalisingly close to success (Bridges et al., 2017).

If new low-cost scientific missions to the Moon become more frequent the economics of Martian scientific exploration will extend to many other nations and crucially to the private sector, indeed the role of private companies is a basic tenant of Space 4.0, the envisioned next generation of space exploration, Fig. 6.7. The first era of space, “Space 1.0”, can be considered to be the early study of astronomy as humanity developed the ability to “observe the heavens” with the development of telescopes. The next era, “Space 2.0”, was the age in which Russia and the USA engaged in a space race that led to the Apollo Moon landings. The third era, “Space 3.0”, with the conception of the International Space Station, opened space to others and saw it as the next frontier for humanity, where cooperation between nations is envisaged. Space 4.0 is to see the evolution of the space sector into a new era unfolding through interaction between governments, the private sector, society, and politics. It is the era where many of the satellites and the services they provide are

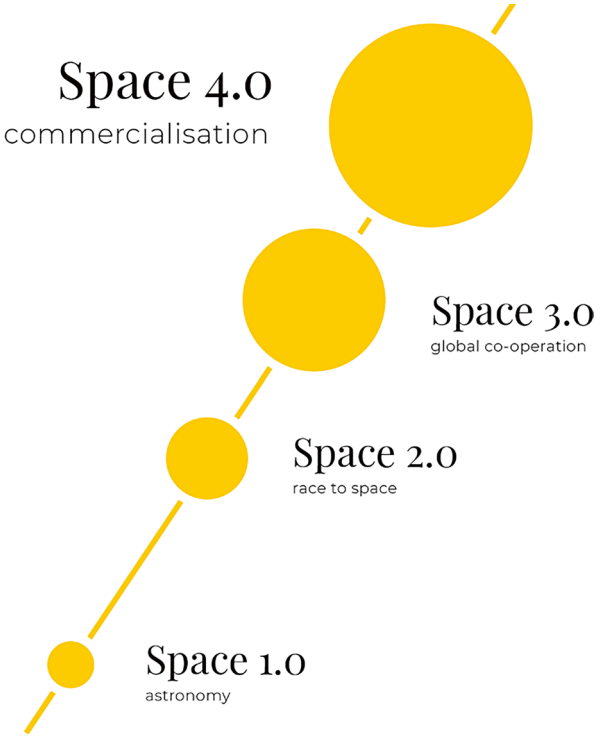


Fig. 6.7 The four eras of space exploration. We are now entering Space 4.0 which will determine human exploration and settlement of Mars. In each era the budgets and number of people engaged in space studies have grown, as indicated by the size of the circles (credit Nigel J. Mason)

independent of governments (and their funding) with an economic model that allows the private sector to secure profits from its space-borne activities and hence develop the space economy. The space economy includes all public and private actors involved in developing and providing space-enabled products and services. It comprises a "long value-added chain", starting with research and development in universities and manufacturers of space hardware (e.g. launch vehicles, satellites, ground stations) and ending with the providers of space-enabled products (e.g. navigation equipment, satellite phones) and services (e.g. satellite-based meteorological services or direct-to-home video services) to final users.

Europe (and ESA) has bought in the Space 4.0 philosophy and will build it into its future space exploration and programmes. Meanwhile the USA with NASA have already adopted the stance through up to $100 billion contracts with Space X to provide the rockets necessary for NASA to travel to space stations, including the lunar gateway, and to support the Artemis project. In 2021 NASA selected SpaceX to build a human Moon lander, or a variant of its Starship rocket that will transport Artemis III astronauts from Orion in lunar orbit to the surface of the Moon and back again, a contract worth $2.9 billion. However, in 2023, NASA also gave a $3.4 billion NASA contract to Blue Origin to provide an alternative to Starship to be used in later lunar landings. This latter contract addressed the issue of monopoly, an important issue in future space exploration and exploitation. "We want more

competition", said NASA Administrator Bill Nelson. "We want two landers. That's better. It means that you have reliability, you have backups. It benefits NASA. It benefits the American people. ... It helps NASA share the risk, the technical risk, and the financial risk to enable, at the end of the day, mission success".

The entry of the private sector into the space exploration field was, in part, stimulated by the Google Lunar X Challenge which called for privately funded teams to be the first to land a lunar rover on the Moon, travel 500 m, and transmit back to Earth high-definition video and images. No company met the terms of the challenge, but the Beresheet mission led by SpaceIL and Israel Aerospace Industries, with support from Israel Space Agency and Morris Kah as its major financier, was the first privately initiated Moon mission. This demonstrated that the commercial sector and entrepreneurs will play a key role in the next era of space science and exploration.

In May 2023, the Tokyo-based firm ispace became the first private company, with its HAKUTO-R Mission 1, to attempt to deliver "customer payloads" (rovers from the Japan Aerospace Exploration Agency and from the United Arab Emirates) to the Moon. A software fault led to mission failure but Takeshi Hakamada, Founder and CEO of ispace declared: "We have already begun work on Mission 2 and Mission 3. We are prepared to face the challenges and make every effort to improve. We will ensure that the valuable knowledge gained from Mission 1 will lead us to the next stage of evolution. We believe that this is our commitment and our duty to all our stakeholders. 'Never Quit the Lunar Quest' In this spirit, we will continue to move forward". Ispace is set to be followed by a suite of other private initiatives, some supported by NASA through its Commercial Lunar Payload Services (CLPS) programme, itself aimed to recover some of the Artemis costs by offering commercial services. Others are following the ispace model, including Beresheet 2, which intends to land two spacecraft on the Moon in 2025. 2024 saw a myriad of private funded missions to the Moon, including the despatch of the Nova-C lander, dubbed Odysseus, built by Houston-based aerospace company Intuitive Machines. This was launched on February 15 using the two-stage Falcon 9 rocket flown by Elon Musk's SpaceX.

Such public–private initiatives, whilst heralding a new methodology for space exploration, are nevertheless likely to be matched by missions still led by governments. India with the Chandrayaan-3 lunar missions, and Korea with its planned lunar missions show that governments will remain the major funder of space missions and a counterpoint to private sector and partnerships. China is expected to become the major rival to the NASA (ESA) programme with state control and direction of the China National Space Administration (CNSA), determining the pace and aims of the Chinese space programme, perhaps initiating a new space race, as in Space 2.0. This would be a part of a new global geopolitical regime with China and Russia offering a state-run alternative to the public–private focus envisaged in Space 4.0. China became the third nation after the Soviet Union and the United States to make a soft landing on and establish communication from the Martian surface, with its 2021 Tianwen-1 mission and deployment of the Zhurong rover. In January 2024, Japan became the fifth nation to successfully soft land an operational lander on the

Moon with its SLIM "Smart Lander for Investigating Moon" deploying two LEV 1 and 2 rovers. This "demonstration mission" is estimated to have cost about ¥15 billion ($125 million).

Following these examples of lunar landings, we may confidently expect a strong suite of (robotic) scientific missions to Mars in the next decade, expanding our knowledge of the planet and preparing the way for the first human missions in the second half of the twenty-first century. New actors such as the United Arab Emirates with its Hope mission to Mars will widen the number of nation states exploring Mars and in so doing establishing their "claims" to future bases and potential settlements. However, the cost of such Martian missions is certain to extend the "public-private" initiatives that are being developed for lunar exploration and settlement to future Martian programmes. NASA's Mars Exploration Program (MEP) can be expected to evolve from the government funded programme of today to invite private companies to co-fund the next stage of Martian exploration. Indeed, such a partnership may be essential to place the first humans on Mars, at least in those nations where public support for vast direct government spending is likely to be challenged.

6.5.3 Cost of the First Missions to Mars

So how much will Martian astronaut landing cost? There is no consensus to such a cost. In 2014, an expert panel at NASA estimated a 20-year programme culminating in a crewed mission to Mars would cost between $80 billion and $100 billion.

The main cost of an astronaut-based mission to Mars will be the development of the launch and interplanetary travel vehicles, and the support structure to operate a 2- or 3-year mission. The selection and training of the crew will require further infrastructure which is most likely part of a wider astronaut programme. Indeed the astronauts in the first crewed mission to Mars are most likely to be drawn from those with considerable experience in previous missions (e.g. to the Moon and having had long-term sojourns on space stations).

The payload for a crewed Mars mission will be greater than that used for lunar landings due to the need to support the crew throughout the 2- or 3-year period and the construction of a spacecraft capable of both protecting the crew from interplanetary hazards (e.g. intergalactic cosmic radiation, solar flares and impacts), indeed such a spacecraft is expected to be the largest "space ship" yet constructed. This spaceship will be composed of several (five or six) separate segments that will be launched separately, by using the "heavy-lifting" rockets, such as the SLS and Starship + Falcon heavy booster rockets (see Sect. 6.3.1)—as are currently planned to be used also for the construction of lunar bases. The separate segments of the Mars mission spaceship are then to be assembled, tested, and refuelled either in the Earth or Lunar orbit, to make it ready for boarding of the crew and its launch towards Mars. The costs of SpaceX's development of the Falcon 1 and 9 rockets, according to NASA's own independently verified numbers, are estimated at approximately

$390 million in total, this is in contrast to NASA stating, “it would have cost the agency about $4 billion to develop a rocket like the Falcon 9 booster based upon NASA’s traditional contracting processes”. In 2014, SpaceX released combined development costs for Falcon 9 and Dragon. NASA provided $396 million, while SpaceX provided over $450 million. Launch costs are currently some $67 million (2022).

NASA’s current plans for a crewed mission to Mars include a spacecraft called the Space Launch System (SLS). When NASA’s SLS rocket launched Artemis I on Nov. 16, 2022, it produced a maximum thrust of 4 million kg, exerting more power than any rocket to date. The final SLS configuration will provide 4.3 million kg of launch thrust designed to lift up to 46,000 kg, indicating that we already have the technology for a Mars payload launch.

The spacecraft itself must safely sustain the crew for 2–3 years without resupply and embody all the functions of the current ISS. These requirements include an environmental control and life-support system that monitors and controls partial pressures of oxygen, carbon dioxide, methane, hydrogen, and water vapour. It must filter out particulates and microorganisms, provide thermal control with external cooling loops and pumps, and circulate air. This system for Mars also must provide portable water and perform habitation functions, such as food storage, preservation, and preparation; hygiene; collection and stabilisation of metabolic waste; laundry services and trash recycling. Waste management systems will be needed to ensure crew health, controlling odours, and retard the growth of microbes.

Other critical systems include electric power generation and control, communications and navigation, attitude control (control moment gyroscopes), exercise equipment, propulsion to dodge foreign objects, puncture repair kits, fire suppression equipment, medical equipment for first aid and continuing care of potentially sick or disabled crew, airlock, spacesuits for extravehicular activity, manipulator arm and control stations, and food, extra supplies of oxygen, nitrogen, fuels and other expendables. According to the current plans, also additional supplies and infrastructure, such as landing and ascending modules, habitat and life-support supplies for the surface mission, and fuel for the return mission will be hauled to the Martian orbit and surface by separate cargo flights prior to the crewed mission.

Long-term exposure to space radiation in excess of levels encountered on the ISS will require significantly enhanced protection for the crew probably, including a dedicated compartment in which the crew can take refuge due to periodic high levels of cosmic radiation (e.g. from a solar flare).

Thus, a crewed vehicle may require a mass of some 40,000 kg (Salotti, 2022). He based his estimates on the objective being send at least three astronauts to the surface of Mars, and to bring them back to Earth. A crew of three is seen as the minimum required to reduce human factor risks to acceptable levels, although a greater number would be preferable but the cost scales per crew member both in size of the transporting spacecraft and the supplies needed to support the crew throughout the journey. Adding in propellant costs required to return the crew and a mass in excess of 50,000 kg is to be expected. The cost estimates for transportation to Mars cover

Table 6.2 Mass of the habitable module (kg) as a function of the crew size and number of days, according to NASA data (NASA Design Reference Architecture, annex 2, 2014, page 370)

	Duration (days)		
Crew size	600	800	1000
3	23,505	26,794	30,139
4	27,128	31,144	35,199
6	34,039	39,694	45,333

a large span. From extremely expensive (200,000$/kg) for one-way scientific missions, to a more recent estimate of 1400$/kg in the SpaceX Mars plan.

Table 6.2 clearly shows that an important parameter in determining the mass is the number of days of the mission. The duration of the trip to and from Mars is between 6 and 12 months depending on the trajectory with a similar length of stay in orbit or on the surface as seen in Sect. 6.3. The lowest energy transfer to Mars is a Hohmann transfer orbit, which would involve a roughly 9-month travel time from Earth to Mars, about 500 days (16 months) at Mars to wait for the transfer window to Earth, and a travel time of about 9 months to return to Earth. This would be a 34-month trip. Shorter Mars mission plans with around-trip flight times of 400–450 days would require significantly higher energy. A fast Mars mission of 245 days (8 months) round trip could be possible with on-orbit staging. The use of aerobraking at Mars will reduce the mass required for a human Mars mission lifting off from Earth by as much as half.

It is envisaged that the first mission will, like the Apollo landing, consist of an orbiting habitable module and a smaller lander that will land and return to the orbiter prior to return to Earth. NASA and collaborators are developing the Orion spacecraft to transport astronauts to and from the Moon. Orion uses the same basic configuration as the Apollo command and service module (CSM) that first took astronauts to the Moon, but with an increased diameter, updated thermal protection system, and other modern technologies. The Orion spacecraft is designed to be able to hold up to four astronauts and will have a volume of around 11 cubic metres. The Orion spacecraft includes both crew and service modules, a spacecraft adapter, and an emergency launch abort system. The crew module is the only part of the spacecraft that returns to Earth after each mission with a mass of about 8500 kg. The project costs for Orion $26.3 billion (inflation adjusted to 2022).

Reviewing all of the costs and different scenarios the cost of the first human landing on Mars may therefore be around $100 billion in excess of the committed budgets for lunar missions (Artemis). Launch and construction costs may be reduced by building the spacecraft in low earth orbit or even on the lunar surface.

As a first step a $17 billion flyby mission has been proposed for 2033 at “The 2023 Human to Mars Summit”, to make use of a planetary alignment allowing “sling-shot” to Mars via Venus that would allow the mission to last just 570 days (Humans to Mars, 2023). Such a mission goal would be similar to Apollo 8 the prequel to lunar landing on Apollo 11. A Martian landing would then take place in 2040s.

Is a crewed space mission to Mars at an additional investment of $100 billion over the next 15 years ($6–7 billion per year) practical? Following the discussions above and compared to cost of the Russo-Ukraine conflict, such a sum is modest. It can also be compared with other scientific costs. ISS operational costs are about $3 billion a year, roughly a third of NASA's annual human space flight budget. In 2019, the pharmaceutical industry spent $83 billion dollars on R&D, with the cost to develop a new drug—including capital costs and expenditures on drugs that fail to reach the market—being between $1 and $2 billion. The most recent official cost estimate for the ITER fusion project is $22 billion, though the US Department of Energy recently somewhat controversially has stated that the actual cost is $65 billion spread amongst seven project partners (China, the European Union (through Euratom), India, Japan, Korea, Russia, and the United States). Indeed, ITER is perhaps a good example of how Space 4.0 envisioned a human mission to Mars, as a worldwide collaboration. Such a collaboration operates the ISS with operational costs provided by the United States, Russia, Japan, Canada, and the 22 countries comprising the European Space Agency. Spread amongst the economies of the G7 or G20 countries, a crewed mission to Mars is therefore entirely fundable. In the foreseen changing geopolitical landscape, it is possible (probable) that at least two crewed missions will occur, each "encouraging" the development of the other in a new space race. This may lead to different scenarios for the settlement of Mars, as discussed in Chap. 8.

The successful establishment of lunar base provides the possibility of using the Moon, or the Lunar orbit, as a low gravity point from which to launch a Martian mission. Although seemingly appealing, it will still be necessary to assemble enormous quantities of material on such launch site prior to launch. A problem in using the lunar surface as the launch site is that the nature of the lunar dust is highly abrasive and can (will) cause damage to equipment and the spacecraft itself as it is lifted into mobile dust clouds upon take-off.

6.5.4 Environmental Cost of Lunar and Martian Programmes

Whilst considering all the advantages and possibilities for humanity's exploration and settlement of space, it is necessary to consider the environmental cost of such a programme. If we are launching hundreds (if not thousands) of rockets per year to build and sustain our extra-terrestrial bases will we do further irrevocable harm to our own planet, Earth? In exploring and settling beyond Earth, will we condemn our own planet, where 99.9% of the human population will remain, to further environmental damage?

NASA has been required to consider the impact of its launches on local and global climate since the 1970s. Whilst effects of expulsion of large amounts of rocket fuel may produce short-term local effects, for example by the deposition of carbon (soot) particulates, these have been deemed short lived with little or no measurable effect on local populace. Then, to date, few launches per year make any

environmental impacts negligible compared to other industries. Furthermore, since the space industry has been a government led, it has been treated similar to other actors of national security and defence and being deemed "vital to the Nation's economic well-being and national security", and thus given some leeway in its environmental consequences.

However, if we are to embark upon a major and enduing programme of flights to the Moon and Mars, etc., such a generous (and lackadaisical) approach to the environmental consequences of space flight may no longer be either ethically or legally viable. There were 104 successful launches in 2020, 133 in 2021, 174 in 2022, and 223 in 2023. The ultimate goals of the private space industry far exceed these numbers. For example, SpaceX stated that the ultimate design goal for Starship is to launch up to three times a day, equivalent to approximately 1000 flights a year. Similarly, Virgin Galactic's stated goal is to offer 400 flights per year per launch site. Eloise Marais has predicted that in order to consider harmful environmental impacts, launches would only need to exceed 100 launches per year, a number that will now be apparent every year.

What are the main causes of environmental damage that can be ascribed to space launches? The main "pollutants" are released greenhouse gasses (GHGs) such as CO_2 and H_2O but compared to global budget these will remain trivial. However, other emissions such as NO_x, HO_x, and ClO_x are directly involved in catalytic cycles leading to ozone loss in the stratosphere. It has recently been estimated that a fleet of 1000 launches per year using current rocket fuels could cause ozone loss up to 6% in polar regions.

However, even a far greater risk comes from the release of particles of alumina and black carbon. Black carbon is particularly concerning. Black carbon is defined by the EPA as "a major component of soot" with a "complex light absorbing mixture that also contains organic carbon" and is "a solid form of mostly pure carbon that absorbs solar radiation (light) at all wavelengths". Some rockets can emit approximately 10,000 times more black carbon particles than modern turbine engines found in airplanes and jets. Thus, it has been predicted that the amount of black carbon emitted by rockets into the stratosphere may already be comparable to that emitted by the entire aviation industry. The effect of alumina particles is more difficult to predict as they can cause both heating and cooling effects which are currently poorly understood. Nevertheless, some models have estimated that rocket emissions contribute to the warming of the stratosphere, with 70% of such warming caused by black carbon and 28% by alumina, with only 2% to assigned to the emitted water H_2O, and the effect of CO_2 being negligible.

Clearly, it will be possible to mitigate these effects by utilising fuels that emit less ozone depleting compounds and black carbon/alumina. However, such fuels are expected to be more expensive and thence the space industry is unlikely to voluntarily adopt such measures, requiring legislation. As with current global climate treaties, some nations may choose to ignore such measures.

Another environmental consequence of a greatly upscaled space flight programme will be the use of many rare elements both for rocket construction and the onboard electronics. Already strip mining and seafloor raiding to collect cobalt

(used in batteries), platinum (used in catalytic converters), and molybdenum (used for strengthening steel) is a concern which a major space programme will rapidly place stress on the stocks we have. Unlike the use of such elements in mobile phones, such materials are unlikely to be recycled once launched into space. Hence the discussion of obtaining such elements by space mining.

Finally with more and more space launches, the increase in amount of discarded material in Earth orbit—"space junk"—will grow to unsustainable amounts particularly in Low Earth Orbit. Therefore, a legal requirement to remove and return your space waste is likely for global security and sustainability of humanity's space infrastructure, again adding to the economic cost of each and every space mission. However, it also provides the opportunity for a new industry dedicated to this mission to emerge.

6.6 Crewed Missions: Ethical, Societal, and Political Aspects[6]

6.6.1 Astronauts and Professional Ethics

The first visitors on Mars are not going to be ordinary people casually migrating from one planet to another. Instead, they are most likely going to be trained professionals, and at least in the beginning, most likely astronauts from a space program. So far, more than 50% of astronauts have had a military background (in particular at the Air Force) (Smith et al., 2020). In addition to their intensive training, astronauts have been governed and protected by specific laws and regulations (e.g. the Rescue Agreement, OST Article V), a code of conduct (e.g. Code of Conduct for the International Space Station Crew), and agreements by different parties. The first humans on Mars are also most likely trained professionals, and they will be aware of the dangers involved in the harsh Mars environment, the adverse health effects of long space flights, and constraints on their personal freedom. The first humans are certainly not able to enjoy many of the everyday life comforts and activities that they could on Earth. In short, they know what they are signing up for and their participation is voluntary. Because the first humans on Mars are likely to be trained professionals, a full exploration of the ethical issues faced by the first stages of Mars settlement requires more research. Here we provide some clues to where such exploration could start, and what sources it could draw from.

These things have some ethical implications. First, as crew members at this stage are voluntarily there, the heightened risks are ethically more acceptable. This is fairly straightforward. Going to Mars is from this perspective not unlike climbing Mount Everest. People are free to put themselves at risk, sometimes even for frivolous reasons. Secondly, as professionals on a mission, the astronauts give up many freedoms, and their autonomy may be restricted to serve the mission and secure the

[6] This section is authored by Mikko Puumala, Oskari Sivula, Jacques Arnould, and Tony Milligan.

safety of the group. This, again, is not unlike other types of missions on Earth, especially military operations, but also, some scientific expeditions to remote areas such as Antarctica. However, we need to remember that informed consent does not necessarily solve everything. It could be that some missions to deep space are so dangerous that space agencies or private companies should not let individuals embark on them even with their consent. There is also the issue of whether and to what extent public means should be used to assist and rescue astronauts on private missions. The costs of rescue in space may be so high that a simple rule, such as a the one provided in the Rescue Agreement (in the spirit of article V of the OST), stating that states must do everything to rescue and assist astronauts in distress, may become problematic in a way it usually is not when people are in danger on the seas where a similar rule in international law exists.

Perhaps curiously, there is not much literature on professional astronaut ethics. While previous space missions have set up certain practices, a full, philosophical analysis on this is lacking. In fact, it is not even clear what is meant by an "astronaut", which causes some confusion with space tourism. Does OST Article V, for instance, refer only to trained professionals or to anyone who is wearing a spacesuit and travels high enough from Earth (Lyall, 2010)? Much of the space-related professional ethics literature focuses on engineering ethics, a discussion that followed the tragedy of the Challenger accident (Davis, 1991; Dunbar, 2005). There are also documents and discussions on the code of conduct onboard the International Space Station (e.g. Brünner & Soucek, 2007) that may give guidance to the right code of conduct on crewed Mars missions.

To develop professional astronaut ethics further, it may be useful to examine other professional ethics with similar occupational hazards, group dynamics, chain of command structure, and limit to personal freedom. A "professional ethic" is a specialised moral system that differs from "ordinary morality" (Freedman, 1978). Different things are morally permissible, required, and forbidden for professionals guided by their professional ethics, and for laypeople. There are different options and constraints for professionals as people dealing with high personal risks and limited autonomy. For instance, in this regard military ethics may be a suitable candidate for establishing an analogous case to astronauts. It is also plausible that astronaut ethics for scientific missions should draw from research ethics, for instance, related to environmental research (e.g. see Curzer et al., 2013). However, there are also features in space missions that may be unique for astronaut ethics. For instance, there is an interesting bioethical discussion on the need for human enhancement interventions for long-distance space missions (e.g. Huttunen & Sivula, 2023; Szocik et al., 2020, 2021). For more on human enhancement, see Sect. 7.7.1.

There is also a deeper, more philosophical aspect to a crewed mission to Mars. The fact that we could explore with the help of robots, automatic or remotely controlled instruments in no way detracts from the human taste for exploration and the responsibilities associated with it. Among such responsibilities is respect. First and foremost, respect for oneself and for the team: while explorers must be prepared to take risks, they must never forget that part of their mission is to report back to their fellow human beings on their exploration and discoveries. Here a connection

between professional ethics and research ethics is evident. Then there is respect for the territory explored: before using and exploiting it, its natural value should be considered (see "Environmental protection" in Sect. 7.7.4). Also, many have argued that scientific use should precede economic use (e.g. Persson, 2019; Schwartz, 2020).

Article V of the OST states: "States Parties to the Treaty shall regard astronauts as envoys of mankind in outer space". While this reference primarily concerns the commitment of states to assist astronauts who have accidentally landed on their territory, it can also be interpreted from a broader perspective: that of the responsibility of astronauts themselves towards the humanity they represent and to which they are accountable. The exploration for which they are responsible, like that of the planet Mars, is not just a personal experience integrated into a scientific and technological program; it is that of a group that goes beyond the space community; it is that of humanity. As we shall see in the following section, the idea that astronauts represent humanity places a great burden on the inclusivity of the astronaut selection process, as well as the demand for diversity.

This responsibility demands a kind of self-sacrifice on the part of astronauts. Here the analogousness with other professional ethics is clear, as many professions include risking oneself for the benefit of others, sometimes in admirable and heroic ways (Tomlinson, 2008). Without neglecting to "cultivate" their personality, to enrich it with the singular experience of being confronted with a territory hitherto unknown to humans, of staying there, of living there for a while, the first astronauts on Mars will also have to "cultivate their humanity". Neil Armstrong's words ("That's one small step for [a] man, one giant leap for mankind") and the plaque on the Apollo 11 lander ("We came in peace for all mankind") reflect this awareness, while at the same time acknowledging the gap and abyss between the individual and the species.

Contemporary concern for inclusion and diversity is part of the answer to this challenge, but it is clearly not enough: carried by the collective, by the crew, the mission of being "sent by humanity" also demands of each astronaut a curiosity, a personal exploration of their own belonging to humanity.

6.6.2 Diversity and Inclusion

Diversity concerns group composition. In the case of a Martian mission, it concerns the makeup of the crew. Inclusion concerns the availability of suitable pathways to become part of the group, and so secure the goal of diversity. While diversity and inclusion (D&I) are not exactly "means" compared to "end", as both may be regarded as social goods, there is a broad overlap between the inclusion/diversity and means/ends distinctions. While D&I are generally associated with equality, both have a complex relationship to equality. The aim of being diverse and inclusive is to overcome forms of ongoing or historic injustice, and so create a situation of equality. But steps to secure D&I will often involve treating people unequally (even unfairly) as a corrective. Moreover, people may be disadvantaged in one respect but advantaged in another. For instance, someone can be simultaneously a member of a

historically disadvantaged minority, but also personally affluent, or have benefitted from a privileged education. And so there is a continual risk of unintended outcomes which trade new forms of injustice for old. Critiques of the entire diversity, inclusion (and equality) discourse tend to challenge the idea that D&I matter more than getting the person most qualified for the job, or, in the case of mission crews, prioritising anything other than mission-relevant skills.

When there is a large range of tasks to be performed, as there would be in any Martian settlement, higher-level questions about what an overall situation-optimal community would look like become difficult to avoid. But in the case of mission crews, brought together for shorter periods of time and on a much smaller scale, non-diverse and non-inclusive crews might (inconveniently) turn out to be just as efficient. There is a reasonable concern that such crews *might* turn out to be sub-optimal. A case of a general sort can be made and eventually evidenced. But we do not, at this stage, have any real empirical evidence to back up the claim that mission optimisation requires either diversity or inclusion. If, however, we regard mission crews as representatives of humanity as a whole, or if we worry about anti-space narratives gaining popular support, then both D&I will be important, irrespective of whether or not it makes crews optimal in a strictly technical sense. The humanity-representing role is not something that we routinely expect in the case of terrestrial employment, but we may well expect it in the case of mission crews. And so it is possible to argue for caution about D&I in terrestrial matters, but still insists upon both for future crewed missions to Mars.

In space it is notable that both the private sector and space agencies *have* promoted mission crew diversity. The potential for inclusion has been a strong selling point for space tourism by Blue Origin and Virgin Galactic, with relatively diverse crews selected for their widely publicised 2021 flights. The crews were far more diverse and inclusive than the white, male, and notionally heterosexual crews for the Apollo missions. In the case of a Martian settlement, military approaches to inclusion and group diversity may also have strong relevance, given that some degree of command structure may initially be in place. And, to some degree, the same will apply to mission crews and so the military models for D&I may exercise great influence even when crews are not themselves military personnel. NASA has been following on from this lead by trying not only to diversify mission crews but to promote inclusion at the level of mission command and in selection processes for other senior positions. Again, the complex relationship between diversity and inclusion, on the one hand, and equality on the other, comes through. Command structures should not be authoritarian, but they are not strictly egalitarian, even if crew membership establishes a level of comradery and depends upon patterns of trust which push in a more egalitarian direction.

At the level of institutionally supported humanities commentary upon space, the selection of Sheri Wells-Jensen as the 2022–23 Blumberg/NASA/Library of Congress Chair marked a significant public move given that Wells-Jensen is herself blind. The choice may also be read as a tacit institutional acknowledgement that crew members who have experience of functioning without vision, or with impaired vision, can be an asset in space where tasks may need completion under a variety of adverse circumstances (Heinicke et al., 2021).

In both the direct military case and the NASA case, the guiding thought has been that diversity itself is a good and that a "right stuff" approach of entirely white, male and notionally heterosexual command may fail to mobilise all the available capabilities. Again, the idea is that crew optimisation might be enhanced. Neurodiversity, for example, might enhance rapid decision-making in life-threatening situations of a sort that we would anticipate in any settlement situation, and NASA has already established a Neurodiversity Network with a focus upon learners who are on the autistic spectrum. Evie Kendal (2023) also gives special focus to this aspect of diversity in space in her overview.

The case for D&I continually returns to this idea that D&I is both functional and a social good. These are two quite different ideas, even if they tend to be blurred together. In the case of the military and NASA, heavy emphasis has been placed upon the functional importance of D&I, as a way to optimise performance at a time when there is a tendency for technological costs to squeeze manpower budgets. Significant transitioning to a greater reliance upon reserve lists with periodic mobilisation strengthens the imperative to get the most out of staff. And while this may seem to be of greater relevance for the military, a growing volume of Mars missions may result in something similar, with potential astronauts activated and placed in reserve. The periodic nature of Mars mission launch windows may also favour this. While we are focused upon sending one crew within 30–40 years we do not worry about having a large number of people waiting around to do their job. Once missions become regular, this can quickly change. Trying to get an optimal active roster then becomes important, with D&I offering possible pathways to optimisation.

Within the space advocacy and critical community, the D&I literature has expanded considerably over the past half decade, particularly within politically liberal and activist literature. Often with a presupposition that the reasons for D&I are more than functional, and about more than crew optimisation. Again, the idea that D&I are societal goods comes through. The Schwartz, Billings, and Nesvold volume, *Reclaiming Space: Progressive and Multicultural Visions of Space Exploration* (2023) exemplifies the trend, setting out a series of critical and inclusive perspectives focused strongly upon the idea of public good.

6.7 Take-Home Message

While humans have so far visited Mars only with robots, the fast progress of spacefaring technologies may soon enable crewed missions. The main driver may be political will, stimulated by intense competition, but mission goals will lie primarily in science: the human exploration of the surface, whether from orbit or in situ, can advance our understanding of planetary evolution and enable unprecedented investigations on putative traces of life—whether extant or long extinct. The first crewed mission will also be a proof of concept, an important testbed for the development of human spacefaring technologies, and a critical step in the preparation of subsequent missions.

Robotic missions have shown that Mars's surface environment is detrimental to any terrestrial organism, and survival is possible only with adequately protective gear and shelters. Besides, for the first crewed missions, large amounts of life-support supplies (including oxygen, water, and food) will need to be transported from Earth. A recent description of technologies considered for various steps of the mission, as well as their challenges and maturity, is given by NASA's 2023 Moon to Mars Architecture Definition Document. Most are in early developmental stages.

The main challenges of a Mars mission stem from the physiological and psychological dangers and stresses caused by the environment in deep space (radiation, microgravity, vacuum) and on the Martian surface (radiation, low pressure, unbreathable air, extreme temperatures), and by extended confinement in small habitats. While extensive knowledge on the effects of the space environment on human physiology has been gained in low Earth orbit, the limits of human endurance in longer deep-space trips remain unknown. One could argue that they cannot be fully revealed before the first mission to Mars. Extensive efforts must nonetheless be directed towards anticipating risks to the crew and keeping them as low as reasonably possible.

A large part of the mission costs will be due to the development, building, and testing of the infrastructure, to expenses related to the technical, design, and administrative personnel, and to the construction of launch facilities. Rough estimates can be obtained from previous crewed space programmes, e.g., the Apollo programme, as well as from current estimates of the Artemis programme—in the range of US$ 100 billion. This cost may seem high, but it depends on one's perspective: many other human endeavours are significantly more expensive. The mentioned price tag is comparable to the annual revenue of the global film industry, and the monetary price of a war, or reconstruction thereafter, can be an order of magnitude higher. In addition, the costs of space technologies are rapidly decreasing due to the emergence of a profitable space economy, and to collaborations between public and private actors.

Space exploration is governed by a strict international legislation and by non-legally-binding (but strictly enforced) agreements, which among others dictate the behaviours (related to, e.g., planetary protection, non-appropriation, and respect of the rights of all humanity) that must be observed when landing on other celestial bodies. Finally, ethical considerations are essential: crewed missions will be risky and involve a certain level of danger. This level may be argued to be acceptable when involving well-informed astronauts.

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Chapter 7
Mars as a Science Base: Towards a Small Permanent Outpost



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7.1 Why Establish a Science Base?[1]

From the point of view of astrobiology and planetary sciences, the scientific objectives stated in Sect. 6.1 will remain alive whilst a permanent outpost will be established on the surface of Mars.

As a working hypothesis, such an outpost will be permanently or intermittently occupied by a crew. Amongst others, the limitations of the missions and operations will be due to the costs of the launches, of the transport of supporting consumables, instruments, tools, and of the flights and the mission control from the Earth. The crewed missions are based on the current "conjunction" model (see Sect. 6.2). In a continuation of the preceding exploratory missions, it is envisioned to proceed with fairly small crews travelling back and forth. Taking in account the launching windows, there is little chance that the successive crews may cross paths on the station if the increments are not extended to missions of four- or five- year duration, or longer.

In this case, the local infrastructure will be larger, more expensive, and will require more consumables and energy. The profiles of the astronauts could also be different with a clear cut between the scientists and the operational engineers and others. In such an outpost, the habitat could be equipped with more sophisticated scientific instruments and some steps of the research work could be performed on site. The limitations induced by the transmission delays will remain the same and the communications between the Martian base and the Terrestrial control centres will remain indirect. Thus, the interactions between the scientists on Mars, and those on the Earth, will be complicated.

[1] This section is authored by Michel Viso, Jean-Pierre de Vera, and Jorge L. Vago.

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7.1.1 Advantages of a Long-Lasting Outpost

The advantages of Mars for Astrobiology and Planetology which have been presented in Sect. 6.1 must be modulated depending on the final site which will be selected for the establishment of a permanent outpost. For a "simple, self-sustaining visit" we assumed in Sect. 6.3 the landing sites, three areas envisioned for the three first missions to Mars, will be selected mainly for scientific expectations, although there will be numerous technical constraints (altitude, slopes, boulders, latitude etc.). For long-term use, several decades, there will be many new constraints due to the development of in situ resource utilisation (ISRU) (typically, of water), solar seasonal illumination, and suitability of the surrounding sites for multiple landings and launches. Most of these constraints were briefly reviewed by Golombek et al. (2021).

The other advantage of a long-standing outpost is the organisation of long-term exploration strategies with a web of secondary stations, energy filling stations and safe havens for the astronauts in case of hardware failure or any kind of problem.

Finally, in a permanent, long-standing base it is possible to envision long-lasting operations such as deep drilling or sustained prospection of selected areas for the sake of science or ISRU or, even if it is not in agreement with the Outer Space Treaty (OST), for potential commercial use.

7.1.2 Consequences of a Long-Lasting Outpost

The outpost will be visited successively by several crews, and some crews could stay for up to 7 years. This, in our current understanding, requires the development of a certain degree of self-sufficiency and the recycling of most of the essential components and consumables. Such projects also require a lot of research and development efforts on the engineering and technical sides to be supported also by scientific research activities. It is not possible now to establish an exhaustive list of the disciplines concerned. But some knowledge gaps concerning various disciplines could already be identified.

7.1.2.1 Human Physiology and Medicine

The effects of the long stays in microgravity and long-lasting cosmic radiation exposure have been investigated on board space stations and other spacecraft missions The crew members travelling to and from Mars will be exposed to these harmful conditions for even longer times (several years). Besides, the level of cosmic radiation on the Martian surface is roughly twice higher than on the ISS. Short travel to Mars by an "opposition" type trajectory, including a flyby of Venus (Kludze et al., 2023), would expose the crews to higher radiation levels that have been tested

so far. These challenges will initiate new research in this domain as well as the investigation of the pathological effect of the level of radiation on the Martian surface. The effect of partial gravity may also cause distinct physiological effects, which will be investigated during the Artemis missions on the surface of the Moon. The medical effects of these stress factors are thoroughly described in Sects. 6.4 and 7.4.

For these investigations, all the domains of physiology and psychology are concerned. The astronauts of the earlier short missions will be subjected to continuous monitoring and analyses to document the effects of reduced gravity, confinement, artificial atmosphere, group dynamics, nutrition, isolation etc.

These continuing investigations are needed to prevent eventual appearance of pathology, to propose early treatment, and to prepare further missions and prophylaxis. These studies will also provide useful knowledge for medical sciences towards people on Earth.

Beyond these aspects, the evolution of the microbiome of the astronauts, and of the microorganisms in the closed environments, as well as the effects this will have on the health of the astronauts, will raise many questions and foster many scientific activities. The evaluation of microbial-induced corrosion (Gu et al., 1998) will also generate crucial research programmes.

7.1.2.2 Agronomy, Microbiology, and Plant Sciences

In establishing a permanent base on Mars, the development of an environmentally closed life support system is claimed by several groups to be necessary to decrease the dependency of the crews on supplies from Earth. It would be based on the regeneration of the atmosphere using photosynthetic microorganisms (cyanobacteria or eukaryotic microalgae) or plants, combined with the cultivation of vegetables and other edible products.

Indeed, this research has been going on in various laboratories on Earth already for several decades, completed by some tests in microgravity, onboard the ISS. Such bioregenerative life support systems (BLSS) will be rigorously tested. Different ingredients of this type of BLSS, such as the cultivated species and their growth conditions, the suitable hardware and their control mechanism, and the recycling of the different chemical substrates are currently intensively studied, in terrestrial labs by different teams involved in genetic engineering, agronomical research, and technical development. They need to be studied on Mars, by the early crews and it necessitates quite a large permanent base. The performance of the biological and technical components of these systems, the culture facilities (either bioreactors for photosynthetic microorganisms, or growth rooms for the plants) and the performance of the selected organisms will be studied directly in real conditions. The effects of an absence of gravity or low gravity, the effects of the minor volatile components of the real surrounding atmosphere on cultivation and productivity of the system etc., must be determined. This work in real Martian conditions will require many astronaut-working hours.

7.1.2.3 Prospection

Currently in the speech of the private actors, and of some of the managers of the space agencies, the idea of an industrial or commercial use of the resources from the Moon and Mars are discussed. The usable resources are, at this stage, hypothetical. We assume that such resources may occur in the ground of Mars in the form of ores, containing interesting compounds or elements ranging from water to rare metals. The eventual industrial activities will be preceded by a prospecting phase. It will be performed by exploration from a permanent base. This activity relies on the knowledge of the geological history of the sites of interest, in situ observations, analysis, and measurements. Various drillings will be needed to evaluate the potential extension of the sites of interest. The programme will use as much as possible similar techniques as on Earth, combining all available methods and data from a whole range of instruments. Data obtained from a dedicated remote sensing satellite will be integrated. Specialised drones, after the success story of Ingenuity and the plan to develop new operational hardware (NASA Ames Research Center et al., 2023), will be also considered and operated directly by the astronauts. Geological maps of the Martian surface and of the underground, of selected areas, could be one of the end products of this phase.

7.1.2.4 Technology and Science

Up to now the technology development to prepare any technical or scientific programmes for Mars is benefiting from the development of similar applications on Earth. However, on the surface of that planet the tools, the instruments, and the infrastructures will be used in harsh environmental conditions. The safety of the astronauts and the preparation of the long-lasting stays will require to consolidate the knowledge gained during the former short stays. The tools, hardware, and infrastructure to support mobility, energy production, and storage for daily life must be subjected to thorough studies and tests. Measuring the effects of radiations, low pressure, large temperature variations, and dryness of the surrounding atmosphere on the objects will prepare the eventual future development and will have spinoffs on the daily life on Mars and on Earth.

7.1.2.5 Ancillary Science

Presently there is no real plan to develop ancillary science: science activities that address research questions beyond the funded scope of the original study or mission. However, if the transport capability exists, and if the human presence is demonstrated possible, scientists will find many possible subjects which could be better explored either on, or from the Martian surface than on/from the Earth or its near environment. Many of the proposals made for the Moon could be adapted to Mars, including radioastronomy and the observation/identification of the asteroids of the

asteroid belt. Some visionary papers propose the deployment of rovers equipped for planetary interferometry (Hao et al., 2013).

7.2 What to Do There?[2]

7.2.1 Reference Missions

From the Mars Armada of Werner von Braun with seven vessels carrying each 10 crew members at once, to the 4–6 crew members of the DRM 5.0 of NASA, there is a wide range of possibilities and hypotheses. The SpaceX company envisioned to transport up to 100 passengers at a time. For this section, we will use as a reference mission a crew of six, landing on Mars after a Hohmann-like transfer of 7 months. The crew will live in a Martian base landed before the arrival of the crew, including the resource utilisation units, the nuclear power units, the tools, the mobility vehicles, the secondary habitats, and everything needed for a safe stay and a safe return to Martian orbit. There are numerous hypotheses about the habitats, the level of autonomy, and the recycling and production of various products, but there are few descriptions of the detailed daily occupations of the crew. It is admitted that there is a permanent base for a crew of six, well equipped with some systems for the recycling of organic wastes, water, and CO_2 and to enrich some daily meals with some edible plants grown there. The base will be intermittently occupied by a crew spending around 500 days at the surface of Mars.

If this size of mission succeeds, the possibilities are that the base will be extended to house larger crews. The growth of the base may take place stepwise, such that the next stage can house a crew of about a dozen occupants, and further on, even larger numbers. The futuristic visions for larger bases (up to 1000 members or more) are discussed in Chap. 8. The larger the base, the more the use of the ISRU will be necessary. This will foster the research to find those resources and use them in an optimised and, hopefully, sustainable way.

7.2.2 A Wide Range of Hypotheses

Unless otherwise needed, the crew will switch to a Martian time calendar. The switch to a daily duration of about 24 h 40 min does not seem a physiological challenge. It is not possible for now to know at which stage of the mission they will change their "calendar." On Earth, the control centre will stick probably to the local or UTC time because trying to follow on Earth a Martian daily cycle leads to quickly disconnecting the daily life cycle and is exhausting and costly.

[2]This section is authored by Michel Viso, Jean-Pierre de Vera, and Jorge L. Vago.

For the past robotic missions, during the commissioning phase (from a few weeks to several months), the terrestrial operators have been aligned with the Martian local time to benefit as much as possible from the opportunity to use solar energy and light both needed for the use either for the scientific and technical cameras and the spectrometers. This "planet lag" was managed and for some of the operators "fatigue countermeasures" have been required. The fatigue management programme was efficient on Earth whilst external drivers of the circadian rhythm were present but such a disconnected rhythm cannot be sustained for a very long period of time (Barger et al., 2012).

The exact amount of working days, actually available, during the stay of the astronauts within the base is not yet define. On such a long-duration mission, there will be only one shift daily. According to some preliminary estimates the daily work duration will not exceed 8 h at the base. The working time during sorties and multi-day activities out of the base could last longer. Depending on the mission sequence, crew activities will be split into various phases, which are described with some detail in *The Martian* outpost (Martian Outpost Seedhouse Erik, n.d.).

The stay on the surface after more than 200 days in space will begin with a progressive rehabilitation phase. In the hypothesis of intermittent occupation of the base, the outpost reactivation and the verification of the systems, pieces of hardware, mobility systems, the preparation of safety measures in case of a problem, and preparation and verification of the ascent spacecraft and the ascent rocket will take time. The Martian base will be very complex, and there will probably be a duty cycle for two astronauts to monitor the habitat during the days off. The organisation of the work will be very complex.

After a 90-day physical rehabilitation in the Martian outpost, and the recommissioning of the outpost, crew may split their time between let us say 100 days of duty (exploration, maintenance, science work) and 7 days of rest/recuperation. At the end of the long stay, they will spend 60 days at the base shutdown, preparation for the ascent and then, launch to the interplanetary spaceship awaiting in Martian orbit. The crew will reactivate, verify, and eventually adjust the systems of the spaceship to prepare for the Earth return leg. In this hypothesis, the schedule will be severely constrained by the "departure windows" from the Martian orbit toward the Earth.

7.2.3 Selection of Activities

7.2.3.1 In Situ Resource Utilisation

Depending on the hypothesis, the amount of use of the in situ resources can vary considerably. In some cases, the crew will have to produce the propellant for the ascent rocket, and in such a case they will possibly devote a significant amount of time to this duty. In some other hypotheses, by the miracle of Artificial Intelligence, 3D printing plus automation, everything will be manufactured in advance before the crew's arrival. They will have to check and transfer the propellants from the

propellant tanks to the ascent vehicle. At this stage it is not yet planned to produce the propellant needed for the Earth Return spacecraft (except for the SpaceX visions), thus this fuel needs to be transported from Earth or Moon, and kept waiting in the Martian orbit (Jurga et al., 2019). In any case, all these activities will require a lot of working time. The production, processing, cooling, storage, and transfer of tens of tons of oxygen and hydrogen or methane requires extended factories and machinery. It also requires a lot of energy. The ratio between the cost of sending all these needed propellants from the Earth compared to the benefit of installing a Martian plant to produce them in situ (providing that the resources are available) must be evaluated case by case. The benefit of this in situ production will be significant if the number of Martian missions is high and if the resource is abundant, accessible, and close to processing plants and storage locations.

7.2.3.2 Waste Recycling and Plant Production

The recycling of the grey and black waters as well as the CO_2 provides a means to decrease the station's dependence on the Earth. The level of independence varies considerably from one hypothesis to another. They are just mentioned and never realistically described. In any case, as already stated in this book, the experience gained on board the space stations (ISS, MIR, Tiangong), with recycling systems, shows that failures are common in these complex systems. Any increase in the dependence on the local production or recycling of the basic supplies will increase the time devoted to the maintenance, repair, and overhaul activities of all the systems. It is not yet possible to imagine the extent of time and personnel needed in a long-lasting base for these crucial or vital activities, but clearly this time will be significant.

The same principles will apply to the production of plants either as a leisure or as a food complement. The level of plant production to reach certain degrees of autonomy seems difficult to envision. Most of these plans in general literature are based on the use of aeroponic (Jurga et al., 2019) or hydroponic (DeMattio et al., 2020; Velazquez-Gonzalez et al., 2022) cultivation systems. Any system that will play a crucial role in providing resources for the base and its inhabitants will also require a large amount of time to plant, control, monitor, care, harvest, store and process the products, and to care for the production chambers. In most of the papers presented, the number of elements needed, i.e. the light, the water, the carbon dioxide, and the nutrients are clearly presented or calculated but the amount of human work required is never mentioned.

7.2.3.3 Communications, Physiology, and Psychology

Because it will not be possible to have instantaneous communication between the Earth and Mars and because of the difference in the daily rhythm, the preparation of the messages and reports between the crew and the Earth will also take a significant amount of time.

The monitoring of the psychological and physiological state of the crew members and the evaluation of the social status of the crew implies that private communications with a terrestrial supporting staff will also take place and will require additional time. Although there will be time for privacy and a kind of exchange with family and friends on Earth. A certain level of regular physical exercise will be also needed to keep up the physical conditions of the astronauts, to face the challenges of the low gravity environment and the limited living space in the pressurised modules. Presently the daily average exercise time on board the ISS for long-duration flights is estimated to be 2 h. Because the gravity at the surface of Mars is different, the exercise requirement will probably be less, and the nature of the physical exercises will be different to maintain an adequate physical status of the astronauts.

7.2.3.4 Supporting and Extending the Base

Another activity linked to the development of this permanent base is to explore and identify the nearby sites to prepare its extensions, to create a network of infrastructures to travel, to communicate, to secure the nuclear energy sources, to prepare the extension of the living and the service quarters (green houses, mechanical and storage facilities etc.). The extensive exploration will also require the landing of numerous large spacecrafts (cargo and successive crews) and probably also several launches of vehicles to the Martian orbit to prepare for the Earth's return. It is almost impossible to imagine such traffic without the preparation and the installation of a large infrastructure. It is difficult, for now, to thoroughly describe these future tasks but evidently they will require a sustained effort from the crew leaving little room for the actual scientific work.

7.2.3.5 Exploration Activities

The exploration activities will be conducted using either a non-pressurised vehicle in the vicinity of the base or a pressurised vehicle for long-distance exploration. In any case, these extra-habitat activities (EHA) will require preparation, multiple safety checkouts for the main vehicle, for the rescue vehicle, for the EHA suits, and so on. As the exploration will go further and further, the precautionary measures will take more and more time.

Basic Geology and Pedology

Whilst being on Mars, the astronauts will continue the work of the rovers and of the remote sensing satellites, studying with the appropriate portable analytical instruments the soil, the rocks, the regolith, and the ice (if they are in reach). The astronauts will deploy several suites of instruments to collect seismic, atmospheric, and meteorological data. The subsequent crews will maintain the existing networks, extend them, and create new ones. The goal of this crewed exploration is to assess the variety and versatility of the Martian surface. These activities will serve

simultaneously the basic geological sciences, the communities searching for traces of early prebiotic chemistry or traces of a simple form of life. The gained knowledge will be useful to determine the most interesting sites for detailed and focused investigations. This will be of interest to the science community, to the technical teams, and to the possible future settlers.

Drilling

Either for scientific objectives or prospection, deep drilling is presented as a primary objective of a crewed mission to Mars. Deep drilling is almost impossible to practice without a human presence. The objectives will be diverse: searching for a hidden form of life, identifying or quantifying resources, and producing detailed geological maps. The drilling core analyses will be mixed with the information gathered by the remote sensing satellites and, possibly, by drones combined. Then in selected locations, the crew will proceed to various drilling activities. The extent of this drilling, and the amount of time and work required will depend on numerous factors: the depth of the aimed drilling, the objective, the location and the direction of the drilling, and the nature of the encountered layers. If we take the example of Exomars, depending on the nature of the drilled rocks tested, the advancing speed varies between 0.03 and 10 mm/min (Magnani et al., 2011).

In any case, the advancing speed will vary considerably with the size of the drilling system, the nature of the material to be drilled, the constraints and the objectives of analyses planned on the core. For instance, in the plan of the Exomars drilling system (able to drill up to 2 m), the drill is retracted if the drilling is stopped for any reason (power shortage, for instance), to avoid freezing in place of the drill head and shaft, which could create a blockade of the entire system. This process slows the overall speed of the action. At this stage, the drilling activities are envisioned for instance for the water prospection and eventual exploitation of this resource. The objectives vary from a few tens of metres up to hundreds of metres or even more. There will be a mixture of geodesy, sampling, and in situ analysis.

Analysing

Within most of the anticipation papers, it is claimed that the science will be "done" directly in situ in an appropriate, well-equipped, and well-staffed laboratory. This would require a lot of instruments, a lot of crew time, and a wide range of competencies. The science activities will, most likely, be very simple for the early missions, having only a limited pressurised volume and because of the workload required by the other tasks. For instance the astronauts will be occupied by organising the living and working quarters, setting up the tools, instruments and, vehicles.... In these situations, the laboratory activities will be limited to preliminary characterisations and identifications. Then, through communications (indirect) with the science teams on Earth, the operators will select what to investigate a little bit more, what to discard or store, and what to bring to Earth for further analyses. However, if the missions are to be pursued with larger crews and longer duration, and within larger pressurised habitats and laboratory spaces, then more extensive scientific analysis may also become feasible. In any case, as demonstrated in Sect. 6.3, analysis, interpretation, and calibration will take longer than any Martian stay, require a full range of

instruments and people and, full-time scientists. If such missions are to take place, it is possible to expect that science would be one of their main goals and that more space, resources, and crew time will be devoted to it.

7.3 Requirements for a Permanent Outpost on Mars: Current Knowledge[3]

If the first Mars missions turn out not to be excessively risky and costly, missions are assumed to continue, with the aim to establish a permanent base with intermittent or continuous occupation. Initially, it would be likely that the crews are transient, i.e. that they arrive on Mars only for a mission of a predefined duration (e.g. the 500 days that would allow the interplanetary travel via the Hohmann transfer orbit) before returning to Earth. New crews would replace them and continue the research work, as well as the maintenance and construction of the base.

It is assumed that larger numbers of people will not be sent to Mars before safety has been ensured. Consequently, early missions will rely on crew numbers similar to those on the ISS today. Once these small initial missions have succeeded, spaceships, landing and ascent vehicles, as well as long-term habitats, may be developed to host larger numbers of people. Because a sustained effort will require regular flights using stable launch capabilities it is also assumed that the travel will be based on Hohmann-like transfer orbits. Robots will be major assistants and contributors in setting up the crewed bases on Mars, and most hardware and human shelters will be automated and self-regulated to a high degree. Many operations, especially those performed outdoors, would be done by autonomous robots, or by robots controlled remotely though real-time vision systems. In this way, humans are exposed much less to radiation than if they would work outside, leaving this latter option for operations when it is absolutely required. All this infrastructure will require large information management and storage systems to control all sensors, regulators, and actuators. Digital twins of installations should be used on interlinked systems so that in case of a failure of any system or component, it will be replaced by another until the lost system is replaced.

All the essential infrastructure, i.e. the assistance and guidance of the landing, the functional life support systems, and suitable conditions in the habitats, must be available at the time of arrival of the crews, and ideally be monitored by artificial intelligence (AI). This means that a local computing server and a reliable power source are operational and running. In principle, these processes can be mediated by the computing, robotic and solar power technologies that are currently known at least on a conceptual level, or to be developed within the Artemis programme. These vital functions need to be maintained on an absolute fail-safe level. According to

[3] This section is authored by Elias Chatzitheodiridis, Akos Kereszturi, Gisela Detrell, Natuschka Lee, and Kirsi Lehto.

Amini et al. (2022), they should be set up in threefold redundancy of their parts and sub-systems, provided via independent technologies.

7.3.1 Technological Background

7.3.1.1 Development of New Habitats

As the next crews will subsequently land and stay on the surface for extended periods of time, typically at least 500 days per visit, using the conjunction trajectories for the travel, then (more) permanent and comfortable housing units will be required for their accommodation (Fig. 7.1). Such missions are not feasible with the current technologies; however, it is important to study their feasibility by planning all steps "in advance", in order to evaluate and develop the solutions to the different challenges that will arise. Multiple analogue studies have been run to test human adaptation in closed and isolated habitats over extended periods of time, often using different extreme environments on Earth (NASA, 2023a). Currently (in 2024), NASA is running a 1-year-long simulation of a 4-person-crewed mission: the "Crew Health and Performance Exploration Analog" (CHAPEA) experiment (NASA, 2023a). Similar experiments have taken place at the Russian Institute for Biomedical Problems (IBMP) in Moscow, most notably Mars500 (Ushakov et al., 2014) and SIRIUS (Lungeanu et al., 2023). There has also been the NASA-funded HI-SEAS programme (including the 1-year HI-SEAS IV mission), and several Antarctic stations have been used as analogue sites for long-duration isolated stays.

Habitat Safety

The habitats need to be equipped with life support systems, initially by using consumables (notably oxygen, water, and food) transported from Earth and recycling

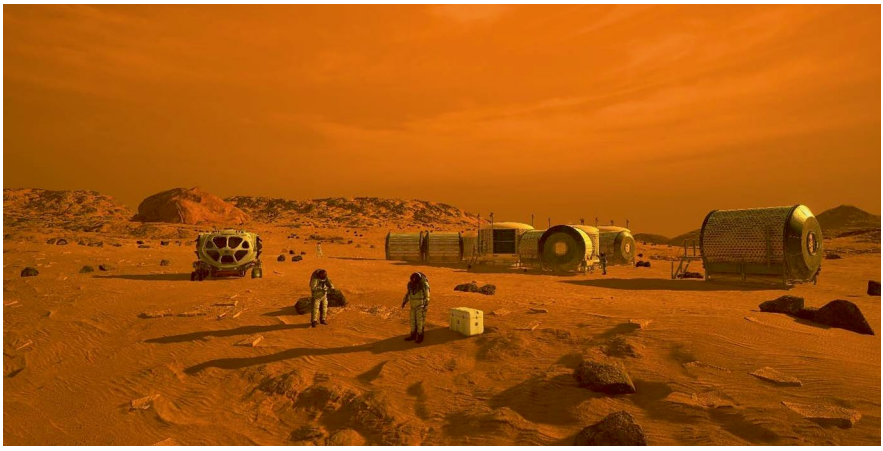


Fig. 7.1 Artist's view of the first (semipermanent) crewed science base on Mars (@NASA)

them on Mars as much as possible. Current physical and chemical technologies on the ISS are capable of recycling most of the water and regaining part of the oxygen from the carbon dioxide released by the astronauts. Similar (or more advanced and adapted) technologies would also be used during the interplanetary travel to Mars, and further on, in the surface habitat. Some form of a bioregenerative life support system, such as ESA's Micro-Ecological Life Support System Alternative (MELiSSA) could also be available as an additional means of recycling. In situ resources can supplement the imported supplies and will likely play an increasingly important role in crewed stations.

The radiation shielding materials of the first permanent habitats could be the same materials as those used in spaceships during deep space travel, such as aluminium, polyethylene, ethylene tetrafluoroethylene (ETEF) membrane, polyether ketone, water, aerogel, and/or carbon fibres (Edwards et al., 2023; Naito et al., 2021). Water used for shielding must not be used for human consumption, because space radiation produces free oxygen radicals and reactive oxygen species (ROS) such as hydrogen peroxides (H_2O_2) and hydroxyl radical ($^{\bullet}OH$) in interaction with water (Georgiou et al., 2017). These are highly biotoxic in the long term, or even immediately, if consumed in high concentrations (Sies & Jones, 2020). Sensors for ROS molecules, such as the OxR sensor (Georgiou et al., 2017), are currently under development. The same instrument can also test wall surfaces and monitor other internal surfaces, since the same toxic compounds can be produced in the adsorbed humidity, a necessary component of the breathable air in the habitats. Methods for the removal of these harmful contaminants are described in Sect. 6.3.2.1.

Safety rooms should also be available within, and/or in the vicinity of the habitats for situations of strong SPEs (see Chap. 1). As the flux of SPE particles fluctuates according to the solar activity and interplanetary plasma propagation, a monitoring and alarm system is to be used to indicate periods that are too dangerous for EVA. An early warning system similar to the current STEREO solar monitoring missions (Chi et al., 2022) should be in operation, providing an early warning. This system can observe the coronal mass ejections (CME) very soon after their eruption from the Sun, but the interplanetary travel of the particle clouds will take several days, and their arrival to Mars can be modelled precisely. Under strong solar activity and the arrival of large particle clouds to Mars, astronauts will need to stay in the safest (best protected) part of the habitat for up to several days.

The habitat must maintain and withstand the pressure difference between the innermost compartment at about 1 atm (or reduced down to about 0.5 atm, which would correspond to the atmospheric pressure at 5500 m altitude on Earth and be suitable for human breathing) against the external air pressure of about 0.006 atm (6 mbar) at altitude zero. Therefore, no leaks, cracks, or fractures are allowed as these would result in collapse or an explosion of the whole structure, or at least in loss of the internal pressure. Different habitat designs have been presented in recent years, where the habitat is composed of two or three overlapping constructs, the innermost of which provides the highest radiation shielding and is used for the vital living spaces (personal compartments), and the outer ones for additional living space (living rooms, laboratories, agriculture) (Amini et al., 2022; Ruede et al.,

2019). An important feature in the layered habitat is that the outermost layer(s) is maintained at a lower pressure than the inner enclosure, producing a smoother pressure gradient between the habitat interior and exterior. The multiple layers also provide heavier radiation shielding to the innermost parts.

With new crews returning repeatedly to the same site of interest on Mars, this site will develop into a (more) permanently occupied science base. It may initially be occupied by consequent crew(s) of 4 or 6 persons, but if the objectives require more workforce and expertise, the size of the stationed crew could gradually increase, and the base could grow into a small permanent base, something similar to the science bases in Antarctica. Thus, housing would be needed for the increasing number of inhabitants, who are there not to stay permanently, but for variable lengths of visiting times. To build up more living space, the initial habitat structure should be designed in a modular fashion so that it can be extended, as needed, by adding similar and symmetrical units to it. In a design by Amini et al. (2022, 2023), a modular honeycomb-like structure would provide the stability of the weight- and pressure-bearing structure throughout the extended habitat. The structural stability of each section needs to be confirmed and balanced between the internal pressure and the weight of the covering layers.

An important requirement for the habitats is that they efficiently support human wellbeing and health in the dangerous and stressful mission environment. Physiological wellbeing is dependent on the direct environment (e.g. radiation level, quality of the breathable air and drinking water, food, temperature, and availability of water for hygiene and other uses). Light colours and a well-designed visual interior provide a more spacious feeling in the tightly built habitat. Large telecommunication screens facilitate professional communication and data maintenance, but also provide means for social connections, culture, and entertainment, as supplemented with augmented and virtual reality. Living plants or greenery walls provide significant positive psychological cues, produce oxygen, and maybe also edible or otherwise usable biomaterial (Amini et al., 2022).

7.3.1.2 Life Support Systems

Maintenance of Breathable Air

The habitat will provide a breathable atmosphere, which is fully closed and sealed from the Martian atmosphere. The composition and pressure of the breathable air must be continuously controlled by provision of O_2 and by removal of the CO_2 that would otherwise accumulate, using, for example absorbent beds. The CO_2 can be further processed, for instance by using a Sabatier reactor. This process combines the CO_2 with some H_2 to produce methane and water, which then can be electrolyzed to regain the oxygen from the CO_2. The atmosphere can be adjusted to similar parameters as prevails in the terrestrial atmosphere (about 1 atm pressure, 21% O_2, 79% N_2) or at lower pressures, as long as adequate partial pressure of oxygen is maintained to avoid symptoms of hypoxia; the required air quality can be ensured, e.g. via air conditioning systems similar to what is currently used on the ISS, i.e.

filtered through High-Efficiency Particulate Absorbing (HEPA) filters and a Trace Contaminant Control System (TCCS), and monitored via gas chromatograph/mass spectrometers (GC/MS) (Amini et al., 2022). Temperature and relative humidity must also be controlled.

Water Management

The water management system currently used in the ISS can process and purify nearly all of the used water so that it is reusable, in a nearly complete closed-loop system (Czupalla, 2003). In those systems, urine is treated chemically to remove its dissolved chemical components: it is treated with ozone and sulphuric acid, then processed in the Vapour Compression Distillation unit (VCD) and in the Air Evaporation System (AES), then the remaining water is combined with the wastewater from laundry and hygiene sections, and with the condensate water from the habitat and the pyrolysis (incineration) processes. This pooled wastewater is then purified via filtration and osmosis in the Ultra Filtration unit and by the Reverse Osmosis filter. The obtained brine water is further purified by evaporation and absorption technologies (the VCD and Milli-Q absorption bed) to reduce the total organic carbon (TOC) to an acceptable water quality level. Microbial control is achieved by adding iodine.

Similar waste water treatment systems would be adapted to the Martian conditions. The quality of the purified water stock could be monitored for pH, conductivity, TOC, and iodine levels before use for plant cultivation or as household water. To make it potable, the iodine must still be removed and controlled, e.g. by using Ion Specific Electrodes (ISE). Many of these ISS-adapted or even new technologies need to be (re)-adapted to Martian gravity and pressure conditions.

Food Production

For the first crews, all food will be transported from the Earth, but a long-term aim is that food production will be included in fully enclosed bioregenerative life support systems: In such closed-loop systems, the removal of CO_2 would be mediated by the photosynthetic organisms (either plants or algae), and used together with water and nutrients to generate new biomass (food production), whilst simultaneously producing oxygen. The products would be utilised by the crew, and the waste products (inedible biomass) would be returned to a cascade of various degrading and fermenting microbes (in bioreactors) to break down their organic compounds. Such a process would allow recycling of biological waste, but would, at the same, time produce other substances like CO_2, which photosynthetic organisms would also need to treat. Degradation and fermentation would significantly increase the size and complexity of the system, and therefore its integration is highly dependent on the duration of the mission, and should be analysed in detail for each mission scenario. If used, the nutrients released in the degradation process would be fed again into the plant or microbe growth compartments to convert them to different bioproducts—which again are consumed by humans as needed, and turned back to the degradation steps. Such a closed-loop circular bioregenerative life support system, based on a set of subsequent growth chambers for plant production, and microbial tanks and fermenters for different degradation steps, has been developed in the

past decades in different ESA projects (Lasseur et al., 2010; MELiSSA Foundation, ESA, 2023). Several projects are also studying different elements that could be part of a biological life support system, such as the DLR Combined Regenerative Organic food Production (C.R.O.P.) (Hauslage et al., 2018), the EU-funded EDEN ISS project (Zabel et al., 2020) and the Photobioreactor Experiment on the ISS (Detrell et al., 2019). A detailed explanation of the challenges to be solved in the development and use of biological life support systems has been published by De Micco et al. (2023). Such systems are likely to be tested by the early crews to Mars, with the aim of scaling them up for permanent use later by larger crews and bases.

A fully closed biological life support system resembles in principle, on a miniature scale, the large global cycling systems that provide energy and oxygen for the biosphere on Earth. However, when based on, and constructed using technical infrastructures, these systems bear a definite risk of failure or malfunction (e.g. due to break-up, power shortage, and contamination). An alternative or complementary facility may be provided by artificial photosynthesis (European Space Agency, 2023), however, the development of this technology is still in progress.

Waste Management

In the waste management system, the processable and reusable solid wastes (faeces, garden waste, food waste) are also recycled via biological degradation, to produce nutrients and a growth substrate for plant or algae production. They may be processed in a closed-loop bioregenerative system, such as the MELiSSA concept for instance, where organic materials are degraded stepwise by aerobic and anaerobic microbial processes (Lasseur et al., 2010; Verbeelen et al., 2021), and/or by pyrolysis. If these methods are not accessible, the wastes can be stabilised and stored, possibly for later use via recycling, or disposed by incineration (in case further use is not foreseen). General views about waste management during Mars missions are discussed by Douglas (2022).

In any case it is important that all the human wastes are maintained in the closed habitats, or in their associated storage or plant production areas, to minimise the risk of the biological materials spreading around and contaminating the pristine Martian environment. The waste materials can also be treated as valuable resources (water, carbon dioxide, nutrients) that can be recycled in a closed-loop system to produce food, pure water, and oxygen on site. This is required to prevent the expensive transfer of the daily supplies either from Earth or from storage in an orbital base, and to make the base (more) sustainable (Starr & Muscatello, 2020).

7.3.1.3 Laboratory, Research, and Exploration Facilities

The most important task of the first missions will be to carry on the predesigned exploration programme. Most likely, this will be to inspect, characterise, collect, and study samples from the preselected target sites (most important sites of interest) in the proximity of the landing site, to search for any identifiable biomarkers, signs of extinct or extant life, or traces of ancient or ongoing biochemical processes. Suitable instruments for these studies are included in the mission. This research—as

well as any other manoeuvres in the base camps—must be performed according to the planetary protection principles, to prevent the contamination of the site(s) by terrestrial microbes.

Sample analysis work must be accomplished first by visual inspection and by analysis of thin sections via different microscopic methods and chemical analyses, as developed in the studies of various Mars analogue sites on Earth [e.g. studies of the Archean sedimentary terrains containing microbial mats (Noffke, 2015, 2021), or of the serpentine rocks containing ancient lipid biomarkers (Carrizo et al., 2024), or by using laboratory-derived analysis methods for detecting biomarkers (García-Gómez et al., 2023)]. Caves and sedimentary terrains formed by ancient waters would be good targets for these investigations, as they provide a protected environment that may preserve ancient samples.

Due to the limited staff and laboratory facilities, most of the analytical work must be performed by automated analysers, such as different mass spectrometers (e.g. the Time-of-Flight (ToF) mass analysers or orbitraps) as tools to detect organics in ultra-trace quantities, and chemical tests for specific types of molecules (amino acids, nucleic acids, lipids, different metabolites such as carotenoids). The laboratory must also provide storage facilities for appropriate archiving of samples before and after analyses. If putative organic samples are detected, they need to be transported to Earth for further analysis. If the research is to be continued on a broader scope, then more laboratory equipment and personnel need to be imported for more comprehensive and accurate analysis.

Another important task is the exploration of the geochemical, geological, hydrological, and paleoclimatic information, and its recording before it is compromised by the presence of humans at that site, and in its vicinity.

There are additional research goals on Mars: exploring the capability of terrestrial life forms to live on another planet, for instance; and gaining knowledge and experience that will make further missions easier and safer to realise. For these purposes, the first missions need to test and develop facilities and infrastructures for the next crews, and establish a permanent outpost, determine the access to local water supplies and their suitability for harvesting and consumption (chemical analysis by, e.g. gas or liquid chromatography), investigate the level of the soil and water toxicity by plant and cell culture tests, prospect for other valuables such as plant nutrients, and search for and explore natural caves. Possible nearby caves or lava tubes may serve as a non-invasive access route to potential resources for both geological, palaeohydrological and potential biological histories of Mars, as well as for industrial activities (Viudez-Moreiras, 2021).

7.3.1.4 Interplanetary Traffic

The continuous occupation of a Martian base requires frequent travel for the crew members and for cargo, and possibly for some tourists, between Mars and Earth. Several flights are taking place at every opportunity, i.e. during the time windows with access to the Hohmann transit orbit. This occurs every 26 months, with a

waiting period on Mars of about 500 days for the entry into the same orbit for the return trip to Earth (Rapp, 2023).

If the occupation of the base(s) is growing, the traffic system needs to be updated in many ways. Interplanetary travel must be made shorter and, probably, relatively economical, thus fission energy will be used for both the Nuclear Thermal Peipulsion (NTP) or the Nuclear Electric Propulsion (NEP). It must be safe, with efficient shielding from radiation with low Z composite shielding materials, with the opportunity for efficient recycling of biomaterials en route by using bioregenerative life support systems (see Sect. 7.3.1.2), and with a possibility to produce fresh and healthy food. Landings and launches to and from the Martian surface must become safe for larger ascending and descending vehicles, or for the direct landing and launching of interplanetary spaceships (such as SpaceX's Starship) (Heldmann et al., 2022). Eventually, the landing and launching terminal, or "spaceport" facilities, must also provide a safe airlock-entry to and from the local pressurised vehicles used for transport between the spaceport and the habitat.

7.3.2 Technological Infrastructure

7.3.2.1 Energy and Material Resource Requirements

Starting from the first establishment of the habitat and base for more permanent human occupation, adequate, constant, and reliable supplies of electricity is required to keep up all its necessary functions, including the life support systems, computing, and communication. Most likely, electricity should be available on the base site prior to the arrival of the crewed mission, to allow all the necessary robotic manoeuvres to prepare the habitats and the infrastructure.

Nuclear, Solar, and Wind Energy

Mission designs published so far indicate that the most reliable power source for the habitats will be nuclear reactors. The habitat design of NASA's Human Spaceflight Architecture team, for example is based on the use of Kilopower 10 kWe-class nuclear fission reactors (Mohon, 2017; NASA, 2023b) (Fig. 7.2) or an eventual upscaled 40-kilowatt class fission power system to support the first human crew of 4–6 members, the crew requiring about 20 kWe of energy supply. The energy need increases a few-fold if the fuel for the return launch is also to be produced by ISRU (see Chemical fuels, see next section) (Drake, 2009). Some challenges of nuclear power are the sensitive landing and installation of heavy high-precision machinery, and the radiation shielding requirements (Drake, 2009). The technology for these reactors is still under development, but it would be similar to the NEP engines to be used in the spacecraft (NASA, 2024), with reactor heat transduction and cooling achieved with a natrium heat pipe cooling system (Gibson et al., 2017, 2020).

The habitat design described by Amini et al. (2022, 2023), with a larger pressurised volume of the habitat, and with a variety of applications and activities

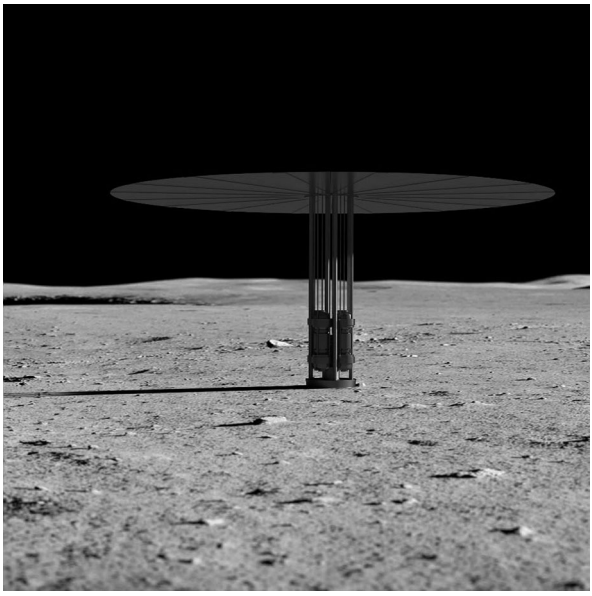


Fig. 7.2 Artist's view of the 10-kWe class nuclear reactor on the lunar surface. NASA fission surface power (NASA, 2023b) (@NASA)

including a plant growth structure, assumes a power consumption of 30 kWe (i.e. three 10 kW reactors) per crew member. This scales to a minimum of 18 and maximum of 27 Kilopower reactors per habitable unit (6–9 crew members). In this design, the highest amount of electricity (one-tenth) is spent on the LED illumination of plants (once the greenhouses are established). Almost as much is spent on atmosphere management. Other energy-consuming items are LCD screens, water management and pumping, waste processing, thermal control, compressor, computing, exercise, food storage and cooking, LED habitat light, dust removal, and airlock manoeuvring. In addition to this consumption in the habitat, a significant amount of energy is needed for ISRU production of the H_2 or CH_4 + LOX fuel for the launch of the return flight (Drake, 2009).

As power is an absolutely required resource, some parallel and back-up sources for it are needed (and needed already to install the nuclear reactor) (Drake, 2009). An obvious energy source on Mars is sunlight, which is available at the low latitudes in similar levels as in the Scandinavian countries or Alaska on Earth, thus, enough to produce 12 V charging power throughout daylight time. Due to the dry and thin atmosphere there are no clouds, the sunshine continues through all days, and in low latitudes throughout the year. During sunny days, solar power can be directly used to provide electric power to cover all the energy needs of the settlement. Amini et al. (2022, 2023) estimate that the total solar panel area, with a safety factor of 1.5, for a 9-crewmember habitat, would be approximately 3400 m^2. However, the major problem is the frequent and long-lasting sandstorms that easily block the sunlight and cover the solar panels with dust. The storms can be either regional, as wide as continents or even global, and last up to several months. An

obvious further problem is that the blowing sand will wear out the solar panels rather soon.

To provide a constant energy supply from the solar panels throughout the days and nights, high-capacity energy storage systems or batteries would be needed. However, the batteries have a limited use-time, and new batteries would need to be imported from Earth every now and then—thus, the issues of battery recycling on Mars need to be solved. Currently, intensive research is ongoing to develop next-generation lithium-based solid-state batteries (Liu et al., 2023). It might eventually be possible to produce these on Mars if lithium resources are identified and in adequate volume.

Solar power in not available in the stormy seasons, but then the wind itself might provide a substitute energy source, to be harvested with windmills. Wind power can be produced with a standard wind turbine, e.g. Amini et al. (2022, 2023) report that one large wind turbine with 40 m-long blades would be enough to produce the energy required for a 9-person habitat during sandstorms. However, this reference does not acknowledge the problem that the heavy turbine blades would not be turned by the low air pressure of the Martian wind. A further technical problem with a windmill of this size would be the transport of its parts from Earth, and the assembly, requiring a helicopter, or a crane even higher than the blade length. Thus, multiple small and lightweight wind turbines would be preferable. These would also provide redundancy in case the rotors are jammed in the sandstorm, which may be a major risk for the use of rotational technology.

A clear benefit of harvesting local solar and wind energy is that it can be setup with fairly simple, well-known, and robust technologies that would be easy to build and maintain with simple spare parts. The first photovoltaic films and wind turbines would have to be transported from Earth, and they might be set up by the preparatory robotic mission(s) even prior to the arrival of the first crews. In the long run, these turbines might be built on site with some local resources: silicon for constructing the photovoltaic cells, and maybe also the windmill blades, is available in the Martian regolith (Pineau et al., 2020; Squyres et al., 2008). However, other materials, e.g. rare earth elements or bearing-class steel, are needed for the rotors and for the electric motors and wires of the network. Some materials, high-technology components, and spare parts would thus need to be transported from Earth.

Chemical Energy Storage: Dihydrogen, Methane, and Other Organic Fuels

The primary energy form on Mars is expected to be electricity produced by nuclear and/or solar power, as described above. However, energy will also need to be converted to a chemical form for storage and transport, and for use as fuels, which would be analogous to the fossil fuels on Earth. These should be based on chemistry that relies on local resources. Considering that water should be accessible at the landing site in adequate volumes, it can be used to produce oxygen (O_2) and hydrogen (H_2) with electrolysis. Oxygen can be used for human respiration, and hydrogen, together with carbon dioxide (CO_2), can be used to produce methane (CH_4). Oxygen again is needed to use either hydrogen or methane as combustible fuels for rockets and other mechanical manoeuvres.

Methane and O_2 have been chosen, e.g. by the SpaceX company to be the fuel for the propulsion of the Starship (Heldmann et al., 2022), and thus, according to current plans, these would need to be produced in situ to refuel the spaceship for the return trip. These could also be used as fuel for rovers, or for other surface or aerial transport vehicles on Mars. However, more effective fuels may be necessary for certain situations, i.e. liquid H_2 and O_2 for rockets that rely on NTP propulsion (Edwards et al., 2023). One technical problem is that H_2 is difficult to store and manage, in space conditions or on the Martian surface, due to its easy leaking and evaporation (boil-off) (Drake, 2009; Edwards et al., 2023). On Mars, a leak-free H_2 technology may become necessary for other purposes: H_2 gas is an essential component of the chemical energy production chain, as it is the primary reducing component obtained from water and would be required for the production of methane.

Various processes for fuel production on site have been proposed. The most widely known and tested process for methane production is the Sabatier process (already tested in Earth-based laboratories; see Zlindra et al., 2021), where atmospheric CO_2 is reacted with hydrogen (produced locally from H_2O by electrolysis), at elevated temperatures (300–400 °C) and pressure (3 MPa) wia the reaction: $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$. The Sabatier process for methane production on Mars was recently improved with a zinc-containing catalyser (Starr & Muscatello, 2020). However, massive amounts of methane, and of its precursors water and CO_2, would be required to produce adequate amounts of fuel for rocket propulsion. For instance, producing the methane and oxygen fuels for the return trip of a Starship by the methane-LOX propulsion would require a total of 840 tons of CO_2 and 600 tons of water, corresponding to an ice volume of about 730 m^3 (a cube of about 9 m per side) (Heldmann et al., 2022).

There are other possibilities for methane production, including biomanufacturing. As an example: using local CO_2, sunlight, and H_2O, cyanobacteria would take the CO_2 from the Martian atmosphere and create sugars using sunlight (under properly isolated conditions but without the need for Earth-like pressure or atmospheric composition). Even a well-known bacterial model species, *Escherichia coli*, would be engineered to convert those sugars into propellant-like butanediol (however, its use as a fuel has not yet been tested). However, compared to the commonly proposed chemical process (such as the methane production from CO_2 and H_2, as mentioned above), this biological process is slower and although it may require about 32% less energy than the chemical process, it demands roughly three times more infrastructure mass to be transported (Kruyer et al., 2021). Storing of the gases needs to happen under cryogenic conditions and under pressure. Liquid H_2 cryocoolers in sizes needed for zero boil-off cryogenic storage are not available as yet (Drake, 2009).

Besides methane, other hydrocarbons, such as propane, have been suggested which require further or different processing, such as the Fischer-Tropsch synthesis. However, amongst them methane seems to be the easiest solution and most "green" propellant. It is also worth mentioning that almost twice as much oxygen is needed as methane to use these components as rocket fuel. For instance, for the ascent vehicle of a crew of four persons, 24 metric tons of oxygen would be required. This

could be produced by the electrolysis of H_2O, or, with a higher power requirement, of CO_2, e.g. by using the MOXIE technology, as already demonstrated by the MOXIE instrument carried on the Perseverance rover on Mars (Hecht et al., 2009; Hoffman et al., 2022).

There are also developments going on to adjust solid oxide electrolysis cells (SOEC), various materials, catalysts, and instruments for electrochemical or photoelectrochemical-based processing (Wolf et al., 2023). CO_2 can also be directly reduced to various hydrocarbon gases suitable as fuels by using energy and suitable catalysts, as described in a Special Issue of the Industrial & Engineering Chemistry Research journal (Xiao et al., 2022). These new technologies may provide useful solutions for the production of hydrocarbon fuels in the future, on Earth and maybe under Martian conditions, but for the moment one cannot predict how efficient, economical, or applicable they will be.

7.3.2.2 Vehicles, Machinery, and Equipment

Local transport needs to be available as the first crews arrive to allow them to move safely from the descended vehicle to the protective habitat (or, according to the current design, to use the rover as the habitat at least in the beginning). Mobility is also needed for the astronauts to pursue their terrain exploration and other designated mission tasks, i.e. search for the designated geological sites for studies, and collect and transport samples to the laboratory. The vehicles should be terrain-capable and radiation-shielded (by lightweight composite materials) cars, or, as described in the current NASA plans for the first Mars mission (NASA, 2020) a mobile home, powered by rechargeable batteries (to be charged by solar power; see below). Later on, the vehicles could also be powered by H_2 or methane + O_2 combustion engines.

Various large machines, such as cranes and utility carts, are needed for the unloading of cargo, setting up of the base camp, and construction of the infrastructure (Drake, 2009; Rucker et al., 2022). These, as well as large 3D printers and bulldozers, are also needed for the construction work of the habitats. Bulldozers and diggers, electrolysers, plumbing, and water and gas storage systems are needed for ice and water excavation and transport (for specific water harvesting machinery, see the following section). This machinery must be lightweight to reduce the costs of its interplanetary transport; but still needs to be robust enough to move on the rocky unlevelled terrain. These machines should be running either with electric batteries, with H_2 or with methane and oxygen fuels, initially transported from Earth, but later produced in situ from local water. As with all mechanical machines, these would also be affected by the harsh environment, notably the radiation flux, rapidly alternating temperatures and the sandstorms.

Technologies for Water Prospecting and Harvesting

Water is one of the most important resources that would be needed for sustainable human survival on Mars, and water ice prospecting should be carried out early. According to the SpaceX company's plans, this is to be done even before human

missions, or as the first activity during the missions. Heldmann et al. (2022) describe equipment that they consider useful for water prospecting, including a mobility platform carrying instruments such as VIPER (Volatiles Investigating Polar Exploration Rover, see Sect. 6.3.1.2), which has been developed to identify volatiles as deep as 1 m in the lunar subsurface, and the Neutron Spectrometer System (NSS), which is used to measure bulk composition and hydrogenous volatile abundances, as well as buried water abundances. The Near-InfraRed Volatiles Spectrometer System (NIRVSS) is another lunar instrument to measure volatile composition, mineralogy, and other parameters at excavation sites and on drill samples, and to provide information on the water and the other volatile contents of the regolith. The Mass Spectrometer Observing Lunar Operations (MSolo) instrument is another volatile analyser to be included in the first Artemis mission to Moon, and also on Mars, to detect and identify low-molecular-weight molecules, allowing estimation of water (H_2O) abundance, as well as relative intensities of various volatile species such as H_2, He, CO, CO_2, CH_4, NH_3, H_2S, and SO_2.

Martian water is expected to be found in the ice layers underneath the upper regolith, inside rocks and in permafrost. Specific drilling, digging, and other geological and mining machinery will be needed to access these underground deposits. For instance, small-depth prospecting for water can be performed by specifically-developed drill tools, such as the Regolith and Ice Drill for Exploring New Terrain (TRIDENT) (Zacny et al., 2016) of the VIPER instrument. Similarly, the mechanical drill developed by ESA for the ExoMars mission to drill down to two meters in the subsurface of Mars is another low-depth integrated drill-sensor system that can detect water. However, the exploration of deeper water layers, down to a few tens of metres, requires different geophysical techniques, such as a ground penetrating radar, DC resistivity sounding, seismic refraction, and electromagnetic surveys. The prospecting of water deeper than several metres in the regolith may be done more easily using airborne instruments than with rovers, especially because large areas need to be covered. Impactors can also be used to unravel the subsurface composition at higher depths, not only for water detection but also to study the overall geological structure of the subsurface. When adequate resources have been identified and mapped, and shown promise for further prospecting, and if their exploitation does not violate planetary protection rules, then only the accessibility and trafficability of the site will affect their extractability and utilisation (Heldmann et al., 2022). As on Earth, roads must be opened to easily access the mining areas. The next step is to excavate and transport the water to the camp site, where it can be stored as liquid water, or as ice, to be converted to liquid water on demand. The quality required of the water vary with applications, which should be considered within this phase. Water can for instance be made potable, be electrolysed to H_2 and O_2 for use as propulsion fuels (or in reactors to produce heat for the temperature regulation of the habitat) or be used to generate breathable air.

At each step of water mining, processing, and utilisation, several alternative methods can be considered depending on the exact physical status of the remotely detected H_2O. For example, ice could be directly dug out by using typical strip-mining machinery and methods, such as jackhammers, drilling, and sawing, to

break the subsurface ice into large blocks. Another method is to use the Rodriguez well (Rodwell) technology, which involves drilling and melting locally the underground water ice. This method is based on a drill with a heater and a tubing system; it applies pressure on the melted underground water pool, inducing its flow towards the surface tank where it is stored (Zacny et al., 2016). Melting of the ice can be also performed using microwaves. All the above-described methods require huge infrastructures and are energy consuming. Specific machinery (bulldozers, lorries, pipes and pumps, plumbing, reservoirs, insulation systems) are needed to transport and store water at greater distances from its mining location.

If adequate concentration of water is identified in small depths in the regolith, for example as permafrost, the water source can be mobilised and concentrated using electrokinetic phenomena (Stavrakakis & Chatzitheodoridis, 2017). Electrokinetics requires the application of a DC electric gradient between two electrical poles which are inserted into a porous medium (such as the Martian regolith). Then, several phenomena take place: (a) electrokinetic phenomena are initiated, such as electroosmosis during which water masses can be mobilised tangentially around the mineral grains of the soil towards one of the electrical poles; (b) heavy metals or polar organic pollutants are moving with electromigration phenomena due to charging and water is cleaned (electrokinetic water remediation); (c) the medium has electrical resistance and thus its temperature increases and the ice between the mineral grains melts to fluid water; and finally, (d) the voltage difference induces electrolysis of water with the electrolytes being present in the soils, and oxygen and hydrogen gases are produced on the electrical poles. Both released gases can then be used as propulsion fuel, whilst oxygen alone can be used for human respiration. Electrokinetics can also be used for dewatering (removal of water) from wet soil masses and to induce mineralisation, resulting in soil cementation which can be used to form bricks for habitat construction from the local materials. Electrokinetics are slowly evolving phenomena, but they can operate on a permanent basis in an area, resulting in an additive effect in line with terraforming activities on the planet.

Further parameters influence water acquisition and its relevance. For fuel production, water needs to be processed by electrolysis, to produce liquid hydrogen and oxygen ($4H_2O \rightarrow 4H_2 + 2O_2$), and the produced gases can be directly used as fuel, or the H_2 can be further reacted with CO_2 to produce methane fuel. These gases need to be stored under high pressure, cryogenic conditions in liquid phase (Heldmann et al., 2022). The distance between the water mine and the processing plant, or the location where H_2O is finally used, does matter. The ice or liquid water should be stored or transported either in original or in processed form. Storing and transporting water in liquid form would be challenging, as the storage system and water pipes should be maintained at adequate pressure and temperature above 0 °C; the water would be easier transported and stored as ice.

Although the plans listed above are useful, several knowledge gaps exist about how to implement them and how they can be financed over longer time periods. Several technologies for exploitation are under development, but none of them has been tested on Mars yet. More information is required to evaluate their suitability

for mining with realistic, practical approaches. During the technical development, application of industry standards and pilot programmes are needed. In these operations, planetary protection aspects must also be considered, including the role of the produced liquid water and emergence of stripped locations at the given site.

Utilities and Utensils

A large variety of utilities and utensils will be necessary to provide a reasonable level of comfort throughout crewed missions. These include elements of the infrastructure, e.g. water and gas pipes, vents, valves, regulators, paints, wires, screws and bolts, tools, sockets, frames, fixing clips and fixtures, lamps, controlling units, sensors, computers, monitors, and more. They also include objects of day-to-day use (e.g. furniture, bedding, dishes, food storing and processing equipment, audio-visual screens, computers, clothing, and office items), spacesuits, and hygiene products (toilet paper, soap, toothbrushes and paste etc.). At first, these supplies and the associated spares need to be transported from Earth, either prior to the arrival of the crew, or with the crew, and the "packing list" must be very carefully planned. Such planning is necessary to reduce total cargo volume and costs. Currently, various figures are claimed depending on the proclaimer. Space X is advertising between 130$/kg in a routine mode and 100,000$/capita to send humans (roughly 1250$/kg) to Mars. Other works are trying to evaluate the cost of missions to Mars. This is difficult whilst some proposers are taking into account the cost of the launch only, forgetting the cost of the travel and landing system as well as the cost of the mission control on the Earth which is not marginal. It also depends if you are taking into account the cost of the return trip for the people. That means that many figures are circulating with no strong basis to support them. The cost of the first exploratory missions was evaluated in the Sect. 6.5.3, but this is not directly applicable to a routine, regular traffic back and forth between the Earth and Mars. After almost 70 years of launches of rockets, the cost to deliver 1 kg of cargo on the ISS or in LEO is evaluated between 2700 up to 47,000$/kg, such a range for routine flights make difficult any realistic forecast for an eventual Martian settlement possibly in the next decades, however, by technological development the scale of 1000–2000 seems to be achievable in the near future. With time, and as a presence on Mars becomes routine, the on-site production of specific items will increase, mostly on-demand, often using 3D-printing technologies of different materials. It would be of advantage if all these objects were made of materials that can be recycled in situ and reprocessed into new ones. The outcomes of agricultural production may be biodegradable plastics that can be produced by different species of bacteria (Anjum et al., 2016; Nduko & Taguchi, 2021; Silva et al., 2021). Polymeric materials (e.g. from starch) can also be produced from wild type or genetically engineered biomass (Val Siqueira et al., 2021), or from biogenic chitin (Zhou et al., 2022). Finally, glass and ceramics can be produced from the Martian regolith (Radlinska et al., 2021). As the technology of 3D printing advances, more materials can be produced and shaped on demand. All these futuristic possibilities could reduce the amount of cargo needed from the Earth.

7.3.2.3 Water Resources and Autonomy Level

The relevance of ISRU increases with the number of inhabitants in the base (Starr & Muscatello, 2020). ISRU should remain coupled with reuse and recycling to reduce the consumption of raw materials and limit waste production. The most critical resource on-site may be water.

Overall, the hydrogeology of Mars is different from that of the Earth, mainly because tectonism is extremely limited (Good & Fox, 2021) and because sedimentation processes differ. Rough and general information is available on the spatial distribution of H_2O on the surface of Mars. The highest volumes are in the polar caps, then in the polar layered deposits. Significant amounts have also been identified in the middle latitudes, where decimetre-thin loose regolith, and a few meters thick regolith (including rock blocks) can cover massive ice deposits in depressions. Water is also present in localised deposits of hydrated sulphates; its volume, however, likely fluctuates seasonally.

Less known, however, are the actual amounts, locations, and purity of these "water ores", as well as the internal structures that influence the feasibility of their exploitation. The thickness and level of cementation of the regolith covering the ice layers in the middle latitudes is also poorly known, and orbital or drone-based mapping is therefore required to better understand the areal distribution and depth of the reserves. Such activities are being prepared by several space agencies, notably with the International Mars Ice Mapper (I-MIM) project (Viotti et al., 2022). Interestingly, a recent observation by the Mars Express orbiter reported a potential large water ice deposit (hundreds of kilometres wide, and up to 3000 m deep) near the equator, in the Medusae Fossae Formation (Cooper, 2024). If confirmed and accessible, this might provide a source of water for the settlements at low latitudes.

The most obvious resources for H_2O are the permanently frozen polar caps, but it is not easy to set bases at the polar locations because of the extremely low wintertime temperatures. Right adjacent to the polar caps, larger area deposits provide a large mass of water ice and dust mixture; both polar caps and adjacent regions contain approximately 1.6 km^3 of water ice. Outside the polar caps, important locations are middle-latitude, buried snow-ice masses, where bulk ice deposits are covered with some pulverised material (see Chap. 1). Ice may occur under a decimetre-thin dust and regolith cover, ranging between 50 and 70 cm; these deposits would be easily drillable, but they may contain a relatively thin layer of H_2O. The ice masses in the valleys and craters, or so-called concentric crater fills (CCF), lobate debris aprons (LDA), and lineated valley fill (LVF) features, are thicker. However, these are covered by 10–100 m thick sublimation debris from the nearby outcrops and are more difficult to drill. In both cases, these shielding layers should be drilled through or transported away for H_2O exploitation. The level of cementation inside this debris cover is unknown, but the difficulty of reaching the ice below is mainly influenced by the physical thickness and not the state of the cover.

Various hydrated minerals on Mars, especially polyhydrated sulphates and phyllosilicates, might also serve as H_2O sources. Their exploitation might require more effort than the buried ice masses, but such minerals could be more widespread than

buried H_2O masses, and especially located at lower latitudes. These minerals usually hold low, though occasionally up to 8–10%, H_2O content (Milliken et al., 2007), and water is not free adsorbed water but hydroxyls that participate in the crystal makeup of the minerals. In the case of H_2O access from minerals, pulverisation and heating to elevated temperatures (425 or 575 K, depending on the mineral) are needed. Based on field and laboratory tests, an extraction rate of a few kg/hour is realistic (Sanders, 2016).

Further possibilities for H_2O exploitation include the mining and processing of permafrost (a mixture of ice and rock debris), which could be present at shallow depths at high latitudes, but also deeper at low latitudes. However, permafrost is a hard material to process, much harder than pure ice or hydrated minerals. Some H_2O could be acquired also from the atmosphere, though it is usually very dry (it contains, roughly, 0.004 g/m^3; extracting 1 kg H_2O would require processing 200,000–300,000 m^3 of atmospheric gas), and the atmospheric gas would need to be strongly compressed. Despite some theoretical argumentation and some observations enabled by the MARSIS instrument (onboard the Mars Express mission) in the southern polar region, it is likely that no large subsurface liquid water reservoir exists on Mars today.

Water has been in contact with Martian regolith for more than 2 billion years, and a further practical problem in water usage on Mars is the various harmful contents dissolved in it. Water may be contaminated with dissolved metals or with reactive oxygen species (ROS), such as hydroxyl radicals and hydrogen peroxide, as well as perchlorates which abound on the Martian surface. The reshuffling of the surface by multiple bolide impacts has also induced temporal hydrothermal systems (Chatzitheodoridis et al., 2014) which may have contaminated the subsurface waters with ROS and heavy metals. Generally, ROS is a continuously emerging problem, not only in the subsurface water but also in the cleaned stored water, which will be exposed to ionizing radiation. Thus, a set of detectors is needed to permanently monitor the water quality (Georgiou et al., 2022) and to apply remediation technologies, amongst others to neutralise ROS. This neutralisation can be relatively straightforward: some nanomaterials such as molybdenum disulphide (MoS_2) (Yu et al., 2021), binuclear Cu(II)-Core materials (Squarcina et al., 2020) and manganese dioxide (MnO_2) (Georgiou et al., 2022) have strong catalytic activity that can effectively quench ROS, and filters made of such materials could be used to neutralise the ROS in water. Some of the above materials are even investigated for use as ROS scavengers in vivo (i.e. in the human body).

It has been shown that perchlorate can be degraded by perchlorate-reducing bacteria; their use for bioremediation on Mars could be explored (Coates & Achenbach, 2004; Fang & Naidu, 2023; Xu et al., 2003). For purification of the water from metal contaminants, electrochemical methods have been used extensively on Earth (Alkhadra et al., 2022), and they can easily be applied also on Mars. As it is not known whether life ever existed on Mars, and especially, if dormant life still exists in the subsurface, excavated water needs to be further analysed for its actual microbial content (undefined method for now), together with minerals and other chemical

pollutants. It should then be purified to the level required for the intended purposes, and most strictly for human consumption (Pickett et al., 2020).

7.3.3 Risks Related to the High-Tech Infrastructure

With increasing numbers of inhabitants in the settlement, and the increasing duration of occupation, the risk of accidents and system failures is likely to escalate. In general, multiple risk factors are related to the prevailing conditions on Mars, which are very harsh not only to the people but also to the infrastructure—and the environment does not allow for easy and frequent cleaning or repairing of the structures. Some failures, for instance of life support systems or of the habitats, may have deadly consequences for the people; and overall, even without major failure, life expectancy is likely to be shortened (see also Sects. 6.4 and 7.3). Risks may stem from the following facts (the list is not exhaustive):

- Sand and dust flying in the air are prone to wear out the surfaces of photovoltaic films and jam the windmill rotors. Dust contamination, or contamination with other impurities, can block the water or air filters. Dust can also drift into the habitats, causing wear and tear on all surfaces, and to the sealing structures.
- Essential processes, functions, or structures may fail due., e.g. to power failure, computer crash, fire, or human error or sabotage.
- The strong radiation causes the generation of reactive oxygen species (ROS) in water and in all moist materials, thus producing strong toxins in the habitat environments.
- Strong particle radiation causes excessive disturbance to all electronic devices, and particularly to data processing and AI-mediated functions. UV and particle radiation quickly degrades all organic polymers, like plastics. All these risk factors are prone to cause failure of any part of the life support systems or any other essential function.
- Due to the large pressure differences between the external air and the pressurised gas containers (e.g. large reservoirs for rocket fuel) or the pressurised habitats or vehicles, these structures are prone to explode or leak out their pressurised gas.
- Dome-like habitats, made of transparent cover material to obtain daylight, should be made of mineral material (not polymers) to prevent break-up by UV light. However, these would soon be worn out by the blowing sand. These structures would shield against UV radiation, but not adequately against the high-energy cosmic radiation.
- As water mining continues, reservoirs in the habitat vicinity will run out. The caving out of the subsurface reservoirs causes risk of the collapse of the overlaying surface. With time, water is to be transported over longer distances. Water purification mechanisms such as filters wear out with time. Either high-quality membranes must be locally produced, or the water must be purified using alternate ways (e.g. distilling).

- Toxicity (e.g. due to high mineral levels) may turn the water unusable.
- Local food production may fail for many reasons, e.g. the crops or cell cultures fail to grow well in those conditions or become contaminated by pathogens/parasites. To prevent contamination of the entire system, a modular design is required, allowing isolation of the contaminated crop area or cell culture. Food, water, and oxygen resources need to be backed up by redundant reservoirs.
- The space suits wear out, become dirty, and non-functional. Vehicles wear out. Airlocks, landing, and launching facilities wear out. This is strongly enhanced by the abundant dust and sand.
- Interplanetary transport may become reduced due to failing political or economic support on Earth, or due to major accidents.
- The space vehicle may get hit by micrometeorites, space debris, or larger asteroids during the interplanetary travel. Whilst this may be more likely during take-off and landing, this risk cannot be ruled out during the interplanetary travel (NASA, 2022; Schultz, 2013).
- Human endurance and the potential of dysfunctionality in these conditions are difficult to predict. Resilience may be stretched thin, leading to conflicts, other malfunctions, and even terrorism, even if extensive efforts are made to prevent such risks. The society and infrastructure far out in space are very vulnerable: Major attacks or malfunctions on Mars would be more serious than the same occurring on Earth.
- Pathogenic species may emerge in the microbial flora. Isolation may not be possible in tight quarters, so the whole settlement may be affected (Space Hygiene—NASA, 2024). Chronical symptoms may appear for which there is no cure.

7.4 Years on Mars: Physiology and Psychology[4]

Developing a permanent science base on Mars will bring an additional set of challenges for human physiology and psychology. Life in Mars's 0.38G environment will probably have fewer detrimental effects on health than life in microgravity, but if astronauts stay for over a year, a certain adaptation to the environment will nevertheless take place. There is no long-term data yet on how living in partial gravity affects human physiology—a physiology that is comprised of many different systems interacting, sometimes in delicate ways, homeostasis of each system necessary to sustain life. We can only guess how much gravity is needed for our bodies to be able to thrive. Will life on Mars be comparable to life on Earth? It is entirely possible, as is often stated, that there is a linear relationship between the effects of microgravity (bad for health) and the effects of 1G (optimal health). Living on the Moon would accordingly be quite bad for health, with its 16% of Earth's gravity perilously close to microgravity. Life on Mars would be somewhere in between space and

[4]This section is authored by Carmen Possnig.

Earth, but a healthy lifestyle will probably mean regular use of countermeasures. However, the relationship between gravity and our physiology might be entirely different. The low lunar or Martian gravity might not at all be enough to sustain health and instead have similar effects to those seen in microgravity. In this case, daily countermeasures such as physical exercise will be needed to simply avoid deconditioning. On the other hand, the opposite is just as likely: Martian gravity might be sufficient to keep astronauts from deconditioning, rendering the use of countermeasures obsolete. In fact, Earth's 1G might actually be too much. Indeed, with age, we all experience deconditioning: loss of muscle strength, bone density, a weaker heart, performance plummeting and a spine bending towards the centre of the planet. It is possible that on a planet with a gravity level of, for example 0.7 or 0.8G, we might live healthier, longer lives. In any case, few studies to date have investigated effects of Martian gravity on human physiology, and methods are often not ideal. This gap in knowledge will have to be closed before a long-term settlement is planned, and appropriate countermeasures anticipating the worst-case scenario (i.e. Martian gravity being detrimental to health) must be available as long as we do not know better.

Most importantly, countermeasures for a several-year stay on Mars must take two factors into account: health and fitness on Mars, and preservation of the astronaut's ability to return to Earth. Focusing solely on optimizing countermeasures for life on Mars might make workload and survival easier whilst on the red planet, but this strategy can lead to detrimental effects once returned to Earth. In addition, the return journey means another 6–9 months spent in microgravity, deconditioning included. Therefore, whilst planning training schedules for the stay on Mars, both the return journey as well as the astronaut's health and quality of life after the mission must be considered.

7.4.1 Years on Mars: Physiology

As discussed in Sect. 6.4, astronauts will arrive on Mars with the consequences of several months spent in microgravity. As long as countermeasures are regularly applied, most physiological changes will probably not exceed those seen in a short-term mission.

As mentioned above, we cannot as of today say for sure what effects a long-term stay on Mars will have on physiology. What follows are therefore speculations not backed up by data.

Biomechanical loading, even if reduced to 38%, should ensure that bone demineralisation and loss of muscle mass and strength will be less than the equivalent stay in microgravity. A certain hydrostatic pressure gradient will exist, affecting the cardiovascular system and helping against deconditioning of its performance capabilities. Exercise capacity is likely to decrease below levels that would allow for optimal functioning back on Earth, and therefore countermeasures (e.g. physical exercise) will have to be applied on a regular basis. Devices to perform endurance training, as

well as strength training, will need to be provided in a Martian habitat, and sufficient space will need to be allocated for these workout sessions. The type and duration of training will have to be optimised before, depending on equipment used, individual needs of the astronaut, and time spent off-Earth.

The thin atmosphere of Mars should provide some shielding from radiation, but will certainly not be sufficient. A strategy might be to construct habitats underground, perhaps inside old lava tubes, or coating habitats with regolith, as this provides an adequate shield against radiation (see Sect. 6.4.3). Permanent dose rate monitoring will be essential. Transfer vehicles should, if possible, be either constructed in a way that allows for sufficient shielding or be equipped with the possibility to quickly construct a shelter, in case of a solar particle event or a coronal mass ejection.

Whilst Martian soil can protect against radiation, hidden inside it lies another risk for humans: its high level of perchlorates. At high doses, perchlorate can be detrimental to thyroids, as it competes with iodine ions which are needed to produce thyroid hormones (Davila et al., 2013). Thyroid hormones interact with a wide range of bodily functions and can easily incite disruptive changes in an acute or chronic fashion. In addition, the soil is believed to contain certain cancerogenic substances, as well as reactive oxygen species (ROS, see Sect. 6.3.2.4) that, when inhaled, can affect the respiratory and cardiopulmonary systems. Martian settlers will therefore have to protect themselves from direct contact with dust, taking care to clean their Mars-suits before entering any habitat or vehicle.

The crew of the science base will need to be independent from Earth in many ways, including medical care. As discussed in Sect. 6.4.6, diagnosis and treatment of common or anticipated diseases, accidents, or injuries must be possible, both onboard the transfer vehicle, as well as inside a science base. Ideally, several crewmembers would be trained in these procedures. They must be able to treat minor injuries such as fractures, burns, open wounds, sprains, or contusions, but also be prepared for treatment of serious medical emergencies such as a heart attack, cerebral stroke, or an infected gallbladder.

Once humans stay on Mars for several years, novel medical challenges will arise. An example of this may be the way our bodies fight infections.

Mars and the Immune System

Hundreds or even a thousand people on site, in combination with regularly rotating crews, will bring a steady supply of new potentially disease-inducing agents that will challenge immune systems of space travellers. Emergency plans for incurrences of epidemics will be needed. Being independent from Earth will mean the ability to produce vaccines, potentially even the invention of novel ones against new pathogens, will be an asset.

A combination of microgravity (and possibly also Martian gravity), radiation, and psychological stressors are hypothesised to weaken both the innate immune system (which reacts quickly in a non-antigen-specific fashion) and the adaptive immunity (a delayed and antigen-specific response, which also results in long-term protection): The function of NK-cells (which are part of the innate immunity) as

well as T-cells (part of the adaptive immunity) is weakened, whilst inflammatory plasma cytokine levels are increased for the duration of spaceflight (Crucian et al., 2018). Today we have data mostly for 6-month missions in low Earth orbit.

Reactivation of latent viruses and allergies are examples of signs that the immune system is dysregulated in space. Many humans are carriers of latent viruses without illness occurring, but a healthy immune system is necessary to keep them from being activated. In space, multiple occurrences of reactivation and shedding of latent herpesviruses have been observed (Mehta et al., 2017; Rooney et al., 2019), which can be seen as a sign of a compromised immune system.

Despite being isolated from typical terrestrial agents, some previously allergy-free ISS crewmembers report the development of symptoms of new allergies, as well as infections of the skin or respiratory tract. The formation of biofilms inside the station, as mentioned in Sect. 6.4.8, may be responsible for this. Sometimes antihistamines are taken for the remaining mission in order to alleviate symptoms. Why some astronauts are affected and others show no symptoms at all remains unclear (Crucian, Babiak-Vazquez, et al., 2016).

The immune system is complex, exchanging information and interacting with most other bodily systems. It is difficult to pinpoint what exactly causes its dysregulation in space, but this also gives us a wide selection of countermeasures to try from:

- Hypocaloric nutrition (which was often seen in early spaceflights) has been linked to increased inflammatory responses and oxidative stress. Oxidative stress can activate the immune system and incite inflammatory processes. It can be increased by radiation, resulting in an exacerbation of the inflammatory response as well as DNA damage (which, in turn, would lead to more oxidative stress and thus a vicious circle targeting the immune system). Ensuring adequate and individually adapted nutrition may support the immune system in working properly (Crucian et al., 2018).
- Exercise is not only beneficial for muscle, bone, and cardiovascular health but has a positive influence on immunity as well. On Earth, regular moderate-intensity exercise improves normal functioning of the immune system (Simpson et al., 2015). However, the duration, intensity, and type of exercise are of importance and would need to be optimised for this particular aim. On Earth, a slight preference is given to aerobic exercise in terms of effects on immunity. However, exercise may have negative effects as well if performed too strenuously.
- Bone health is possibly also linked with immune functions, as some immune cells are formed in bone marrow.
- Psychological health and immunity are directly linked. Behavioural and stress management is therefore an important pillar in preserving physical health on Mars. Strategies for psychological wellbeing will be very different from todays in low Earth orbit. Regular sessions with terrestrial psychologists, phone calls with family and friends and regular care packages delivered into orbit will not be possible. On-site psychologists, space allocated for relaxation and practicing resilience strategies such as meditation, stretching exercises, or yoga might prove beneficial in the long term (Crucian et al., 2018).

In addition, certain pathogens are thought to become more virulent when the immune system is thus weakened, and some bacteria (*Escherichia coli* and *Staphylococcus aureus*) have been shown to develop a stronger resistance to antibiotics when in space (Moatti et al., 1986; Tixador et al., 1985). Effects can range from antibiotherapy being ineffective (Crucian et al., 2015; Crucian, Smith, et al., 2016) to a need for higher dosage. Reduced gravity may also have an effect on pharmacodynamics, as absorption (especially of medication taken orally, as stomach content floats), and elimination can be affected.

7.4.2 Years on Mars: Psychology

Human beings can endure almost anything, is one of the rather calming lessons learned from Jack Stuster's book *Bold Endeavours* (Stuster, 1996), in which he analyses knowledge learned thus far from expeditions. This does not mean that we should ignore challenges to psychology. They will surely accompany any journey to distant planets and how astronauts deal with them might define mission success. Mission scenarios including years spent on the surface will have a different set of challenges than any previous short-termed ones. Just as it happened with the Apollo missions, public excitement may fade after a few successful visits to the red planet. Whilst the first astronauts to land there are pioneers, will have their names in history books and venture out with a strong motivation for exploration, science advancement and inspiration for others to follow, the situation for the first long-term missions will be a different one.

Whilst the first settlers will certainly be selected for personality and psychological stability, restrictions might slacken once more and more people venture to Mars. For a science base with 1000 inhabitants who each stay for several years, the chances are high that not everyone will react with perfect adaptation to daily life at the frontier. Antarctic research bases are considered the best available analogue concerning mission duration, real danger, and degree of isolation. The number of inhabitants varies depending on the size of the base, but is typically somewhere between 50 and 1500 people during summer season and between 8 and 200 for winterovers. The crews are very diverse in social, cultural and professional background, and also in their individual motivations to spend a winter in isolation. Whilst some go for the science, others seek excitement, monetary benefits, or simply a change from everyday life. Conversely, some people experience more difficulty in coping with the extreme environment and isolation. It is likely that after some years of initial exploration, the situation on Mars will be similar. The challenge will therefore not only be to keep up crew cohesion, avoid interpersonal conflicts from escalating and preserve individual mental health, but also avoidance of serious psychiatric illnesses from occurring.

In Antarctic research bases, the occurrence of psychiatric issues (e.g. personality disorders) is about 0.052 cases per person-year, comparable to levels in the general population (Fariba et al., 2024). However, these are people preselected for having an

extremely low risk of developing a psychiatric illness and under the circumstances 5% is deemed a rather high number. It is possible that, next to minor mental health issues, serious problems will occur in a Mars settlement, and preparations should be made in order to be able to cope with these—be those countermeasures such as psychological care on site, or pharmacological treatment for severe cases.

When staying on Mars for several years, a balance will need to be found and mission success is also defined as preserving psychological and physical health of the crew living and working there. This balance will mean compromises and a focus on human wellbeing. Ideally, mental wellbeing ought to be taken into account from the start, starting with habitat design (e.g. with acts such as providing windows in spacecraft and habitats, and designing the interior with the aim of creating a pleasant atmosphere). Other measures include providing adequate space for time off, hobbies and relaxation, and countermeasures whose application is realistic, always considering that these will be used almost daily for years and must therefore be sufficiently agreeable to work with. The need for personal space must be addressed as well: klack of privacy is one of the most important stressors under isolation and the longer the duration of the mission, the more important personal space becomes (Stuster, 1996).

Interestingly, food and celebrations of any kind become more and more important over time as well. Early polar explorers, just like those today, broke the monotony of daily life by celebrating any holiday they could think of. They noted the importance of a good meal, taken in company, to preserve morale and wellbeing. Crews on the ISS mimic that behaviour to an extent, by being provided with special festive meals to share, and receiving fresh food via cargo vehicles from time to time. Trying to provide a diet as varied as possible, potentially including fresh vegetables grown on site, might be of enormous help to future Martian explorers. Growing food also has additional benefits: the sight and smell of nature in an otherwise artificial and lifeless environment can enhance mood and contribute to mental wellbeing (Stuster, 1996).

Unexpected events will occur and coping mechanisms will need to be available. With longer mission durations, catastrophic events such as the death of a crewmate will also become more likely. This can have detrimental effects on mental health of the rest of the crew, with post-traumatic stress disorder development possibly endangering safety of the concerned individual as well as the mission.

7.5 Governance of Small Science Bases[5]

For small missions, the regulations could be modelled from the legal framework that is now used on the **ISS** (based on an intergovernmental agreement, signed in Washington D.C. on 29 January 1998, between 15 states). Some Martian assets,

[5] This section is authored by Marie-Clotilde Runavot.

whilst led by the United States, could be based on the *Artemis Accords* which are already encompassing Mars beyond the Moon. An international agreement between the states leading the exploration of Mars could even use the *Antarctic model*, based on the Antarctic Treaty (Secretariat of the Antarctic Treaty, 1961).

There are now 56 states that have signed the Antarctic Treaty, including 29 Consultative Parties, i.e. states which, having demonstrated their "interest in Antarctica [notably] by conducting substantial scientific research activity there, shall meet at the City of Canberra within two months after the date of entry into force of the Treaty, and thereafter at suitable intervals and places, for the purpose of exchanging information, consulting together on matters of common interest pertaining to Antarctica, and formulating and considering, and recommending to their Governments, measures in furtherance of the principles and objectives of the Treaty" (Article IX).

The Artemis Accords are a set of bilateral agreements between the United States and other states, under which the latter adhere to the model agreement proposed by the United States, which is defined as follows in section 1: "a political commitment to the principles described herein, many of which provide for operational implementation of important obligations contained in the Outer Space Treaty and other instruments". The first group of seven states signed this agreement with the United States on 13 October 2020 (United Arab Emirates, Australia, Japan, Canada, Italy, Luxembourg, and the United Kingdom).

Note that, China and Russia signed an agreement to jointly build an International Lunar Research Station to be operational around 2035. The implementation of that agreement, which is open to other states, will be also a model for the step towards Mars. The OST is providing, up to now the only common reference.

This proposed legal framework should be enriched by an institutionalisation in the form of a PPPM as described above and adapted to the specificity of missions to or on Mars.

7.5.1 An Enriched Legal Framework

Several intergovernmental agreements provide for cooperation between states for the peaceful exploration and exploitation of non-sovereign zones or celestial bodies. Whether it is the ISS or the Artemis Accords, these agreements are in fact based on a plural normative structure, i.e. with several hierarchical, dependent, and complementary levels of norms.

Firstly, an intergovernmental agreement (which may or not be multilateral or binding) establishes or restates a set of principles and general rules (cooperation, use for scientific, civil, and commercial purposes, and in any case for peaceful ends, the interests of mankind, and freedom of use). It is open to any state interested in its subject matter, even if it does not necessarily have a direct interest (for example, because it does not yet have the capacity or means to access space or, in the case of Antarctica, has no territorial claim). This agreement thus provides the legal and

general framework for carrying out operations, which nevertheless requires the adoption of other technical norms if they are to be carried out effectively. This is the purpose of the second set of norms, concluded at a lower level—generally administrative (rather than governmental), but which could also involve private actors—and which generally consist of memoranda of understanding or implementing agreements.

The examples found in existing regulations originate from the initiative of one state (the United States) or a group of states, whilst remaining open and placing themselves at the service of humanity. However, the balance between the participating states is not guaranteed, as the interests of some are clearly favoured, which casts doubt on the reality of a partnership (Dongar, 2020). To address this, the agreement underpinning the system of governance for the small missions to and on Mars should be proposed and supported by one or more international organisations, thereby enabling individual sovereign interests to be overcome. By virtue of its universality and its objectives, the UN seems to be the natural choice. Beyond that, if the partnership approach is to be effective, it must be backed up by an institution: the Private–Public partnership for Mars (PPPM) (see Chap. 5).

To ensure a partnership between all interested actors, the basic agreement should therefore establish a partnership institution responsible for producing the technical implementation norms and monitoring their application. Its organic structure should allow the voice of all stakeholders to be heard and, in particular, include a governing body bringing together all partners on an equal footing. In order to avoid a body incapable of taking decisions, and still taking inspiration from what has been achieved in the health sector, the various partners should be represented by a group with equivalent decision-making power, so that no particular interest (whether public or private, commercial or environmental, etc.) is favoured a priori. However, in order to avoid an imbalance in terms of responsibility—since only (inter)governmental entities can be held internationally responsible—an internal mechanism for "recourse action" could be envisaged, based on the involvement (and therefore the risk) of each of the partners, whilst taking care not to have a dissuasive effect on certain private partners.

7.5.2 A Legal Framework Adapted to Small Missions to and on Mars

A mission to the Moon or a fortiori to Antarctica differs from a mission to and on Mars, for example because of the time delay in communication between the two planets. Since nothing can be decided in real time for Mars from Earth or vice versa, the institutional governance structure must be adapted. We therefore need to distinguish between governance on Earth and governance "on-site", establishing a clear chain of command between the two.

For these small missions, admitting that it would be a concerted endeavour between several parties, the main headquarters of the PPPM should be on Earth (on the territory of a space-faring nation or, better, at the headquarters of the United Nations). On Earth, it would be the steering committee of the PPPM that would make decisions and take responsibility for the entire programme, ensuring compliance with treaties and notably the core international agreement. In particular, it is at the level of the PPPM's terrestrial headquarters that the authorisations for the installation and operation of the bases on Mars would be issued, the data and the eventual samples collected will be equitably distributed between all the partners, taking into account the interests of humanity and future generations. On Earth, the PPPM steering committee would also have to settle disputes, arising in connection with the mission, that could not be handled "on site".

By contrast, operational management should be the responsibility of "on site" governance. The base commander would be tasked with managing scientific and possible private operations carried out from the Mars base in accordance with the authorisations granted by the Earth headquarters and the law and regulations applicable to the base. As for the International Space Station, the role of Base Commander could be assumed on a rotational basis between the most experienced astronauts.

7.6 Cost of Establishing a Mars Base[6]

After the first successful Martian landing(s) we can expect a series of missions based on Martian exploration. Visits to several sites to explore different geological features, and to identify regions where water and other useful resources may be found similar to the planned visits to the Moon, are to be anticipated. Regions where extinct or extant life might be found will undoubtedly be a high priority and will be probably performed by earlier robotic missions. Should life have been identified on Mars by earlier missions then we can expect a major debate about whether humanity should even visit Mars (see Chap. 3) but if there is no evidence for life (at least prior to human landings) then initial landings can be expected to follow the protocols and procedures developed for human exploration and settlement of the Moon.

After several astronaut landings, we might expect the arguments for the first habitable structures to be built on Mars as they will on the Moon. The infrastructure for a Martian base will be similar to that of a lunar base and it is to be expected that humanity's experience in constructing lunar bases will be used when seeking to build similar structures on Mars. However, Mars has some advantages over the Moon in that it has an atmosphere, mainly CO_2, that could be used to produce oxygen and ice caps that contain sufficient amounts of water to support larger habitats and act as a source of rocket fuel without the complex extraction techniques needed to obtain same resources from lunar regolith. Indeed, more than 5 million cubic

[6] This section is authored by Nigel J. Mason.

kilometres of water ice have been identified at or near the surface of today's Mars. Melted, this is enough to cover the whole planet to a depth of 35 m (115 ft) and even more ice is likely to be locked away in the deep subsurface.

Since transportation costs to Mars will be a major restriction in order to construct Martian structures, it will be necessary to exploit in situ resources, the ambition being to create a local 'concrete' to build Martian structures. Cement can harden in the air or in water, and can firmly bond sand, stone, and other materials together, which makes it a favourable construction material. To make concrete in the Martian environment it will be necessary to identify in situ materials to produce concrete including binder, water, and aggregates. It has been postulated that Martian regolith (which due to its nature is now commonly called 'soil') can be used as an aggregate (Liu et al., 2022). However, to date, we have only been able to study Mars soil samples with robotic landers, but some Mars sample-return missions (MSR) are being planned by which Martian soil may be brought to Earth for more advanced analysis and its potential for a building material confirmed. Since 2006 NASA has been investigating many types of binders including sulphur and polymers. In 2016, (Wan et al., 2016) combined regolith and molten sulphur binder to develop Martian concrete and found that this concrete had higher strengths and was feasible for use as a construction material under the atmospheric pressure and temperature ranges found on Mars. Reches (2019) systematically listed potentially applicable binder types existing on Mars including bassanite or gypsum, opal, and ferric sulphate.

Martian soil also appears to be receptive to the growth of terrestrial crops which can be watered by local resources. Many essential plant mineral nutrients have been found in the soil on Mars or in Martian meteorites. However, the level of most of these nutrients is too low for healthy plant growth, so Martian soil will need to be improved with fertiliser such as may be produced from the waste products of astronauts (during their flight to Mars or whilst resident on the surface). Trials in Martian soil simulants have shown the growth of alfalfa, broccoli, kale and lettuce, garden cress, rocket, tomato, turnip, radish, rye, quinoa, spinach, chives, pea, and leeks (Kasiviswanathan et al., 2022; Wamelink et al., 2021). However, real Martian soil may be rich in metals and the perchlorate of calcium ($Ca(ClO_4)_2$) or sodium ($NaClO_4$) that may be toxic to both plants and humans. Extraction of perchlorate may be made by simply rinsing the soil since perchlorate dissolves in water. Another way is to use perchlorate-eating bacteria, which produce oxygen as a metabolic byproduct bolstering the breathable air supply.

Furthermore, unlike the Moon, there are other in situ resources that can be used, e.g. as local energy sources, most notably wind energy. Mars probes have shown that the wind speed on the Martian surface is generally 2–7 m/s which is compatible with current terrestrial wind turbines—4 m/s for small wind turbines and 6 m/s for utility-scale turbines. However, 40 m/s dust storms have also been recorded (Savijärvi et al., 2020), on the planet's surface which, whilst seriously affecting Mars exploration and habitability, are also potential wind resources. This aerial resource has to be modulated by the tenuous Martian atmosphere which will make the wind less effective.

Thus, in contrast to the Moon, we can foresee a more sustainable ecosystem being developed on Mars requiring fewer materials and food supplies being transported to the planet and the opportunity to sustain a large habitable population. Nevertheless, there will be a huge initial outlay to establish the first Martian bases. To date costings of such an endeavour are speculative. In 2019 Elon Musk placed the price to build a "New Mars City" at somewhere between $100 billion and $10 trillion with these calculations based on the assumption that this would require one million tons of cargo from Earth for such a city to function. At the low estimate, SpaceX would only need in the region of $3 billion per year to fund its Mars city over a 30-year period. Its rocket launches in 2018 brought in $2 billion revenue and Starlink, the company's Internet connectivity satellite constellation, could bring in $20 billion in revenue by 2030. $100 billion is about half of New Zealand's annual gross domestic product at $205 billion and equal to the $100 billion per year the Paris Agreement committed countries to spend on fighting climate change.

If at the upper end of the estimate, then the venture would cost somewhere between half a percent to one percent of the world's gross domestic product per year over a decade. It sounds like an unbelievable amount of money, but it is still a fraction of global wealth. It is around half of the United States' 2021 annual gross domestic product at $23.3 trillion, and double that of Japan's at $4.9 trillion (Table 7.1). In fact, it is around 7% of the annual total global economy with every annual gross domestic product added together, estimated at 146 trillion dollars per year (Table 7.1). Global real estate is estimated to be worth around $217 trillion. It is also a figure that is commensurate to the amount humanity spends on cosmetics and the amount it spends on healthcare. The value of military spending globally has grown steadily in the past years and reached 2.24 trillion US dollars in 2022. Nevertheless, it would still be the most expensive science project of all time, a record currently held by the International Space Station—$150 Billion—but it would break humanity free from the confines of Earth and spark a new era in our history.

Table 7.1 GDP of the top countries in the world in 2021 (billion $)

Countries	GDP current US dollars, 2021	Global rank
United States	23,315.08	1
China	17,734.06	2
Japan	4940.88	3
Germany	4259.93	4
India	3176.3	5
United Kingdom	3131.38	6
France	2957.88	7
Italy	2107.7	8
Canada	1988.34	9
South Korea	1810.96	10

7.7 Small Permanent Outpost: Ethical, Societal, and Political Aspects[7]

After the first human return missions, the most probable next stage of Mars exploration will be to establish one or more permanent outposts. Some ethical, political, and societal issues surrounding such outposts will differ depending on the purpose of the outpost—will it be a science base like those in Antarctica, a commercial outpost most probably for mining or construction purposes, or a military outpost? These purposes can also conflict. In space ethics literature, it is often stressed that scientific goals should precede other goals (Schwartz, 2020a). The ethical, political, and social issues will probably also differ depending on who the founder is—will it be a national space organisation, a consortium of national space organisations, or a commercial actor (Persson, 2015)?

There are, however, also a set of ethical, political, and social issues that can be expected in all these cases. The following sections deal primarily with these issues. A permanent outpost can be expected to be dominated by specialists and a very strict command structure similar to what can be expected on the first human return missions on Mars. Living on Mars for extended periods of time creates new demands, and also new issues regarding the relationship between the Earthlings and their new home planet.

The demands of the new environment may for instance create a need to alter the human body. Some ethical theories see this as problematic in itself and raise questions of freedom, autonomy, and consent, whilst others are only concerned with the possible effects of this alteration. Ethically relevant effects may not only turn up on Mars but also on Earth if the enhancement technologies catch on amongst those who stay on Earth, or if members of the crew want to or need to move back to Earth, which could be made impossible or very difficult if their bodies are changed to fit the very different Martian environment.

Political complications could arise if outposts are run in cooperation between different countries or if outposts from different countries are close to each other or need to interact in other ways, for instance, in order to assist each other. There could also be competition about the most attractive spots, especially if we talk about commercial outposts. Both these kinds of conflicts will inevitably engage those in control of the outposts and may in the worst case spread to Earth. The opposite situation is also possible, that is, conflicts on Earth could complicate the relations between outposts on Mars.

Social issues will probably be limited by the special composition of the crew and the strict command structure in the outposts, but can never be totally excluded when humans are involved. Even highly trained and motivated professionals are—human.

[7] This section is authored by Mikko Puumala, Oskari Sivula, Ondřej Ditrych, Erik Persson, and Nikola Schmidt.

The question of the relationship between the newcomers and the host planet will be much more emphasised in a permanent outpost than it would be for a come-and-go mission. A permanent outpost will also inevitably affect the local environment and we need to ask questions such as—what kind of effects on that environment should we allow?

Some of these questions, as well as some others, will be scrutinised in the coming sections.

7.7.1 Human Enhancement and Pantropy

Given the distance from Earth and the demanding environment on Mars, the issue of human enhancement to facilitate space exploration emerges (Abney & Lin, 2015; Huttunen & Sivula, 2023; Schwartz, 2020b; Szocik et al., 2020, 2021). Human enhancement refers to the idea of improving the capabilities of humans beyond what is considered as therapy. This enhancement can be done in various ways. Some are mundane such as drinking coffee to make us more bristling with energy. However, other means are controversial, especially those that are biomedical in nature or even involve genetic engineering. Moreover, advances in technology make it possible to anticipate various forms of human enhancement that may sound like science fiction now.

The rationale for enhancing a space crew is apparent: it increases the likelihood of successful missions by helping humans survive the extreme conditions of deep space and Mars. To meet such ends, various enhancement modifications have been discussed. For example, enhancement in inner ears could help deal with altered gravity, eyes could be modified to improve performance and safety, and gene editing could be used to heighten bone and muscle regeneration (Szocik et al., 2021). Also, pharmacological and neurotechnological interventions could be used to combat psychological challenges in space and increase cognitive capabilities (Huttunen & Sivula, 2023). Since the conditions on Mars are so harsh for human body, many envisioned biomedical interventions would better serve as remedies to help humans survive on Mars rather than enhancements. Thus, in some cases it may be wiser to talk about *pantropy* instead of human enhancement (cf. Jebari, 2024). Pantropy is a term coined by science fiction author James Blish in the 1940s that refers to the hypothetical process of modifying humans to survive in alien environments.

Such human enhancement or pantropy raises interesting philosophical questions; are these interventions morally desirable or safe? If radical forms of *body and mind modifications* are justified in space, are they also acceptable on Earth? What are the wider societal implications and risks of medical and technological human enhancement or pantropy? Should some forms of human modification be mandatory for astronauts or anyone who wants to settle on Mars? Could selection, alterity, and enhancement concomitant to space exploration open the possibility of evolution of particular political identities ("Martians") established around *biological* differences, to the point of the emergence of a new human (sub)species, and if so, is it

desirable? For now, human enhancement at the forefront of technology remains a debated topic that will likely stay controversial for a long time. That said, we may see new forms of human enhancement utilised in future space missions and it should be acknowledged that these technologies are not neutral. Instead, they come with ethical issues and perhaps wide societal ramifications.

7.7.2 Property and Territorial Issues

From its earliest articles, the OST establishes the broad principles governing space law, stating that space exploration and the use of outer space must be carried out only "for the good and in the interest of all countries" (Article 1) and that outer space "shall not be subject to national appropriation by proclamation of sovereignty, by use or occupation, or by any other means" (Article 2). Thus, whilst the treaty states that "scientific research is free", it makes the conduct of scientific research conditional on its peaceful nature, prohibiting all military activity, and, more importantly, on the manner in which it may be carried out, stating that scientific research is "the prerogative of mankind". Similar rules can also be found in treaties governing science in the Antarctic or on the Moon.[8]

Whilst it is possible to set up a scientific base on Mars, as the International Space Station was set in Earth orbit, it will have to be set up on the basis of cooperation between states and no state will be able to legally claim ownership of Martian soil or the resources it contains. This is not to say that there is no property right in what material is used to create this scientific base or in the results that are achieved. First, there is a full right of ownership by states over the objects they send into space. Each object is registered in the name of a state and the state retains ownership of the object when it is sent into outer space. Second, similarly to what has been put in place for the International Space Station, it is possible to imagine cooperation between states allowing common and shared use of scientific equipment installed on Mars according to the resources invested by each state.[9] Finally, scientists or their organisations remain free to patent their discoveries. However, there is a limit to the principles already mentioned: they cannot claim to have discovered a Martian resource or to have exploited it privately. This idea has been reinforced by the use of the concept of "common heritage of humanity" found in the Moon agreements (though none of the current contenders in the Mars race has signed the latter).

Whilst this state of law, expressed in the various international treaties on the subject, aims to protect the general interests of humanity, it cannot be denied that it could generate difficulties in the long term. Private companies have raised the question of funding a scientific base on Mars in the absence of the possibility of appropriating land or minerals. Some have said, for example that they would not undertake drilling if they were not sure that they could exploit the extracted minerals. Such a

[8] Antarctic Treaty, 1959; International Treaty on the Moon and Other Celestial Bodies, 1979.

[9] The International Space Station Intergovernmental Agreement, 1998.

rule of law may need to be developed in the long term to protect various interests (Billings, 2019).

It was also with this objective in mind that, on 13 October 2020, under US leadership, the Artemis Accords were adopted by eight states before being joined by over 30 others and rising (U.S. Department of State, 2024). Whilst these agreements recall the main principles established in 1967, they also promote interpretations of some of these principles, that are in line with US policy but are contested by some other countries. They also depart from the Treaty on the Moon and Other Celestial Bodies adopted in 1970s but this was only ratified by few states, in part because this treaty described the Moon's natural resources as "the common heritage of mankind". In this regard, the Artemis Accords are more focused on opening up opportunities for the exploitation of space resources. Whilst these agreements do not spell out the possible modalities for extraterritorial resource exploitation, they express the idea that in situ resource use is feasible, including by "trading partners", and encourage states to establish "safety zones" to ensure that they develop activities without fear of harmful interference from other states. To this end, the text itself refers only to the "prevention of interference" between the various activities carried out on outer soil (Article 11), so the regime of these "safety zones" remains unclear, the boundary between the use of a territory and its appropriation being particularly thin.

There are multiple ways to arrange territorial issues on Mars. For instance, Angela M. Dapremont (2021) has found five different possible land-use policy proposals for Mars from the literature, ranging from first possession by landfall to planetary parks and Mars taxes. Although very different, these possibilities are arguably united around one and the same observation: whatever spatial planning policy is put in place, it will have to be the subject of negotiations between the various players and will probably take into account the financial resources that each is prepared to invest. Above all, in order to function peacefully, it will require the establishment of a regulatory authority that will guarantee compliance with the rules that have been adopted (for governance models, see Sect. 7.5).

Here, the already mentioned "Founder Effect" (Elvis, 2022) is important. There will be a system of property, and there is a risk it endures over time and dictates further developments of humans allocating material resources on Mars. Moreover, if Mars missions are driven by economic pursuits, it seems likely that the system of property will be moulded by neoliberal ideas. The question is: is there any way to avoid bringing characteristically neoliberal ideology to Mars? This is a significant ideological decision, and it seems that it will not be made deliberatively. There is a great risk that property and territorial arrangements get reduced to a matter of who takes the initiative.

7.7.3 Access to Resources and Research Infrastructure

The principles regulating or prohibiting economic and research activities are subject to governance patterns, at the core of what can be termed *discoverial politics*. Discoverial politics are structured around particular controversies (Venturini & Munk, 2022) in the space community. The way these controversies will be resolved will determine the practice of settling space and the design of the political and spatial ordering in the near space. The controversies most relevant to the issue of exploration and exploitation concern the *public/private* roles; and the *universal/parochial* imageries of the near space. Private entities are now positioned to benefit from their capabilities and infrastructure to resist regulation on, e.g. resources extraction, environment, health standards (radiation exposure) or privacy (surveillance) or even future sovereignty contestation, in extremis rendering public entities dependent on private infrastructure, and unable to enforce their authority.

These controversies concern the objectives of space exploration, which can be conceived as either universalist and free of territorial appropriation (as ruled by the OST, that designates the space as "province of all mankind"), or parochial and "territorialising", by either private or public entities, seeking to improve one's position on the market or in the emerging hybrid field of *geo/astropolitics*. Dolman (2005) encapsulates the extension of classical geopolitics to space in the scholarly debate whilst MacDonald (2007) presents the position that space should be maintained "free of power" and Deudney (2020) posits expansion into space as an existential threat to humankind, unless cosmopolitan governance is established first.

Appropriation is one particular subject in these controversies—currently prohibited by Article 2 of the OST, yet predictable to be challenged in the future with the advancing space exploration. An early indication of this process is the proposal to establish the "safety zones" already mentioned in the Artemis Accords. Mining, including for transfer to earthly markets and sourcing the settlements, is another. Extraterritorial responsibility (Shapcott, 2019), extending also to the realm of scientific research (driven by universalist objectives to advance scientific knowledge), is yet another, with the risk of contamination in exploring the sites of possible microbiological life being of particular concern with regard to the prospective human activity on Mars. For precaution in scientific experiments, see, e.g. Elvis et al. (2016).

7.7.4 Environmental Protection

Planetary protection in space law and policy discussion is limited to avoiding forward and backward biocontamination, a topic discussed in chapter 5 and in a previous section (Sect. 7.3). However, the broader concept of environmental protection involves a wider range of concerns. Environments, even those devoid of life, merit protection for a multitude of reasons. On Earth, unique or otherwise valuable sites, objects, and features are protected. Analogously, the same arguably should apply on Mars. As

articulated by Tony Milligan and Martin Elvis, "Mars is, after all, a unique place with a distinctive history. It is not another Earth. The Martian terrain, Olympus Mons, the Valles Marineris and all of the features, which go to make it so distinctive, are plausible candidates for safeguarding against destructive use" (Milligan & Elvis, 2019, 171).

Milligan and Elvis (ibid.) also suggest that advocating for environmental protection does not require a total hands-off attitude towards Mars. We may want to conduct science and commercial activities on Mars whilst protecting parts of the environment. This means that, as human influence on Mars starts to grow with the establishment of the first bases and camps, environmental protection ought to be considered. Cockell and Horneck (2004) suggested that a solution to this challenge is to create a planetary park system on Mars to preserve regions of it. The concept involves preserving these areas as "wilderness" minimally impacted by human activities. Reasons for protection are numerous, just like the reasons for environmental protection on Earth. Regions on Mars may have, for example, intrinsic or inherent, aesthetic, scientific, historical, and transformative value that we may want to preserve for current and future generations to enjoy.

This proposition naturally raises a question: which sections of Mars, and how much of the planet, should be protected? To the first part of the question, Cockell and Horneck (2004) have suggested preserving representative parts of Mars so that its diverse features are protected. This could include desert, polar, mountain, impact basin, lava tube, and canyon parks. Sites of historical value could also be protected, such as the areas where Viking I and Mars Pathfinder operated, as could areas of scientific interest such as the southern regions of Mars (Cockell & Horneck, 2004; Milligan & Elvis, 2019).

On the matter of the extent of protection, Milligan and Elvis (2019) argue that merely establishing planetary parks may not suffice. They instead advocate for a "1/8th principle". The idea behind it is to build a buffer mechanism to avoid "super-exploitation", a point at which accessible resources have been entirely exhausted (Elvis & Milligan, 2019). Sustainability, particularly when considering the interests of future generations, gives us strong reasons to avoid such a state of resource crisis. Because economies tend to grow exponentially, this point may come surprisingly soon. Therefore, Milligan and Elvis propose a precautionary measure to prevent super-exploitation: expansion and exploitation on Mars should be restrained beyond the 1/8th mark, except in emergencies. Consequently, seven-eighths of Mars should be left as wilderness. Whilst limiting exploitation to 1/8th may initially seem minimal in what it allows for utilisation because it is more ambitious than Earth's environmental protection efforts, it still equates to an area roughly the size of South America—providing approximately 18 million square kilometres for utilisation (Milligan & Elvis, 2019). The 1/8th principle may be infeasible to implement given the political realities, but this discussion nevertheless shows that extra-terrestrial environmental protection should not be limited to what is traditionally discussed under the more restricted notion of planetary protection.

7.8 Take-Home Message

The first visits to Mars may be followed by a series of missions, with crews composed of around six astronauts who will stay in the Martian system (on the surface or in orbit) for about 500 days. The most important goals of these missions will remain the same as the earlier ones': to carry out scientific sampling and observation; to explore the geological, geo(bio)chemical, hydrological, and paleoclimatic environment at the landing site; and to prospect various resources from the vicinity of the camp site. Amongst these resources, water is key: if found in harvestable amounts, it will become a valuable resource and a strong asset for subsequent missions. Early missions will be entirely, or mostly, dependent on transported goods for life support. The production of some water, oxygen, and food from local resources may, however, progressively become possible. Mission tasks may also involve the production of fuel from local resources (e.g. water and CO_2) for the return trip. For the 500 days on-site, a durable, safe, and comfortable base camp is required. This infrastructure will house subsequent crews, and potentially turn into a permanent outpost. Its key features include a radiation-sheltered habitat, a power source, and automated systems for the provision and recycling of life support supplies.

Our working scenario assumes that the first, short-term crewed missions to Mars have been successful and humans were found to cope well with the effects of long-term space travel and the conditions on the Martian surface. As missions increase in duration, human physiology may face new challenges (e.g. pertaining to immunological responses), and what kind of adaptation will take place remains unknown. Besides, as crews stay "out there" for longer times, new medical problems may emerge. It is unavoidable that some situations will require specific medical care: the diagnosis or treatment of injuries, such as bone fractures, or acute emergencies such as a heart attack or cerebral stroke, will need to be possible. This means that medical expertise (preferably from several crew members), and a whole selection of medication and operating facilities, should be available both onboard the interplanetary ship and in the base on Mars.

Another aspect of the feasibility of extended missions is their cost, and finding sources for funding. Visions for making such missions more economical lie in utilising the local resources as much as possible for the habitats, but this requires high initial investments. The necessary funding for the permanent crewed bases, established for scientific purposes, most likely would come from public national resources. The price is difficult to estimate, but it clearly would be the most expensive science project of all time, beating the $150-billion record currently held by the International Space Station. Elon Musk, the CEO of SpaceX and a strong advocate of settling Mars, has estimated the price for a "New Mars City" to be somewhere between US$ 100 billion and US$ 10 trillion. This cost would occur over perhaps a hundred years, and assume a transport of around a million tons of cargo from Earth to Mars.

The legislation covering current space missions is drawn from the Intergovernmental Agreement, itself based on the Outer Space Treaty. However,

bases on Mars would be set on the solid terrain of another planet and as they become larger and turn into permanent settlements, their legal framework will need to be re-formulated. A new international effort in this direction is inscribed in the Artemis Accords, now signed by the United States and more than 40 other countries. This treaty formulates more clearly the rights to use any local resources, the rules of cooperation and mutual respect, and the obligations and responsibilities of the operators.

So far, we have assumed that the establishment of the first small base on Mars will be led by public agencies, for the purpose of scientific exploration. However, it is conceivable that small bases and settlements would be established by other stakeholders, such as commercial actors or political alliances. Such bases could be set up, for instance, for the purpose of mining, construction, or as a military outpost. Such aims would significantly affect the ethical, political, and social issues of these operations, as well as cause complications and possibly conflicts between the different (and maybe competing) operators.

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Chapter 8
Towards Permanent Settlements on Mars (from 1000 to 100,000 People)



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8.1 Why Settle Permanently on Mars?[1]

Among humanity's most pressing scientific questions is the search for the origin of life and to discover if a form of life has ever developed in the universe on another celestial body than Earth. Mars is the closest and the best candidate, and probably the only one in the reach of the earthlings to search for clues or indices of this

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possibility. Settling many human beings on the surface of Mars before having thoroughly studied the possible existence of an extinct or extant form of life on Mars could prevent science from answering this question. Therefore, one prerequisite to establishing settlements of any size on Mars, even small scientific bases, is a responsible and cautious exploration that would not disrupt the Martian environment.

8.1.1 Small Settlements (up to 1000 People)

8.1.1.1 Prerequisites

Once scientific conservation is ensured, establishing a Martian settlement for about a thousand inhabitants would necessitate meticulous preparation and a comprehensive understanding of the Martian environment. Truszkowski in 2020 claimed that such a settlement on Mars would be conditioned by the discovery of areas capable of sustaining human presence and prepared by robotic missions. These regions would be on the Martian surface or in its near subsurface and near in situ resources that are essential for human survival. Protected structures which would become human habitats would need to be installed by robots and have the capacity for autonomous delivery of essential consumables. These installations, while still in the realm of conjecture, would play a pivotal role in ensuring the settlers' safety and enabling the establishment of a sustainable habitat (Truszkowski et al., 2020).

Another prerequisite for such settlements is the ability to ensure electricity generation to sustain human activities beyond mere survival, such as research, transportation, or manufacturing of goods. The two preferred methods for electricity generation on Mars are nuclear fission energy and photovoltaic panels. Amini et al. (2022), for a settlement of up to 500 people, envision nuclear fission reactors based on the NASA 10 kWe Kilopower reactor as the primary energy source, solar power as secondary source, wind turbines as tertiary source (during dust storms when sun energy is not available), and Radioisotope Thermoelectric Generator (RTG) as back-up source—a choice that is odd since an RTG cannot be switched off. The number of nuclear reactors can be scaled according to the settlement needs but Amini et al. estimate that 30 kWe per crewmember per day (i.e. 15 MWe for 500 people) is needed, which is 3–4 times more than NASA estimates for the first surface missions. According to the authors, this is justified by larger pressurised volumes and more diverse applications and activities. Mukundan et al. (2023) estimate that 6.1 MWe (3.5 kWe/person + facilities functioning) is needed to sustain a 1200-people settlement. This would be achieved with 30 nuclear reactors, which are improved versions of the NASA Kilopower reactor, each generating 100 kWe, and with 126.3 m^2 of photovoltaic cells (assuming 100 W/m^2 and 33% efficiency). In conclusion, estimations for energy requirements vary over one order of magnitude depending on the mission emphasis and comfort level. Even for small 1000-people settlements, energy generation might be one of the limiting factors, as the necessary

technologies are not mature yet and they would require the development of massive infrastructures on the surface of the planet.

Sustaining human settlements on Mars will require bringing a substantial amount of mass from Earth. However, this is not often discussed in detail in Mars settlement scenarios, except to discuss whether the settlement would (or not) be autonomous from an orbiting station or Earth and to state that In Situ Resource Utilisation as well as Mars supply chain would need to be developed. Salotti (2019) developed a rudimentary mathematical model to compute the payload mass (consumables and other objects indiscriminately) per year to be imported from Earth to sustain a settlement on Mars. This calculation relies on an evaluation of the overall needs of the settlement, on a formula reckoning what can be produced using In Situ Resource Utilisation (ISRU), and on the amount of the true available workforce. This formula is based on five parameters: (1) number of settlers, (2) working time capacity per person, (3) total time, per person and per year, needed to produce all consumables and objects needed for one person, (4) a sharing factor representing the number of people between whom an object can be shared, and (5) a conversion factor between the annual missing time into an annual payload mass (Salotti, 2019). Indeed, the author argues that the mass estimation problem can be converted into an estimation of missing time to produce all needed objects and consumables (without any mention of resource recycling, but making use of in situ resources), since the required payload mass depends on the available working time of settlers. The author distinguishes three types of societies corresponding to different comfort levels: modern (complex objects), frugal (basic objects), and survival (only necessary objects). According to this model, in a frugal society, self-sufficiency could be reached at 27,000 people with a peak mass at 300 tons per year with 5000 settlers. This would suggest that a 1000-people settlement cannot be fully autonomous, even in the case of low comfort and low resource consumption. For a smaller settlement of 100 settlers to be autonomous, according to this model, it would require to be in a survival-type society and the two main constraints to be satisfied would be low working hours (i.e. only necessary objects would be produced, thus a low production and associated low working hours) and a high sharing factor. This rough calculation makes the hypothesis that anything (consumables, hardware, engines, nuts and bolts…) could be technically produced locally.

8.1.1.2 Reasons to Permanently Settle on Mars

What we refer to as "small settlements" are Martian bases analogous to the Antarctic scientific station McMurdo or to an isolated oil rig platform, where workers come for a given job (e.g., research or mining activities) for a predefined duration and go back home on Earth, once their mission time is done. In small Martian settlements, the turnover rate would be high, and newcomers would arrive on a regular basis. However, it is hard to imagine what scientific endeavour would require 1000 people to work full time on research projects for several months or years in a row. It is likely that such a settlement on Mars would be composed of a small group of

researchers, supported by other workers ensuring the logistics of the base (food, management, maintenance, recycling, transportation, security, healthcare and well-being, etc.), as well as people dedicated to Mars resource prospection or exploitation for trading. Indeed, although the Antarctic station McMurdo counts about 1000 inhabitants, this scientific base is not self-sufficient or independent, but depends on regular resupplies from the continent (Klein et al., 2008). A similar base on Mars would need to be largely autonomous from Earth. Therefore, a fully scientific settlement would count at most a few dozen people, and this is addressed in Chap. 7. In this chapter, even small settlements cannot be 100% scientifically motivated.

NASA's reference mission scenario (1997) sees the primary rationale for such a settlement as a demonstration of the suitability of Mars as a location for longer term human space exploration and eventual settlement (NASA, 1997). This relatively small-scale community would serve as a testing ground for the technologies and strategies required for more substantial Martian settlement efforts. Amini et al. (2022) emphasises that this endeavour represents the "next step" in the long journey towards eventually permanently settling on Mars for long-term research-based missions, the specifics of which can be defined by future mission strategists (Amini et al., 2022). The reason for pursuing this path has been extensively discussed and varies from terraforming to the exploration of the unknown, with room for future adaptation based on research findings.

However, Stoner (2017) suggests that if the motivation for venturing into space arises from Earth's resource management failures, asteroid mining could be a more economically viable alternative due to its lower costs when compared to reaching and settling on the surface of Mars (Stoner, 2017). The economic justification for permanent settlement, in the view of Stoner, is not compelling. However, Zubrin (1996) lays out a different plan for making large settlements economically viable (see Sect. 8.1.2.2).

Other scenarios for small settlements can be found in recent human history and may pose massive ethical problems and questions, which are dealt with in Sects. 6.6, 7.7, 8.4.3, and 8.5.3. They need to be addressed since they could be envisioned by a few unscrupulous groups. Many isolated places on Earth have been used as prisons or forced labour camps (e.g., French Guyana-France, Australia-UK, Siberian Gulags-Soviet Union…) and Mars could be used in the same way, as a potential strategy for addressing societal challenges posed by certain individuals. These off-Earth prisons could provide a return ticket to the prisoners after several years or keep them on the red planet for the rest of their lives. There is also a risk that prisoners on Mars would be used as inexpensive workforce for mining and other time-consuming, exhausting and risky in situ resource utilisation projects, like it is done nowadays in US prisons or in Chinese Uyghur camps, with conditions like slavery. However, within the European regulations, the objective of sending people to prison is to rehabilitate and to reinsert them into society, and these scenarios go in the opposite direction of actual reintegration.

The case for workers who would be sent to Mars for labour-intensive projects also needs to be discussed, as they could be forced volunteers. Indeed, companies would likely offer high revenues to send people to work on Mars (Zubrin, 1996) and

this could seduce people living in harsh economic conditions on Earth. These people would volunteer themselves, without a real alternative, attracted by the money they could make, without having full awareness of the tough working conditions on Mars and all other accompanying risks and challenges. It could also happen that settlers become enslaved by an eventual Martian governance, in case the governance is not respecting basic human rights as defined by the Universal Declaration of Human Rights of the UN (General Assembly 1949)—this is discussed in Sect. 8.5.1.

Production

In a small Martian settlement of about a thousand pioneers, the imperative for industrial activities emerges from the core necessities of establishing, developing, and maintaining the infrastructure, resource utilisation, and scientific exploration.

To maintain a permanent settlement, it becomes increasingly essential to ensure its longevity in a sustainable way. The hostile Martian environment, with its harsh dust storms and extreme temperatures, demands a proactive approach to building up of the infrastructure, and to its maintenance. This entails the production of spare parts, repair materials, and tools on Mars. By establishing local production capabilities for maintenance, the reliance on Earth for resupply is reduced and the ability to address wear and tear of the infrastructure is increased. In this context, local production enables the fabrication of replacement components, conduction of repairs, and reinforcement of buildings, ensuring their resilience over time. The envisioned production landscape on Mars incorporates a network of specialised facilities, dedicated to produce a broad range of supplies and components. These facilities integrate a spectrum of manufacturing technologies, including 3D printing of large structures and small parts as well as sintering and deep-rolling of oxygen-reduced Mars regolith (Hedayati & Stulova, 2023; Mensching et al., 2023; Wong & Pfahnl, 2016). The manufacturing processes operate in synergy, sharing data and resources to optimise production schedules and to ensure a production on demand.

To achieve long-term sustainability on Mars, the principles of closed-loop systems must be implemented for continuous recycling and reuse of resources (Gumulya et al., 2022). Local production aligns with this sustainability goal by minimising waste and ensuring efficient use of resources. In the context of small settlements, production capabilities on Mars play a vital role in supporting scientific research and exploration. With the ability to utilise on-premises manufacturing processes, researchers and engineers can create specialised instruments, tools, and experimental setups tailored to Mars' unique environment. This opens new avenues for deeper exploration and analysis of the planet's geology and atmosphere, and allows more efficient search for traces of a potential Martian form (or Martian forms) of life. Robotic systems are needed for unstaffed missions and tasks, and their maintenance requires production technologies and capabilities for both mechanical and electrical spare parts.

These endeavours are inextricably linked to long-term aspirations for infrastructure development and economic growth. Establishing production capabilities on Mars enables the potential for a sustainable human presence while mitigating the

burdensome and costly resupply missions from Earth (Arnhof, 2016). Moreover, a small Martian settlement can serve as a pioneer in the realm of space-based manufacturing and technology development. The unique Martian environment, characterised by reduced gravity and novel challenges, offers an unprecedented opportunity for groundbreaking manufacturing processes and advanced materials research. These innovations may have far-reaching implications, not only for industries on Mars but also for those on Earth and in the broader expanse of space.

Leisure Activities

Before the establishment of big settlements on Mars, once arrived on such an inhospitable and desolate planet for the first time after a long travel under physical confinement, humans will likely need to handle the sense of loneliness and melancholy in a new stressful environment with a multitude of challenges and risks. Leisure activities and social events might be key for mental health at this early stage of Mars settlement and might catalyse bonding among people on Mars, helping to create a sense of community and eventually a balanced well-behaved Martian society.

The diversity of the Martian environment might also spur creativity. The first inhabitants of Mars will have the opportunity to be pioneers in the development of new arts. Original paintings could be inspired by the extraordinary views of the Martian night sky and landscape, and novel sculptures could be realised using indigenous materials. New music could be created based on the different way the sound propagates in the colder Martian atmosphere made of carbon dioxide, only 1% as dense as the Earth's atmosphere at the surface, in which sound travels more slowly and turns out to be quieter than on Earth, with higher-frequency noises more attenuated than bass pitches. The lower gravity of the planet might incite dancers and gymnasts to create innovative performances and techniques and push new challenges in both indoor and outdoor sports. The extraordinariness of the actual experience of living on another world might be narrated through novels and poems that would constitute a new field of literature, and the new scientific discoveries would inspire more realistic science fiction literature. These experimentations by the first community on Mars could lay the foundations for more organised activities going forward and attract tourism, turning them into sources of revenue for future large settlements.

Resource Prospection

While scientific exploration and mining opportunities on Mars may be the largest incentive for constructing small research bases on Mars (see Sect. 7.2), material and water prospecting for growing settlements will be clustered mostly around sustaining the settlements themselves and becoming growingly self-sufficient.

The resources that can be extracted from Mars will be needed to sustain and enlarge settlements, but most likely, will never become export goods. Therefore they are not the main driver for building large settlements—although some specific goods might have unique value to be sent to the Earth for money for collectors and enthusiasts. With the current knowledge of Mars (see Chap. 2) and its environment, it is difficult to detect a Martian product with a sufficient added value to be worth the costs of extracting, processing, and travelling.

Availability of Resources

The five most important resources that would be needed for a settlement (of any size) on Mars are energy, water, oxygen, construction materials, and food (Cannon & Britt, 2019). Oxygen can be harvested from the CO_2 in the Martian atmosphere or separated from water either via electrolysis or as a natural by-product of food plantations. Water can be extracted from the Martian atmosphere through air mining (Mackenzie et al., 2006; McKay, 1996), or harvested from the reservoirs in the polar caps and in the low-latitude permafrost terrains (Gale & Edwards, 2004)—see for technical details Sect. 7.3).

Hydrated minerals such as gypsum also bear important concentrations of exploitable H_2O and are present in many regions all over Mars. In addition, phyllosilicates do contain water and could be used for numerous applications. Energy can be provided by nuclear power and—depending on the location of settlement and solar incidence—by solar energy.

The availability of these resources suggests that, over time, settlements on Mars could achieve complete self-sufficiency. Martian regolith contains perchlorates and other salts that are toxic for plants and would need to be removed to use the soil as substrate for agriculture. The preferred solution for growing food in large quantities within small space is to use hydroponic or aeroponic substrates as agriculture methods (Poulet et al., 2022; Wheeler, 2004, 2010). In the longer run, organic acids could be used to break down the primary silicate minerals available on the Martian surface (Cannon & Britt, 2019). Specific fertilisers can indeed be extracted from the Martian soil, as well as other useful mineral resources including applications for glass production, water purification, medicine, and construction materials such as tiles, cement, or ceramics (Biswal et al., 2019).

Due to the high CO_2 concentration in Mars' atmosphere, it would also be possible to synthesise various plastics, which would be useful for different applications (Mukundan et al., 2023). Iron to be used as a material for various technical devises and as a catalyst for the process (Xu et al., 2018) could be extracted from ferrous ore in the regolith by crushing and separating techniques (Biswal et al., 2019) (Table 8.1).

Scientific Drivers and Potential Export Goods

One of the main scientific drivers for going to Mars is to understand Mars' earliest geological history and to compare it to Earth's evolution. In-depth exploration will determine the (past) habitability potential on the surface and in the subsurface of Mars, and, ideally, allow detection of traces of extinct or extant form(s) of life on Mars. A larger base would be needed for building and maintaining many exploration vehicles and mobile laboratories that would cover a large study area on Mars. For the study of samples that may include traces of a Martian form of life, specialised laboratories would be needed, including appropriate quarantine capabilities if the presence of an active form of life is suspected (Gale & Edwards, 2004).

Another reason to establish large settlements on Mars is the production of export goods that are, or will become, increasingly important in the future. One suggested export good for Mars is deuterium, to be used as fusion power fuel and could be exported either to Earth or to mining bases in the asteroid belt or space ships near

Table 8.1 Martian identified minerals and their possible applications from Biswal et al. (2019)

Minerals	Applications
Olivine	Refractory materials
Marcasite	Diamond and graphite
Feldspar	Dinnerware, bathroom and building tiles, glass production, flux
Ilmenite	Aircraft parts, titanium metal, reflective pigments, synthetic rutile
Akaganeite	Adsorption of arsenic to prevent pollution
Haematite	Storage devices, electrical components, inorganic pigments
Magnetite	Water purification, biomedical and environmental applications
Goethite	Cleaning chemical elements in polluted water
Saponite	Water decontamination, rubber, cosmetics, and medicine
Montmorillonite	Nuclear applications, cotton fibre, adsorption of heavy metals and dyes
Serpentinite	Architecture, ornaments, asbestos
Illite	Ceramics, tiles
Kieserite	Cleaning hard water, Epsom salt, fertiliser
Gypsum	Cement, plaster of Paris

Mars' orbit (e.g., Zubrin, 2019). Deuterium is the heavy stable isotope of hydrogen, and its proportion compared to the single proton hydrogen atom is five times higher on Mars than on Earth. It could be produced locally on Mars with water electrolysis.

Water itself will be an important export good together with food, raw and refined materials, mining technology (manufacturing of specialised equipment and vehicles for harvesting mineral resources), and other necessities for the exploration of the asteroid belt and beyond (Gale & Edwards, 2004). Mars may also become an important base for maintenance and repair facilities for space travel and exploitation endeavours.

In addition to actual resources, more important exports that Mars will be able to send to Earth are scientific inventions and patents (Zubrin, 2019). Conditions on Mars are more hazardous than on Earth, and Mars settlers will need to be an inventive group of technologically adept people to be able to make the most out of limited prospects of a Mars settlement. Progress comes from constraints and new inventions and adapted processes, e.g., for plant cultivation and other food production processes (e.g., insects) in limited space, resource mining, storage capacity, energy production, storage and usage, material resistance, recycling, housing infrastructure and genetic engineering, which all will be applicable to other places. This can be on Earth, where the environment will become less habitable due to climate change, or to meet the needs for larger food production efficiency due to

overpopulation, or in space, on other human space stations and spaceships. The development of Teflon for space flight, which is now used in our everyday pans in our kitchen, may be the most prominent example of how inventions can be driven by space exploration.

Land Ownership Without Settling

Business cases for Mars focussing on resource exploitation (such as rare earth elements for use on Earth, or deuterium and other materials for space missions starting from Mars), as summarised above, have been widely explored in the literature already. However, one other business and exploration potential is private investments in land itself, building on the wish to own things in a capitalistic world. Up to now, according to the Outer Space Treaty of 1967, any land of any celestial body cannot be owned or claimed by any state or any private entity (see Chap. 4). Thus, this kind of evolution would require a dramatic change in this international treaty. The situation is different than that on Earth, where almost every place can easily be inhabited by humans. "Calling a piece of Mars your own" would not serve as a private settlement strategy, which anyway is not a viable option on Mars (Utrilla et al., 2017). However, one should not underestimate the collector's item charm—best to be compared to "buying" a piece of land on the Moon or paying money to name a star or comet after a beloved person, with increasing value the larger a Martian settlement grows and with more and more people starting to invest in private land—comparable to limited artists collections.

In addition, ideas for resource exploitation on Mars have just started to develop, and various mining opportunities may appear later, such that a large area with high mining potential, if existing, may have a feasible investment potential—depending on the exact declaration of ownership of subsurface materials below a private piece of land. Chapter 4 and Sect. 7.5 discussed in more detail on land ownerships and how land on Mars can be protected from other interest groups (be it other political parties, national claims, private companies, or robbery activities).

Settlers' Selection

The space age since the 1950s has faced several groundbreaking developments, ranging from engineering and scientific challenges to multidisciplinary challenges and commercial endeavours. This has led to increased human involvement in space activities. Mars has evoked widespread curiosity. The most eloquent example is the 2012 Mars One project's search for four people willing to travel to Mars on a one-way trip to establish the first human settlement on Mars. Despite initial financial support and attracting over 100,000 applications in 4 months, Mars One faced criticism and strong opponents. The organisation went bankrupt in 7 years.

Since Yuri Gagarin's historic flight in 1961, 600 humans have been sent into space to date from only 23% of Earth's countries, with the United States, Russia, and China dominating astronaut representation. Currently, the International Space Station (ISS) can host approximately ten individuals. Sending over 1000 or even a million humans to Mars presents unprecedented challenges.

The early selection criteria for space missions favoured professional pilots and aeronautical engineers. Over time, criteria expanded to include diverse backgrounds,

genders, and nationalities. Emerging categories, such as parastronauts, commercial astronauts and space artists, reflect the evolving landscape of human space exploration.

Based on strange and non-scientific wordings, some authors are "envisioning humanity as a multiplanetary species". Even as widely used in this kind of general statement, the word "humanity" is a little pretentious and the word "species" is inappropriate, "community" or "civilisation" must be used instead of it. Such a vague statement means, in their view, that this level of exploration necessitates careful consideration of the traits required for a successful, self-sustaining, and profitable settlement on Mars (Szocik, 2020). Selecting individuals for this venture requires contemplation on qualities crucial not only for the settlement's success but also for a long-term peace and flourishment of human culture exchange between Earth, Mars, and elsewhere, thereby reducing the future risk of humans on different planetary bodies getting disconnected from each other and developing conflicts on a larger scale.

Critical factors include genetic diversity, mental stability, and ethical considerations, all sparking intense debates. Determining suitable genetic makeup and ensuring mental fitness remains complex due to incomplete knowledge about human genetics and physiology. The ethical dilemma surrounding who holds the authority to evaluate and decide on these aspects adds another layer of complexity.

In contrast to former human migrations on Earth driven by the pursuit of a better and safer living standard or by the forced exile of undesirable individuals, the travel to Mars and the subsequent permanent settlement are high-risk endeavours demanding thorough preparation. Settlers must be prepared to face unforeseeable challenges (see Sects. 6.4 and 7.4), displaying not only physical and mental strength but also leadership, teamwork, and effective communication skills.

Defining these skills presents challenges, as their interpretation depends on cultural and political contexts. For instance, determining strong mental health in a stressful, risky environment with limited prospects of returning home poses significant challenges and may lead to existential crises. Identifying suitable volunteers adds another layer of complexity. With 7.9 billion people on Earth, sending 1000–100,000 individuals to Mars represents less than 1‰ of humanity. The selection process, supposedly amongst volunteers, should ideally strive to represent humanity's diversity in genetics, culture, education, gender, and ethnicity.

Different scenarios, strategies, and workforce with different expertise will be needed depending on how many people (1000, 100,000, or >100,000) will be sent to Mars (see further Sect. 8.1.2 and Table 8.2). Principally, the small settlements on Mars should consist mainly of dedicated persons with a focus on exploration, science, and technology in a pioneering spirit. These pioneers will be professionally trained in providing themselves with all minimal life necessities under critical and stressful conditions, often equipped with only the most basic equipment. Small settlements demand explorers, facility managers able to maintain good connections to Earth (including receiving/managing space missions between Earth and Mars), as well as healthcare and life-support system professionals, and experts on activities for recreation and socialisation.

Table 8.2 Non-exhaustive list of professions needed to ensure a decent living standard on Mars for a large human population

Travel and management, between Earth and Mars	Management and long-term survival on Mars
Space travel and transport	**Accommodation and food**
Engineers	Construction workers
Flight crew	Manufacturing workers (for all necessary goods)
Maintenance and logistics personnel	Agriculture workers
Security personnel	**Health**
Management	Health care workers
Economists	Pharmaceutical industry workers
Lawyers	Fitness workers
Decision-makers	
Communication	
Journalists	
Reporters	
Archivists	

Research on Mars	Creation of a high-quality lifestyle on Mars
Laboratory staff	**A new Martian life purpose**
Researchers	Entrepreneurs
Technicians	Tourism professionals
Engineers	**Recreation and culture**
Fields of research available on Mars	Fine art artists
Astronomy	Performing artists
Biology	Entertainment workers
Chemistry	Wellness professionals
Engineering	
Geology	
Mathematics	
Medicine	
Physics	

8.1.2 Large Settlements (up to 100,000 People)

8.1.2.1 Prerequisites

According to an early NASA's reference scenario (1997), three core capabilities need to be demonstrated prior to the establishment of a large settlement (NASA, 1997). First and foremost, the settlement must demonstrate the potential for some self-sufficiency through In Situ Resource Utilisation (ISRU). The ability to harness the Martian environment for resources such as water, minerals and energy, and to recycle them, is paramount for long-term sustainability. Moreover, the physiological and psychological requirements for human survival and wellbeing must be met comprehensively. This encompasses not only the provision of life-sustaining essentials but also addressing the psychological challenges of living in an alien and isolated environment with high risk factors. Humans must not only survive but be able to thrive in that environment. Finally, the risks to the daily life of settlers on Mars must be meticulously assessed and managed to ensure that they are compatible with

the perceived benefits of permanent settlement. Indeed, for a settlement to grow from about 1000 people to 100,000 people and more, the perceived benefit of settling on Mars must surpass the one of living and working on Earth.

Lordos and Lordos (2019) give some selection criteria for a large Martian settlement site. These include factors such as low altitude for safer landings, abundance of shallow subsurface water ice deposits, suitable rock quality for tunnelling, and proximity to critical resources (e.g., metals, silicates, sulphates). Additionally, proximity to areas of scientific interest and natural beauty would enhance the overall appeal and potential for long-term human presence on the Martian landscape.

Salotti (2019) claims that in a large settlement based on a modern-type society (highest level of comfort in his study), autonomy would be reached with 100,000 people with a peak of imported payload mass at 800 tons per year, when the settlement comprises about 20,000 people. This suggests that large settlements could become self-sufficient under certain circumstances such as initial import of goods from Earth, sharing objects between enough people, and on-site manufacturing. Finally, Levchenko et al. (2021) base their analysis on studies about human population dynamics and emphasise that the success of large settlements on Mars would depend on the ability to produce viable and healthy offsprings. This is somewhat a reductionist view, since it does not consider the challenges associated with pregnancy in an irradiated environment (see Sect. 8.3.1.2), nor with children growing up on Mars—providing adequate education to the children, living in a closed and confined space, dreaming of the Earth like their parents once dreamed of coming to Mars.

8.1.2.2 Reasons to Permanently Settle on Mars

"Large settlements" here refer to settlements where people emigrate to Mars for a new life, with no intention of returning to living on Earth. The parallel can be drawn with settlers in America and in Australia, as a contrast with the small settlement case, where people are motivated by a short-term work-related mission.

The first argument, articulated in NASA's reference mission scenario (1997) and supported by Levchenko et al. (2021), is that this venture would align with "human evolution". Mars is the most accessible planetary body beyond Earth-Moon where sustained human presence is believed to be feasible. According to NASA (1997), it would also serve as a safeguard against potential ecological disasters on Earth, such as asteroid impacts or nuclear incidents, and open the doors to broader solar system exploration. According to NASA (1997), by establishing a foothold on Mars, humanity would be better equipped to embark on further expeditions to distant celestial bodies.

The second argument of NASA's reference mission scenario argues that large settlements on Mars would push the boundaries of human exploration, and represent a monumental technological achievement that would not only benefit those living on Mars, but also enhance life on Earth through the development of cutting-edge technologies and novel applications of existing ones.

The third argument, supported by Levchenko et al. (2021), but critically discussed by Stoner (2017), Schwartz et al., (2021) and Puumala et al. (2023), is inspirational: Mars' permanent settlement would offer unparalleled inspiration and this bold and imaginative endeavour would challenge human capabilities, could motivate youth, foster technical education, and unite nations and peoples worldwide. It would symbolise human achievement on an unprecedented scale, serving as a testament to the power of collaboration and scientific progress (Levchenko et al., 2021; NASA, 1997).

Additionally, as noted by Levchenko et al. (2021), establishing a presence on Mars could confer political and economic leadership to the involved countries and organisations. This leadership would carry geopolitical significance and could translate into economic advantages (Levchenko et al., 2021). Many scenarios advocate that it would be necessary to trade goods and services between the Martian surface and Earth in order to be viable in the long term and cover import costs of goods that cannot be manufactured on Mars (Cannon & Britt, 2019; Zubrin, 1996). Cannon & Britt (2019) envision that about 5–10% of the future Martian GDP would be based on the trade of Mars-grown produces. This would require building the necessary infrastructures ahead of settlement and thus significant upfront costs (Cannon & Britt, 2019). Zubrin (1996) claims that trading with Earth would be the rationale of a permanent settlement on Mars since it could address labour shortages, leading to better-paid workers in the Martian settlement. In this frame, he foresees exporting deuterium with a potential annual revenue of 10 billion dollars in a 200,000 people settlement (Zubrin, 1996). Finally, according to Zubrin (1996), Mars settlements could provide workforce to support asteroid mining.

Such settlements could also serve as a gateway to further exploration within our solar system (Zubrin, 1996). Lordos and Lordos (2019) emphasise the potential for Mars settlements to promote peace and global collaboration by highlighting the common goals of humanity and optimising human skills in the face of environmental challenges (Lordos & Lordos, 2019). Zubrin (1996) goes further and sees Mars as humanity's new frontier, offering a remote environment capable of birthing a new branch of human civilisation (Zubrin, 1996). Stoner (2017) also disusses ideas that large Martian settlements would provide opportunities for experimenting with alternative social and political structures, fostering innovation in the way humans organise and govern themselves. He dismisses these ideas, saying that these arguments are weak and cannot be the moral or prudential impetus for colonizing Mars.

An additional aspect to consider is that, after living for extended times on Mars, people may be unable to return to Earth, due to weakened muscular and bone mass and skeletal strength caused by habituation to the low gravity environment. This certainly would be the case for children who are born and grew up in low gravity conditions (Janhunen, 2020), at least if there are no preventive measures to ensure the good health. This would make it impossible to these Martian born people to visit the Earth, or to return to Earth if desired. This must be considered if the venture turns to be a long-term, permanent settlement.

Moreover, consideration of large, permanent human settlements on Mars raises several issues, including scientific conservation, psychological, biological, and

cultural challenges, overpopulation, resource management, and potential conflicts. Marino (2019) raises concerns about humanity's ability to adapt psychologically to an inhospitable planet and the potential for resource overexploitation and environmental damage, drawing a parallel with planet Earth. Overexploitation, overconsumption, inefficient waste management, and environmental degradation could mirror the challenges faced on Earth (Marino, 2019). Torres (2018) cautions that expansion into space, including Mars, may lead to conflicts and resource wars, perpetuating a state of fear and potentially devastating conflicts among human factions (Torres, 2018), with international tensions and hostilities both on Earth and on the Martian territory.

If Mars is treated like a place to isolate people deemed problematic for society and the planet is populated with convicts in the first place, this may lead to the development of mafias, other similar organisations, or local or general dictatorships. Large settlements would then be based on high crime-rate societies, or an outlaw place like it has been seen in places on Earth where convicts were sent in the past.

In conclusion, the establishment of large Martian settlements presents a plethora of opportunities and challenges. This endeavour is rooted in the search of our industrial countries to foster the technological advancement and to enter global cooperation or, at the opposite, to hold a leadership. Such large projects are also fraught with political, ethical, cultural, and environmental considerations. The complexity and the international implications of such a step in the space exploration warrant careful prior deliberation.

Production

The need for industrial activities in permanent settlements of more than 100,000 people on Mars arises from the fundamental needs of self-sustaining resource utilisation as well as long-term goals on infrastructure development and economic opportunities. The establishment of production capabilities on Mars can unlock the potential for sustained human presence and minimise costly and logistically challenging resupply missions from Earth.

On the road towards self-sufficiency, the utilisation of Mars resources is an essential stepping stone. Local approaches for resource utilisation allow scalability and expansion of industrial activities on the planet. As the settlement grows and evolves, the availability of local resources ensures the capability to meet the increasing demands of a growing population. Resilient and autonomous production capabilities are needed for long-term sustainability of future Martian activities. The production of goods on Mars is closely tied to the concept of in situ resource utilisation (ISRU) (Gumulya et al., 2022). ISRU involves extracting and utilising Martian resources such as water, minerals, metals, and atmospheric elements to produce vital commodities like fuel, breathable air, water, building materials, and even food (Zubrin et al., 2011). Reaching the absolute level of sustainability on Mars requires reducing wastes of any kind and recycling them up to the ideal point known as "Closed Loop Design". No element or component which can be used as a resource escapes the Mars settlements. Everything is recycled in a useful product to be inserted back to the system for repetitive use (Amini et al., 2022).

For expanding human habitats on the planet, the on-premises production capacity and capability is essential. Manufacturing capabilities enable the production of building materials such as bricks, metals and composite materials, which can be used to construct resilient and habitable structures for long-duration missions and eventual settlement. The development of infrastructure construction capacities is therefore necessary to sustain a long-term human presence (Amini et al., 2022). This includes establishing power generation systems, transportation networks, communication systems, and all essential facilities required to produce consumable items and support a functioning society.

Production capacities on Mars can serve as a stepping stone for space-based manufacturing and technology development. Commercial production activities on Mars could open new economic opportunities and industries. Private companies can develop and commercialise technologies, services, and products specifically tailored for Martian conditions. This includes areas such as resource extraction, manufacturing, construction, transportation and tourism, leading to economic growth and job creation.

With regard to the return of resources from Mars to Earth, no economic benefit can be derived from the transportation of raw materials (Stoner, 2017). Resource-rich asteroids, if identified, could already be reached with less fuel than the surface of the Earth's moon, making Mars an unlikely planet for importing materials (Gumulya et al., 2022). In contrast, there may be a market for made-on-Mars products, as a unique selling proposition and the marketing behind it could create high demand.

Leisure Activities

Large settlements on Mars might receive significant revenue from tourism, which might help maintain their self-sufficiency (Biswal et al., 2019). Mukundan et al. (2023) propose four schemes for tourism, based on duration of stay, amount of propellant used, and frequency of travels in a year, estimating revenues between 5.5 billion dollars in a year for a total stay of 95 days and 12.5 billion dollars in a year for a total stay of 450 days once such businesses are operational in a fully developed settlement. A question arises on the number of people on Earth which could afford such travel for leisure trips. It is worth noting that in any case the round trip would take from a hypothetical minimum of 2 years (opposition transfer) to 3 years using the classical Hohmann like transfer (conjunction transfer).

A variety of businesses would be needed for providing hospitality services to the tourists landed on Mars from Earth, e.g., passenger terminal for disembarkation from transport ships, lodging, restaurants, things for visitors to buy, access to places visitors want to see and things they want to do, Mars-unique sports and amusement park experiences (Gale & Edwards, 2004). Tourists might be customers for food locally produced on Mars, a business that would contribute to a significant fraction (likely from 5 to 10%) of Martian GDP according to Cannon and Britt (2019). Similarly, tourists might be customers for novel art pieces produced on Mars.

Another important source of revenue could come from video broadcasts of scientific achievements, broadcasting rights, Intellectual Property rights, entertainment

content, and events (Levchenko et al., 2021). Mukundan et al. (2023) studied the patterns of broadcasting for events of the magnitude of the Moon landings, the Olympics, and the launches of the ISS, and designed a pattern for the broadcasting of events such as the landings of tourists and settlement of dwellers on Mars, and asteroid mining. The author estimated a revenue of about 13.75 billion dollars for 75 broadcasted events during the first 6 years of settlement.

Moreover, for such outreach businesses it would be necessary to develop high speed communication technologies for the Mars settlement, and the relative transponder capacity could be sold for a fee to commercial customers (mainly asteroid and Moon mining companies) or to government and public agencies for scientific missions (Utrilla et al., 2017).

Resource Prospection

The exploitation potential of different resources as well as the geological exploration of potential mining sites may already be sufficiently exhausted by small settlements, and resource prospecting on large settlements will be mostly limited to sustainment of the settlements. Starting from a specific size of settlements, it will be necessary to evaluate whether they would be possible on Mars or not due to increasing demand of limited resources, including the need for different materials or adapted technologies, as compared to small settlements (i.e., large greenhouses might need to use inflatable technology to make the scale of the building process realistic). The larger the settlement grows, the more important becomes the efficient recycling, due to limited resources, i.e., a "Closed Loop Design" (Amini et al., 2022), even though Mackenzie et al. (2006) argue that a recycling rate of 100% may not be needed due to the extraction potential of gases, water, and minerals from Martian air and soil. A large settlement would, however, require the construction and maintenance of larger spaceports for launch of missions to deep space.

Settlers' Selection

When expanding the settlements on Mars to more than 100,000 people, the demands on the expertise of the humans, the general living conditions and social structure will increase correspondingly. Meeting the needs of a larger population involves ensuring safety, health, and sustainable occupations to maintain the Martian base and the communication with Earth. The perspectives for creating a new, self-sustaining complex human society will grow in various ways, some of them may even be unforeseeable.

Compared to small settlements, large settlements will facilitate smoother task distribution among individuals with diverse expertise, enhancing the quality of life on Mars. This approach opens doors for non-scientific professionals to contribute to Mars development. The shift from individual survival tasks to collaborative efforts accelerates progress, fostering innovation and entrepreneurial endeavours. In the long term, this may be beneficial for all humans not only on Mars but also on Earth, and, in a longer perspective, for future human settlements elsewhere in space.

Depending on the size of the large settlement, the demand of different expertise in different fields may vary. It would range from basic purposes related to travels between Earth and Mars and research of the Martian planetary science and

exploration of its resources, to various requirements for a decent life with inspiring activities during the free time, including a democratic management and a sustainable economy (Table 8.2). The expertise and demands in Table 8.2 demonstrate how complex and tedious it may be to build an entire new society from scratch, in a relatively short time and in a stressful, tough environment like Mars. But this does not have to be an impossible task, if all aspects are planned as well as possible.

However, before planning for larger human societies on Mars, including human reproduction, it is necessary to first assess the impact of Martian conditions on health. The risks of chronic diseases, and the life expectancy of future generations must be examined, as well as contingency plans for returning humans to Earth (in a context of overpopulation, climate change, and political conflicts).

8.2 How to Settle Permanently on Mars[2]

Although permanent settlements on Mars are still a futuristic plan, several private initiatives have proposed to transport a human community, with the intention to establish permanent multigenerational settlements there. A widely known vision of such an endeavour was the Mars One project in the 2010s. While it caught much public attention, it faced severe technical and financial issues as well as critique due to its unethical basis, being an one-way mission (O'Callaghan, 2019). Within the community of passionate people, several conceptual plans and discussions on permanent Martian settlements have taken place over the last years (e.g., the Mars Society Competition (Anglada-Escudé et al., 2021)). One of the most prominent projects at the moment has been voiced by Elon Musk, the CEO of SpaceX, who has a vision to build a community of a million people on Mars within a hundred years (Cannon & Britt, 2019; Hollander, 2023; Musk, 2018). This vision entails private individuals and communities on Mars that are able to establish a local economy, where the daily consumables and services are exchanged between the different entrepreneurs, also accommodating and serving tourists. The economic activity would allow the community to grow sustainably, and also to be capable of interplanetary economical exchange (Anglada-Escudé et al., 2021; Cannon & Britt, 2019; Hollander, 2023; Musk, 2018). However, major concerns have been expressed about the viability of a large and permanent community (reviewed in Puumala et al., 2023; Szocik, Abood, et al., 2020; Szocik, Wójtowicz, et al., 2020). A major concern relates to its ability to produce an adequate amount of food, as well as all the daily necessities and utensils for survival. In addition, various health issues have to be considered (see Sects. 6.4, 7.4, and 8.3).

The design of such a large permanent settlement comes with numerous technical challenges, including maintenance of a safe environment for humans to survive,

[2] This section is authored by Elias Chatzitheodoridis, Akos Kereszturi, Kirsi Lehto, Gisela Detrell, Alexandros Krassakis, Natuschka Lee, Carmen Possnig, and Mikko Tikkanen.

providing radiation protection, sustainable agriculture and energy production, all of which need to be solved at large scale. The concept of a permanent high population on Mars would require not only the bare survival of the population, but also various societal and wellbeing services (e.g., health care, education, recreation/leisure activities, security for retirement), and possibilities for individual and collective improvement of skills and knowledge, to ensure an adequate quality of life. A big settlement will not just be a research facility, but a city and community, existing independently from the population on Earth. The financial and political feasibility and ethical issues of such ambitious projects are critical aspects to consider.

The first "nodules" of a big settlement will surely be established via the same or similar procedures as have been described for small crewed bases (see Sect. 7.3): a gradually expanding infrastructure, constructed in situ. A certain critical mass of materials and equipment will first need to be brought from Earth, but the feasibility of a settlement will highly depend on its self-sustainable operation and growth capabilities. Thus, suitable technologies for recycling and in situ resource utilisation, which might have been previously developed for smaller bases, become a key element. These technologies will be required for the collection and processing of materials (including water), production of energy and fuels, and setting up efficient food production (as described in the Sect. 8.2.1.1). Beyond that, habitat configuration, transportation, and manufacturing will be key elements of the settlement design.

One major problem for the development of a permanent infrastructure will be the wearing out of all its parts, which might happen quite fast due to the harsh conditions or natural catastrophes. UV and particle radiation, large temperature variations, sandstorms, and dust can easily damage solar panels and wind turbines, nuclear reactors, valves and connectors of gas and water pipes, heavy outdoor machinery, robotics, and electronics. Thus, new equipment, components, and spare parts will be continuously required, and this need is increased by the ongoing need to expand the facilities for new citizens. Thus, new machinery, equipment, and spare parts must be produced on-site. The demand for on-site production can be accomplished using 3D printing technologies (see Sect. 7.3.2), which in turn require suitable materials to be available.

The initial habitat should be designed to function as efficient as possible, and the construction should use minimal energy and raw materials. Consequently, the activities on Mars should be more efficient than those that are applied for building and managing infrastructures on Earth. A focus should lay on closed-loop reuse of durable materials. Planning will need to be more forward-looking than it is currently on Earth, as a consistent supply of resources and spare components will be needed. Thus, the lifecycle of each component (every switch, plate, battery, shoe, etc.) should be followed in an online system together with their expected lifetime and further reuse after failure or interrupted use.

8.2.1 Planetary Resources and Level of Autonomy

To make a human settlement self-sufficient, at least partly, and sustainable in any new settlement location, it must become capable of producing all necessary life support supplies, i.e., oxygen, water, and food, by using the available local resources. By producing all these supplies locally, people "live off the land", as ancient emigrants and new settlers on Earth used to say. This will be based on the use of local Martian water, carbon dioxide and nutrients to support photosynthetic organisms to produce biomass for food and other purposes, and oxygen for breathing (Verseux et al., 2016).

8.2.1.1 Production of Water, Oxygen, and Food as Life-Support Supplies

Water is a necessity for life on Mars, as everywhere: hydration, humidifying the air, food processing and cooking, as well as sanitation. Water can also be used as a source for oxygen for respiration and for fuel (liquid oxygen in combination with liquid hydrogen serves as combustible fuel and as rocket propellant). Mukundan et al. (2023) estimate that a settlement of 1200 inhabitants has a daily need of 11,520 kg of water and 3360 kg of oxygen. These consumables can be recycled within the habitats and the greenhouses, thus reducing the need for additional supply (apart from maintaining an adequate level of the stock and increase it as the population is growing). However, significant amounts of oxygen and hydrogen are used as fuel for vehicles, machinery, and rockets, and water used in this way will not be reusable. Thus, water harvesting, processing/purification, and electrolysis facilities are needed in the vicinity of the habitat, in addition to cryogenic storage facilities for the produced O_2 and H_2 gases (Heldmann et al., 2022; Mukundan et al., 2023). Water prospecting and harvesting, as explained in Sect. 7.3, will be a key element within a sustainable settlement. As consumption grows, water might need to be transported over larger distances, requiring efficient transportation. Water is a highly valuable asset, and its use and distribution must be well regulated.

The local water will also serve as the easiest and most energy-friendly source for oxygen. However, space agencies have given significant attention to producing oxygen from other sources as well. This goal may be achieved by electrolytically breaking down the chemical bonds of the atmospheric carbon dioxide (CO_2) and releasing the contained oxygen. A technology that has been demonstrated to successfully work in situ on Mars is the MOXIE instrument aboard NASA's Perseverance rover (Hoffman et al., 2022). Currently this instrument produces oxygen gas at about 6–8 g/h rate when operated at about 800 °C. The full release of oxygen also releases carbon, which however must continuously be removed to avoid choking of the instrument. Electrolytic breakdown of mineral oxides into oxygen gas and pure metals has been also extensively investigated (Lomax et al., 2020). The method requires extremely high temperatures to deoxidise minerals with an efficiency of 96% of recovered oxygen in a bath of an electrolyte ($CaCl_2$), a sintered regolith cathode and an SnO_2 anode. Metal alloys are also recovered after the process and can be used for tool construction.

More environmentally friendly technologies include the production via plant photosynthesis, producing oxygen in addition to food. However, distinct cyanobacteria or algae species may be more suitable than plants for efficient and economical O_2 production, as they would be able to grow in most extreme environments including certain levels of radiation, anoxic conditions with high CO_2 concentrations, and more variable temperatures than crop plants, thus allowing their production in the least protected exterior parts of the habitats. Still, the survivability of even these modest organisms in Martian conditions needs further studies (Verseux et al., 2016).

A very sustainable way of producing oxygen can be achieved by using reactive oxygen species (ROS), such as metal superoxides (i.e. KO_2), peroxides (i.e. Na_2O_2), and hydroxyl radicals ($^{\bullet}OH$); all of them present in the Martian regolith. All ROS compounds are highly toxic because they are extremely reactive and rapidly break bonds of organic molecules. Mars contains more than one type of ROS, a suggestion coming from the re-interpretation of the Gas Exchange Experiment (GEX) of the Viking lander mission in 1976 (Klein, 1978; Klein et al., 1976). According to this experiment 1 cm^3 of Martian soil released 770 nmoles of oxygen gas. ROS generally form on the surfaces of mineral grains after long irradiation by cosmic rays and UV radiation, especially on airless celestial bodies such as the Moon, and on planets with thin atmospheres such as Mars, or by the fracturing of crystal grains and the friction between them, as happens during dust storms. Consequently, planetary dusts carry high loads of ROS, which in contact with water produce immediately hydrogen peroxides. From these oxygen gas is released in contact with a strong oxidiser such as manganese dioxide, occurring as the mineral pyrolusite, MnO_2 (Georgiou et al., 2017, 2022). The water can be also recovered, and the soils remediated from the toxic chemicals. The soils will be reactivated by ROS when they are exposed again to radiation or during dust storms. This process leads us to the concept of "oxygen farming" on planetary bodies (European Space Agency, 2022; see Fig. 8.1)

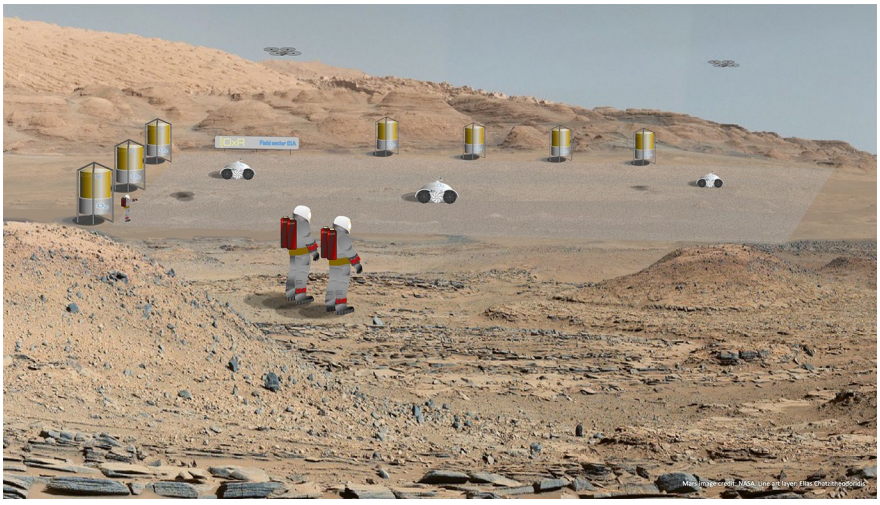


Fig. 8.1 "Oxygen farming" on Mars. Artistic impression and line-art synthesis on a NASA's panoramic image from Mars (by Elias Chatzitheodoridis)

and can constitute an extremely sustainable way of producing oxygen gas from the Martian regolith. From the Viking results, it is calculated that in situ processing only the upper 1 cm^3 of a hectare (100 × 100 m^2) of Martian soil (about 150 tons of soil, which is not excavated or need to be transported), about 77 moles of gas oxygen can be produced. With 20 moles of daily consumption of oxygen per astronaut, the produced volume of Martian oxygen can support almost four persons per Martian day. This is a significant figure, if we consider that oxygen production can be fully automated and continuously maintained, as the soils are reactivated when they are again irradiated for certain periods of time. The processed soil is left behind and no polluting products are formed. Rather, the soil is fully remediated from ROS and becomes usable for crop production, securing the sustainability of this concept for life support of the astronauts. Additionally, the entire process does not require energy, except for the mechanical parts for collecting the upper layers of regolith and for processing it; this process produces thermal energy since the reaction is exothermic. Both the low energy requirement and the release of energy from the exothermic reactions can render the "oxygen farming" concept very appropriate for providing extended mobility, since reactors installed on small autonomous vehicles can continuously produce oxygen and provide autonomy over long distances, allowing astronauts on Mars to reach places far from their habitat.

Food Production

The only natural way for large-scale food production is by photosynthetic plant or microbial cultivation. However, setting up self-sustaining plant production on Mars is quite challenging. First, plants require adequate light energy (100 micromoles of quanta/m^2/s, or higher), but do not tolerate high UV, particle radiation, nor freezing temperatures or strong daily temperature variation. They do not tolerate high levels of mineral salts or reactive oxygen species (ROS molecules) in the growth substrate, meaning that the Martian regolith or water reserves cannot be directly used as their growth substrate, as reviewed in Puumala et al. (2023) and Verseux et al. (2016). Martian soil needs to be de-contaminated before use. The plants need also a radiation-shielded and insulated growth habitat (although not with as high specifications as humans). This habitat needs to be adequately pressurised (e.g., to 0.5 atm) to maintain liquid water and provide adequate partial pressure of CO_2, efficient illumination, and all the necessary macro- and micronutrients. In practice it is difficult to use sunlight directly as an energy source, because the average photon flux is lower than on Earth (at the equator of Mars the flux is comparable to Alaska), and the thick greenhouse cover material (glass, aerogels, and other radiation-shielding materials) would noticeably reduce the available light. Economical illumination of the plant cultures can be obtained using LEDs for artificial light or by collecting sunlight, which would then be piped down maybe through fibre optic cables, or by mirrors into the (subsurface) greenhouses (Cannon & Britt, 2019).

Further challenges with crop production are the rather long growth periods of higher crop plants (stable crops such as grains, potatoes, vegetables), which are in the range of 2–4 months from seeding to harvest under optimal conditions, and that a portion of the crop is unusable for food (stalks, stems, leaves, roots). Productivity

of these crops is rather limited, as the typical maximal yields obtained in terrestrial production are in the range of 0.8 kg/m ^{2} for small grains, 5 kg/m^2 for potatoes, and 10 kg/m^2 for tomatoes per season (Richie et al., 2022). Using the well-known terrestrial greenhouse production systems (Mukundan et al., 2023), we can estimate that 20,000 m^2 of greenhouse area would cover most of the nutritional needs of 100 people. For a scenario envisioning 1200 settlers on Mars, 240,000 m^2 (24 ha) of greenhouse would be needed. There will likely be a need to regularly import certain foods, which cannot be grown in situ, from Earth (Mukundan et al., 2023). One obvious reason for this is that some food plants depend on insects (e.g., for pollination). Of course, part of the pollination needs can be performed manually by humans or by even robots, but pollination by real insects is far more efficient than those performed by humans or robots (Miyak, 2017). This highlights the further problem or challenge of plant production: it would be very labour-intensive, unless it can be automatised to a high degree.

The production efficiency can be improved by using vertical farming, i.e. by culturing plants on tables in multiple overlaid layers, based on optimised water-nutrient substrates and artificial AI-controlled and optimised LED illumination technology (Touliatos et al., 2016; Van Delden et al., 2021). Photosynthetic efficiency in plants is influenced by all environmental conditions such as water availability, temperature, relative humidity, nutrient levels and balance, and obviously also the air pressure, partial pressure of CO_2, gravity, the light spectrum and last but not least, by sophisticated interactions between plants and microbes (Karpagam et al., 2023). Ultimately, the efficiency of photosynthesis is the result of many factors. The best outcome (in human-made conditions) could probably be achieved through learning AI-based optimisation, seeking the best efficiency from light to carbon dioxide fixation, coupled with the available technology and resources. This type of optimisation is likely to improve the energy efficiency of indoor farming by tens of percent (Foyer et al., 2012).

Interestingly, a large variety of useful and nutritious macromolecules are produced by different species of algae and cyanobacteria, which are photosynthetic primary producers. Indeed, such micro-organisms would be very suitable as nutrient and food producing organisms in space conditions (Detrell, 2021; Detrell et al., 2019; Verseux et al., 2016). These organisms have multiple benefits in terms of culture technology: They can be grown either in continuous or batch cultures in closed and fully controlled bioreactors, solely dependent on suitable culture medium and light for energy resources. It should be kept in mind that their products are not limited only to the natural products of the organisms, but that they can be engineered to produce, for example, a fully synthetic protein or any other compound of nutritional importance. The products can be extruded from the cultured cell into the culture solution or can be harvested from the algal biomass (multiple methods already exist for the processing of edible materials). Several experiments with microalgae and cyanobacteria have been carried out in space, including two experiments focused on the development of a photobioreactor as part of a Life-Support System (Detrell et al., 2020; Poughon et al., 2020). Further research on life-support

system photobioreactors and how to adapt them to work under reduced gravity conditions (Detrell, 2021) is still required.

In addition to photosynthetic microbes, heterotrophic microbes such as yeasts, fungi, or bacteria can produce edible biomass and/or other valuable products. They can be used, e.g., as a growth substrate to higher plants, or as part of the recycling process of waste management or, upon molecular engineering, to produce completely new valuable bioproducts (proteins, medicines, polymers, plastics, etc.). Similar to algae and cyanobacteria, these organisms can be grown in controlled bioreactors on a simple well-defined growth substrate. Likewise, cell-culture production of cells derived from different domestic animals or from crop or medical plants will provide new and efficient means for production of animal or plant proteins, or medicines (Verseux et al., 2016).

A further application of the different microbial cultures is to combine different species in a closed-loop circular production and degradation system, such as in the "Micro-Ecological Life Support System Alternative" (MELiSSA) life-support system which is now being automatised and optimised for long-duration space missions (Lasseur et al., 2010; MELiSSA Foundation, ESA, 2023). This system is an interlinked infrastructure containing several bioregenerative units, some of which are plant production chambers that produce edible biomass. Others are chambers containing various organisms that step-by-step break down the waste fractions of the produced biomass. The degradation produces carbon dioxide, water and nutrients, which are again fed back to the plant production chamber, to drive the biological production in a quasi-closed-loop circularisation of the resources

Another feasible and realistic option for food production on space missions is to use insects as edible material. Insects and other arthropods have been used as food on Earth for a long time by different ethnicities. Recently this has also been suggested as a fully realistic option for the Western world in order to combat problems caused by overpopulation and to find new ways of sustainable food production. Compared to plants and higher animals, insects contain a higher amount of protein, including essential amino acids and fatty acids, do not require large cultivation areas or sunlight, and have a short life cycle (thus, food production can be made faster). Further, the biotechnology of insects can be extremely useful for many other purposes on a space station, from efficient biodegradation of wastes to production of compounds such as chitin (useful for, e.g., medical applications), textile (silk), or even methane (Liu et al., 2022) and of fixed nitrogen (ammonia or nitrate) by using symbiotic microbes. Some insects are also tolerant against stressful conditions like radiation and may therefore prove to be useful models for studying the adaptation of animals in space. Last but not least, insects may be used also as pets for psychological comfort if other, larger animals cannot be provided on a space mission.

Departing from the available ingredients, food may also be produced by 3D printing (Santhoshkumar et al., 2023). This can have several advantages such as less issues with shelf-life of the final product, prospects of personalised food, customised diets with a higher potential for delightful and good-looking food, minimisation of waste, and the pleasantness of instant on-site food preparation.

In addition, even more novel means for production of edible biomass are currently being developed, using isolated reaction components of the molecular machinery of photosynthetic organisms, the solar energy, CO_2, water, and semiconductor materials, or artificial photosynthetic reaction systems (Tu et al., 2023; Yang et al., 2021).

8.2.1.2 Energy Sources, Harvest, and Storage

Living in a completely enclosed and sealed habitat requires a lot of energy, yet estimates for actual need vary with different references. While Amini et al. (2022) estimate that the energy requirements in the early scientific bases to be about 30 kWe per crew member, NASA estimates the need to be much lower, i.e. about 1/3 to 1/4 of this amount. Mukundan et al. (2023) estimate that 6.1 MWe (3.5 kWe/person + facilities in operation) is needed to sustain a 1200-people settlement, stating that the lower energy need per person may be achieved by shared facilities and infrastructure. This energy production could be achieved with 30 nuclear reactors, which are improved versions of the NASA Kilopower reactor, each generating 100 kWe, and supported with 126.3 m^2 of photovoltaic cells (assuming 100 W/m^2 and 33% efficiency) (Mukundan et al., 2023). The most recent NASA design reference missions are based on the use of 160 kW fission reactors (Rapp, 2023).

The assumed energy consumption levels of smaller habitats may be considered as a guideline to estimate the energy needs of larger permanent settlements. The energy need may not be directly scalable between different sizes of habitats or communities: first, a lot of synergy and energy conservation may be obtained by building bigger infrastructure, and by housing the communities in larger habitable units. On the other hand, the energy use per person may increase because the permanent settlers may require higher living standards than the first pioneers arriving to Mars. Still, it is clear that maintaining a habitable condition on Mars will always consume considerable amounts of energy. At this stage it can be assumed that electricity will be produced primarily by nuclear power, and that solar panels would be used as a parallel, additional, or back-up energy source. For transportable fuels (to be used in vehicles and rockets) the electricity will be converted to H_2 and O_2, or methane and O_2, via electrolysis of water, or by using, e.g., the MOXIE technology (see Sect. 7.3.2).

However, the primary energy sources (be it either nuclear or solar) have each their technical challenges. The first problem is that energy production and distribution need to be scaled up significantly to provide adequate supply as the settlement grows. If it were fully produced by solar panels, a total of about 340,000 m^2 (or 0.34 km^2) of panels would be needed for a 1000-person community. The solar insulation is varying day by day because of the dust content. Another problem with solar power is that it may be blocked and practically turned out of use during sandstorms, as mentioned in Sect. 7.3.2. This problem could be alleviated by placing the solar panels into areostationary orbit, and beaming energy to the surface using microwaves (Hughes & Soldini, 2020). However, it is not known if it would be possible

to lift up such exceptionally large solar panels from the surface and position them in orbit. This would require a very advanced launch and engineering facility on site.

Compared to solar power, nuclear power is a long-term energy resource which can be installed and utilised almost unattended. Once again, its limited capacity becomes a problem. The most recent NASA design reference missions are based on the use of a 160 kW fission reactor, but several reactor units of this size would be required to maintain a large community. Further problems are related to the large nuclear energy units being high precision technology and materials, as well as uranium fuel and the waste-deposition sites being not available on Mars. Therefore, the community will depend on their continuous transport from Earth for unforeseeable times.

8.2.1.3 Mineral Resources

In addition to water and energy, many other resources will be required to build the settlement and ensure sustainable growth of the population. A first approach to identify resources to be used on Mars, is to look at the materials that are required on Earth and evaluate if those materials could be useful or necessary also on Mars, whether they can be found on Mars, and if not, which alternatives could be used.

All materials and processes should be tested for durability in the harsh environment of the Martian surface, especially for mechanical durability and resistance against disintegration in the extreme conditions. Some materials, e.g., plastics, would become usable only in the habitat interiors where they are not exposed to radiation which causes their disintegration, or to the ultra-cold temperatures, which make them brittle. However, different bio-degradable plastic-like materials produced from various organic materials, such as plants, bacteria, and fungi could become useful for multiple purposes.

Metals, alloys, and glasses composed of local raw materials make better technological materials for building durable infrastructure, and it is well known how to reuse and reform them. Thus, priority should be given in constructing modular parts from these materials, not only to allow better utilisation and application during construction, but also to allow rapid repair of any infrastructure.

Various metals are needed to produce mechanically strong structures (e.g., from steel or iron), while other metals are needed for electronics. The main question in these aspects is whether various ores or ore-like concentrated resources exist on Mars. Because their formation processes on Earth have not been identified on Mars, such ores may not be present (Table 8.3).

The main types of ore minerals occurring on Earth are of sedimentary origin, produced either by magmatic-hydrothermal or weathering processes. Although the specific locations of such sources are unknown on Mars, we expect volcanic and magmatic centres to be concentrated around several large regions (e.g., Tharsis, Elysium, northwest of Hellas), where magmatic plus hydrothermal origin ores may also occur. Importantly, finding subsurface ore-deposits on Mars will be more difficult than on our planet. On Earth, these deposits sometimes get exposed by

Table 8.3 Most important minerals used in industrial processes on Earth, their typical occurrence as ores on Earth, and possible occurrence on Mars

Element	Usage (on Earth)	Occurrence (on Earth)	Expectations (on Mars)
Al	Lightweight structural materials	Subaerial wet weathering products	Poorly crystalline aluminosilicates were found (Michalski et al., 2006) related to possible former leaching process. Might occur at specific early wet weathering sites (Ehlmann & Dundar, 2015)
Cu, Co	Electric devices, motors, cell phones, wires	Hydrothermal processes connected to magmatic bodies	Possible existence in magmatic bodies and around hydrothermal systems
Fe, Mn	Alloys, steel, machinery components buildings, structural materials	Weathered laterite soil, old banded iron formation sediments, magmatic and volcanic magnetite crystals	Expected to occur at magmatic sites, might occur as weathering products. Occurs in abundance on the surface in the form of the hematite spherules (Misra & Acosta-Maeda, 2018)
Ni	Steel making, alloy making, batteries, hard disks	As ore in laterite soils (as limonite), and sulfides (Ehlmann & Dundar, 2015)	Limonite is present in the regolith as weathering product but in low concentration, deep magma bodies exposure not known but possible. Present in meteoric materials (Yen et al., 2006)
Rare earth elements: up to 17 different elements	Electric devices, wind turbine rotors	Occur under specific conditions, associated to carbonatites and pegmatites (Dushyantha et al., 2020; Jaireth et al., 2014)	Unknown occurrence, possibly less concentrated than on Earth as the tectonic activity where alkaline magmatism is present on Earth is missing on Mars
Li	Batteries	In latest magmatic fluids and in evaporitic minerals; in clays after hydrothermal alteration (Zhang et al., 2022)	In carbonate rocks of evaporitic origin, and in clay minerals of sedimentary rocks. Detected only in trace amounts
Nitrogen	Important for plant nutrition, for organic material	Atmosphere, nitrate minerals	Atmosphere (N_2, NO—but very scarce!). Nitrates in soils (see Chap. 2, also scarce) Additional supplies need to be transported from Earth!
Phosphorous	Important for organic material	Phosphate minerals	Abundant in clay minerals (see Chap. 2)

tectonic processes or erosion of thick overburden masses, both of which are non-existent on Mars. It is also expected that magmas and lavas are less evolved on Mars as compared to Earth, due to lack of global plate tectonics; however, it is not known whether there would be some other concentration processes on Mars that are different from Earth. Sedimentary deposits might also be found in areas extensively

processed by water, such as floods in craters, e.g., the Jezero Crater. However, the extent of these deposits is unknown.

Although access to all minerals appears necessary in due time, one of the most urgent is the need for lithium due to its use in rechargeable batteries. Lithium is one of the first elements in the solar system and is found on planetary bodies. It is not an abundant element on Earth or in the Solar System, but can be found in hydrothermal altered minerals such as clays, and as a dissolved mineral in hydrothermal system. It is present in Martian meteorites—in secondary minerals such as carbonates and clays (Chatzitheodoridis et al., 2014). It is thus possible to find and extract lithium from large sedimentary deposits of clay minerals, which are now known to exist on Mars. Hydrothermally altered areas may harbour lithium as well.

Considering the high cost for transport from Earth, any materials that are needed and used on a larger scale and for a longer time span must be obtained from either Mars or its vicinity. The first step in the exploration of local resources is the prospecting of desired mineral deposits—a process which under terrestrial conditions may take decades, and depending on the concentration of the metal be expensive to retrieve. If a potential ore deposit is detected, explored, and found to be adequately rich for mining, appropriate methods for its mining, enrichment, and purification must be found. It should be considered that most materials would be processed at the location of their exploitation, transporting only the resultant low mass/high concentration product.

Biomining is a very low energy yet moderately slow process to separate certain elements (mainly metals) from ores using the activity of prokaryotes, fungi, or plants (Rawlings & Silver, 1995). This method is already utilised by industry to extract, in large plants, some specific metals such as Copper, Cobalt, Uranium, or Gold in several countries. The method was, on a laboratory scale, successfully tested onboard the International Space Station (Cockell et al., 2020), where rare earth elements were separated and concentrated. This method has in addition been suggested to be applicable for space mining (Gumulya et al., 2022). While requiring a large amount of water and specific organisms/consortia, it could work well to support long-term settlements on Mars. In terms of planetary protection however it might be disastrous.

Planetary protection would as such be compromised by the first permanent settler aiming for self-sufficiency and exploitation of local resources. Mining Mars, or perhaps on its moons, might provide a large-scale economic productivity that would justify the development of the Martian community and provide an income and all material resources for its prosperity (see Sects. 8.4.2, 8.5.1, and also Sect. 9.2)—although this is beyond any foreseeable technical capabilities.

A further challenge when aiming for self-sufficiency would be the production of highly complicated devices such as computing systems and data servers, robots, or heavy machinery and automatic production lines. Many devices require for their construction high- or very high-quality materials and components for demanding purposes such as computer microchips, steel and alloys for high-precision mechanics like turbines or nuclear reactors, highly complicated and high-quality structures, parts and components such as bearings.

8.2.2 Infrastructure

8.2.2.1 Settlement Sites

Selecting a suitable location for a permanent settlement is no simple task. On the one hand, a settlement within low latitudes where daytime temperature is almost similar to Earth would have the advantage of avoiding the extremely cold and dark winters of higher latitudes, which would be difficult for any outdoors operations and for the durability of all machinery (for typical conditions at different locations, see Chaps. 2 and 3). Thus, low (even equatorial) regions would be most suitable for habitation as far as climate is considered. On the other hand, access to water ice and permafrost is easier at middle to high latitudes (Morgan et al., 2021; Song et al., 2023). Water in low latitudes is probably very scarce (Dundas et al., 2023), and wide range robotic exploitation may be required to find locations where permafrost water deposits are in accessible depths in the subsurface (Heldmann et al., 2022). Radar sounding is used when looking for ice, and recently some indication of deep ice-rich layered deposit has been found in the equatorial Medusae Fossae Formation by the Mars Advanced Radar of the Mars Express orbiter (Watters et al., 2024).

In addition to water, other essential resources should be available in a settlement's vicinity, notably deposits of valuable metals and plant nutrients. Access to such resources will allow ISRU approaches (In Situ Resource Utilisation), i.e. the use of these materials to make the settlement more self-sustainable. One possibility to optimise resource utilisation could be to have collaboration between settlements (especially those over 100,000 inhabitants) located at several locations, each having access to different resources and exchanging these in collaboration. Each small city could offer all essential services, but specialise in extraction of certain materials: water for those in higher latitudes, mineral extraction for the ones around the equator. This concept has been proposed for a population of 1 million, with five settlements in different locations working in a cooperative manner for resources extraction (Anglada-Escudé et al., 2021). However, this scenario would require the settlements to be interconnected via good networks, allowing for transport of the products from one site to the other, and requiring construction of adequate roads. A more energy-efficient transport mechanism might be the magnetic monorail trains. This long-distance transport of the fuel material might have similar value to the social infrastructure and the economic systems as maritime trafficking of oil has on Earth.

The driving force of a magnetic monorail depends on strong electromagnets embedded into the guideway and rail and in the bottom of the train, thus levitating the train and pushing it forward. On Mars it would work with minimal energy consumption due to the low gravity and the low air resistance. One problem in its construction may the availability of adequate amounts of conductive materials, such as iron, for the rail system. Another problem would be that such a large open structure would soon be covered by dust. Thus, it might be necessary to clean the rail frequently, or to construct a tunnel around it.

The local large-scale and microenvironmental parameters need to be determined in terms of temperature and radiation levels, as these vary according to location (Amini et al., 2022; Mitrofanov et al., 2022). Amini et al. (2022) describe a NASA call entitled "Human Landing Sites Study (HLS2)", which was organised in 2015 for selecting the optimal landing and settlement sites for crewed/human missions on Mars. From 45 submitted proposals, Melas Chasma was selected as the best landing site. Melas Chasma is located in the central section of Valles Marineris, the largest known canyons in the Solar System (Fig. 8.2).

Melas Chasma is located near the equator of the planet, and thus benefits from intense solar radiation and higher temperature throughout the year. A canyon about 10 km below the surrounding planes provides some protection against cosmic radiation and dust storms. The sedimentary landscape preserves the history of Martian sedimentary and weathering processes, with a possible addition of some kind of (bio) markers of ancient (or even recent) microbial biosphere (Amini et al., 2022). Jezero Crater is the second option for the first settlement, for similar reasons (Mukundan et al., 2023).

8.2.2.2 Habitats

New types of habitats and infrastructure will be needed for larger and more permanent settlements. One suggested concept for the structure of pressurised habitats are multi-layered domes (Amini et al., 2022; Heldmann et al., 2022; Starr & Muscatello,

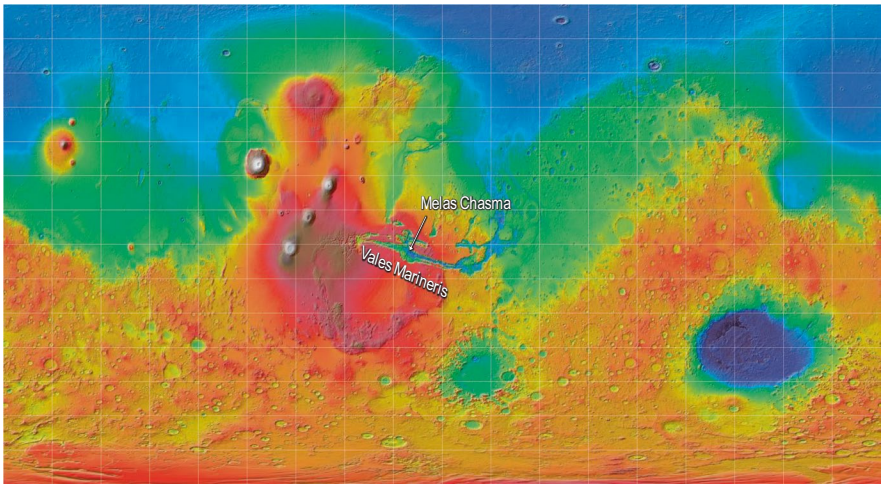


Fig. 8.2 MOLA pseudo-colour elevation maps of planet Mars showing with the arrow the Melas Chasma which has been selected as the best landing site for habitability purposes. It is in the middle of Valles Marineris canyon, one of the largest known canyons in our Solar System. Source: Mars topography from MOLA dataset, extracted with the use of JMars software interface (http://jmars.mars.asu.edu/)

2020), made out of radiation-shielding low-Z composite cover materials. Another option is to use local resources, i.e., Martian regolith, as the radiation-shielding cover material. A layer of approximately 2–3 m of the rocky substrate would be needed, depending on its quality and the water content (Röstel et al., 2020), as water is an efficient absorber of the radiation. The shielding must be adequate to reduce the radiation to inhabitants below a dose of 100 mSv per year. The actual shielding effects provided by regolith can be determined only on site. Further radiation-shielding materials are discussed in Sect. 7.3.1.1.

The habitat constructs could be produced by using modular building blocks and tiles produced by AI-aided 3D printing. Basalt can be used, as well as regolith mixed with local water (Kading & Straub, 2015; Starr & Muscatello, 2020). These local materials will also be used for the weight-bearing structures of the habitat. Due to Mars' lower gravity, the weight of the regolith is only one third of what it is on Earth (in average 1.5 ton/m^3), therefore the load-bearing structures do not need to be as strong as corresponding structures on Earth. The dome interiors could be built of some kind of inflatable structure, for example carbon fibres, ETEF (Ethylene Tetrafluoroethylene), and composite materials. The comparably high internal pressure of any habitat also serves to carry the weight of covering materials.

According to the Mars habitation views, the community on Mars would grow with time either by producing larger habitats, producing more habitats under adjacent domes, or under the same but larger dome (Hollander, 2023; Sabry, 2021). Separate domes should be interconnected by using either connecting tunnels, or radiation-shielded monorail trains with airlock-stations.

Large dome structures have been tested on Earth and have been found to be problematic due to weight and non-durability of the structure itself, as well as air-condition problems within. On Mars, such structures must be constructed with adequately thick and heavy radiation-shielding material. A dome-like shape of the habitat might be more suitable on Mars than it is on Earth because the internal pressure would help to stabilise the dome. If overlapping dome layers would be applied, these would help to maintain the internal temperature and pressure and provide the strongest radiation shield to the inner-most parts, the human quarters.

Another option to expand the habitats and obtain efficient shielding against particle radiation would be to expand into a subsurface direction. As an alternative to domes, the covered habitats could be constructed in the form of (adjacent) blocks (Mukundan et al., 2023), or be built in large (adjacent) caves, be they natural or human-made (Anglada-Escudé et al., 2021). All these various scenarios aim to develop extended city-like habitats and/or their interconnected networks (Fig. 8.3).

As the size of a settlement grows, distances to cover within the city increase. For cities with over 100,000 inhabitants, the required horizontal surface may become huge. A proposed solution to still provide proper radiation protection is to build a more "compact" city within tunnels in a cliff, connected to a tunnel system under the surface (Anglada-Escudé et al., 2021). This compact design ensures shorter distances to all supporting infrastructure, which can be located on the top and bottom of the cliff. This solution creates an efficient and concentrated city development. The material extracted from the tunnels can be used as cover material for the

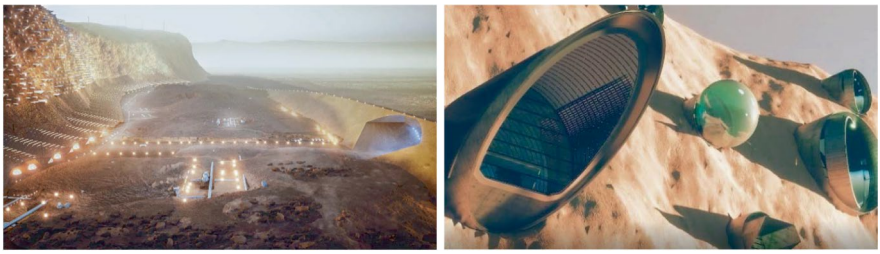


Fig. 8.3 Artist impression of Nüwa, a city planned to be excavated in the cliffs of Mars (Anglada-Escudé et al., 2021). Credits: ABIBOO and SONet

infrastructure in the bottom to protect from radiation. The biggest challenge of this concept is ensuring structural stability of the wall, which would need to be studied in detail. Constructing tunnels would also offer further advantages, e.g., the elevated pressure inside the habitat would be structurally absorbed by the surrounding rock, reducing cost and risk of failure of the habitat structure (Anglada-Escudé et al., 2021).

A circular economy, i.e., sparing and reusing of all available materials, would be essential for a sustainable existence of the community. Thus, when increasing habitat size, all formerly produced building parts or their elements (e.g., wall segments, roofs, various structural units, wires, pipelines, etc.) will be reused and integrated into the new habitats.

8.2.3 Transportation

If the attempt of a permanent human settlement is to be made, the interplanetary transport to Mars—including both the deep space travel and landing on the surface—must become more economical, easy, safe, and comfortable. According to the plans of the SpaceX Company, this would be achieved by the Starship spacecraft, i.e. a large vehicle capable to transport up to 100 passengers, and descending directly to the planetary surface (Cannon & Britt, 2019; Heldmann et al., 2022). Another economical option for interplanetary trafficking might emerge from the concept of Earth-Mars cyclers (Pelle et al., 2019), i.e., a space station placed on the fixed cycler orbit that crosses both Earth and Mars orbits. A station like this does not require any re-occurring launch costs of the interplanetary vehicle, while still, of course the cargo and the passengers would need to be launched from each planet. Still, it would allow a regular, if not frequent method to transfer crews between LEO and Mars orbit, using local launch and landing vehicles to rendezvous between the cycler station and the two planets. A problem with using a cycler station for transport is the high escape velocity that is required to dock the local launch vehicle to the cycler station (Anglada-Escudé et al., 2021).

For the local surface transport on Mars, various efficient "space port" facilities are needed. Air-lock access for pressurised vehicles or perhaps trains are needed to move crews and passengers back and forth from the various habitats. A wide variety of facilities will be required to accommodate the cargo payloads and ensure efficient transfer and storage of perishable consumables, essential goods, propellant compounds, and other elements to be down- or up-loaded.

8.2.4 Sustainability

A resilient presence of a large (in the range of 100,000-persons) community on Mars requires safe and comfortable habitats with uninterrupted access to water, food, and energy. To our current knowledge, such resources are not readily available on Mars, especially not in one single location. They may however be discovered during in situ exploration, even if spread over several locations. Only after securing adequate resources and resolving their process and supply issues, can the population gradually increase in number.

8.2.4.1 Sustainable Infrastructure Build-Up and Maintenance

To achieve this possibility for growth within a sustainable and permanent habitat, a network of automatically regulated monitoring systems must be installed, which will run the habitat smoothly and safely. Such a system requires an optimised interconnection between habitat units to prevent frequent exposure to the Martian surface environment, with a modularity and isolation interlocks to connect the different modules. Efficient space architecture should be adopted in the design, so that the habitat blocks are optimally adapted to the topography and to the locations where resource harvest or processing is performed.

To monitor all essential parameters for such a big infrastructure, a very large number of sensors and actuators should be installed, often in duplicates to further reduce risks of failure. Distributed computer systems are needed to run the fully optimised and easily updatable code, and to acquire the data in real time and perform mitigation actions immediately, as needed. Full automation and self-regulation can be performed by artificial intelligence (AI) systems, which will play a significant role. However, they must be also thoroughly evaluated and continuously supervised by well-trained humans before these systems reach maturity and thus reduce operational and decision-making risks. As the habitat grows to accommodate a hundred thousand or more people, the amount of cabling and interconnects, sensors, actuators, and small processing units will reach immense numbers. It is not clear how much of this infrastructure should be fully controlled by an automatic AI-managed central computing system, or would it be safer to have the subsystems to function under a decentralised, although interconnected monitoring and surveillance network. In any case, all necessary functions must be tightly followed by

self-training AI systems, and secured by parallel back-up infrastructure. The amount of energy required to run such a system with current computer networks is immense, with the only advantage of producing enough heat to keep the habitat warm. However, more advanced computer systems should become available with more efficient networking capabilities, i.e., wirelessly or semi-wirelessly, or with optical fibres.

If the community on Mars would grow to the size of one million inhabitants, this would be comparable in size with a medium size town on Earth. On Earth, such communities are definitely not self-sufficient. Many resources need to be supplied from other communities, often from distant places where they are extracted and pre-processed before they are made ready for use or consumption. Also, most technical pieces of hardware and even lines of software are imported from elsewhere; at their production location they each require high grade materials, and a wide number of very specialised pieces of hardware from nuts and bolt to chips and casings. Production for such highly specialised elements requires wide production infrastructures and must produce a large number of elements. You do not build a complex supply chain to produce a single item.

However, on Mars the high-tech equipment and materials should be firstly transported from Earth. Regular deliveries are not easy due to long-duration transfer windows (by the cheaper Hohmann orbit) between the two planets, but a preparation phase can include storage in orbit of Earth, the Moon, and surely Mars. Consequently, the visionaries' plans for the one-million Martian community habitats seem too simplistic to be realistic in the foreseeable future, as are the different concepts presented in the current literature, which mix contemporary technology with estimates of what future technology could be. The technology will of course grow rapidly, and this is again difficult to estimate in kind, level of advancement and timescale of being achieved. It is clear however that before an eventual settling to the red planet, local resources must be identified and secured in the region where the habitat will be installed. Then, many missions must transport the required basic technological materials from Earth, i.e. the ones that will help building the infrastructure for mining and processing of the local resources into new functional components.

8.2.4.2 Towards a Partially Autonomous Community

Assuming that all the previous is possible, a gradual growth of the population of the community and its expertise can be planned, based on trained people to perform local tasks. The first million people should finally constitute a well-balanced set of labour and expertise, which will take care of the utilisation of the local resources, i.e. mining and processing of the raw materials and production of final products. Once a functional habitat and sustainable community have been achieved, only then competitive markets might evolve. Such a free economy will take a very long to achieve and happens only when local resources will be in excess or reach adequately high technological maturity to be traded with other habitat communities.

If such a Mars settlement is established and becomes progressively almost self-sufficient, it will be based on detailed robotic work for resource identification and robotic labour to prepare the area by building settlements and other infrastructure, concentrate the first resources, and prepare the facilities for agriculture. All the organisations should have been designed already from Earth, based on solid knowledge of the local Martian resources and the general conditions of the area, and include plans for essential basic services such as healthcare, education, laws of justice, easy communication, and security. One must also consider that a significant number of the one-million community members will have tasks other than manual labour, such as research work to expand the knowledge and understanding of the local Martian environment, accompanied by a group of engineers who convert this knowledge into practical tools and consumables. Others will need to re-define legislation and societal rules, as well as risk mitigation protocols for ensuring a sustainable habitat. Maintaining the psychological health of the members of the community will be the task of an additional group of professionals, activating others into pursuing arts and sports, or being engaged with philosophy, theatre, and other cultural activities and hobbies.

The functionality or sustainability level of a permanent community on Mars cannot be predicted for certain. It firstly depends on the volume of identified energy and material resources. Even if adequate resources are found, the community largely relies on its technical ability to sustainably process these resources. A more progressive community will need to have a technical ability to produce appropriate products to trade with other (Martian, terrestrial, or lunar) communities. Communities will also depend on their capacity to build complex technical infrastructures with adequately high productivity to support all their own needs and those of visitors, and also to evaluate the risks and effectively mitigate them.

In addition, a resilient presence of humans on Mars requires special care to be taken of the interaction between the community itself and the local environment, equally protecting both of them. The thin atmosphere, strong dust storms, and other effects of the Martian extreme environment may initiate the mobility or generation of many pollutants and contaminants, alongside with conditions being created through settlement activities and in combination with living in isolated, confined environments. These various generated compounds may be pathogenic to humans, crop plants, or other possible symbiotic organisms as well as detrimental for the objects.

Also new disease agents might arise via mutations, or from known pathogens imported from Earth or adapting and becoming resistant into Martian conditions. Closed-loop circularisation of all resources is very important, because Mars will not offer the “planetary services” or the “geological processes” that Earth does, such as natural recycling and filtering of rainwater. Thus, every by-product of human activities will remain there, possibly contaminating and polluting the environment. Any organic by-products, disseminated outside of the habitats, are probably exempt from this as they will easily disintegrate due to the harsh radiation and peroxides. Resistant by-products will however remain in the environment almost indefinitely, contaminating certain areas without any easy mitigation methods. This will be a major

problem, for instance, in the long term for the nuclear wastes. Some natural outcomes from the human activities will be difficult to manage as, for instance, the effects of the rocket launches generating chemicals and particles in the tenuous atmosphere and uprising, possibly, large amount of dust. The various industrial, mining, transportation activities will also generate various dusts and resistant by-products which cannot be identified at this stage.

8.2.5 Risk Analysis and Evaluation

The exploration of Mars is an important step for humanity. In an attempt to cope with any potential radical societal changes that depend on our inability to predict the future in the new territory of space, the study of risks is necessary, extending current knowledge on risk analysis. In the view of preparing for space colonisation, major risks are primarily identified in the political (i.e. territorial and jurisdictional issues, space debris management, space governance, resource ownership), the economic (i.e. high initial costs, financial instability, uncertainties in demand, rapid technological changes), the legislative (i.e. intellectual property rights, accidents and collisions such as satellite and rocket collisions in populated skies), the human endurance (health, mental stability, medical assistance) and the cultural arena (i.e. cultural representation and diversity, language barriers, ethical and moral standards). Such risks create casualties (such as serious health effects on the astronauts), which also impose further risks to other sectors such as in business and governance (i.e. business interruption and loss of economic power, rapid political changes), or they can introduce environmental issues (i.e. forward and backward planetary protection risks, uncontrolled and unexpected changes to the local environment when terraforming will be initiated). Casualties can be so severe that can result in loss of confidence in societal structures and introduce social and personal uncertainty to individuals. A considerable number of impacts are about to shake our societal structures (Shaghaghi & Antonakopoulos, 2012) and these may mainly affect all above-mentioned sectors. Therefore, it is necessary to be able to identify quantitatively those risks in order to adequately remediate then (Holzman et al., 2003). To achieve a controlled transformation, the *Mars Risk Index (MRI)* follows a Quantitative Risk Assessment (QRA) method for estimating those risks and the requirement for taking optimum mitigation measures for each instance. This is done by listing the different impacts and risks (as we have identified and enumerated throughout this book) based on the importance and the contribution of each asset. Assets are the people themselves that take part in these missions, the critical infrastructure, the supply chain, systems/equipment that will be used, the adopted business operations, the reputation of an entity or the confidence on it, the regulatory and contractual obligations, and last but not least, the planetary environment. Example categories considered for each Mars exploration phase for which an MRI must be estimated include mission(s) and discoveries to Mars, settlement on the planet, its terraforming, constitution and governance made especially for Mars, and Mars economy and

trade. The MRI's methodology is based on the relationship between the "frequency" of an event and the "number of people" suffering by a specified level of harm of this event. Consequently, the results of the QRA are the frequency of events involving fatalities (*f*, vertical axis on Fig. 8.4) and their potential consequences, which is typically the number of fatalities (*N*, horizontal axis on Fig. 8.4). A cumulative frequency (*F*) of events that has *N* or more fatalities is commonly referred to as the FN curve outlining the FN Area Risk status (shaded area) (Vasconcelos et al., 2015). On the same graph we can also plot the "criterion plots" (upper and right straight lines), which are the accepted limits of fatalities before action is taken to remediate them (Fig. 8.4). The expansion of the FN curve is then visually compared with the criterion lines and assists in judging a situation or reaching a conclusion towards mitigation actions (when the FN curves overlap the criterion curves). However, frequencies of harmful events or their factual severities (casualties) are difficult to estimate, because there is no preceding statistical data available from these situations, and because the processes and their technical infrastructure and components are very complex.

An MRI modelling weights the results derived from the business/societal impact analysis to assign the criticality that will prioritise the related risks. The risk calculation is as follows:

$$\text{Risk} = \text{Likelihood} \times \text{Impact}\left(\text{on a scale of } 100\right),$$

$$\text{where Impact} = \left(100 - \left[\begin{matrix}\text{sector} \\ \text{readiness}\left(\text{in}\%\text{values}\right)\end{matrix}\right]\right) \times \left(\begin{matrix}\text{criticality} \\ \text{of the sector}\end{matrix}\right)$$

The estimation of risks can be continuously and dynamically monitored by computers accessing big data, performing Monte Carlo simulations, or using Artificial Intelligence (AI) tools. Human settlements on Mars are *ante portas*. As a consequence, societal risks emerge and are very likely to create an unstable environment. It is our responsibility to adapt our societies to this endeavour by studying the risks and establishing mitigation actions.

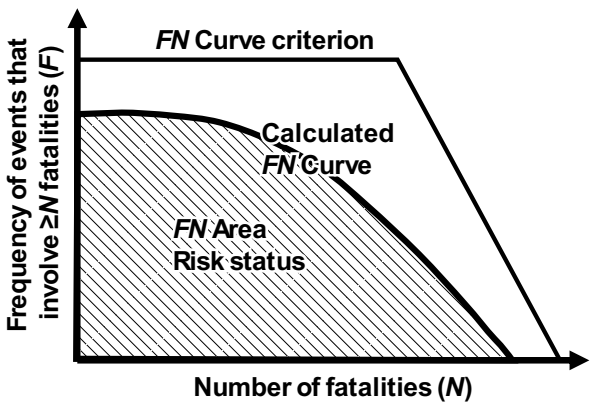


Fig. 8.4 A schematic example of an *FN* Curve plotted together with the line of the criteria that define the risk limits

8.3 Decades on Mars: Living and Surviving[3]

With the longest continuous spaceflight lasting 437 days, and no data at all on the effects of Martian gravity on human physiology, speculations on how staying on Mars for good would affect our bodies and minds are really just that: speculations. We cannot know for sure if we would be able to thrive in 0.38G, if we can withstand the toxic components of the omnipresent dust, if sheltering from radiation will be enough to prevent DNA damage and keep us alive.

While the first Mars missions will focus on prevention and only the fittest and healthiest astronauts will be sent out, later missions aiming for population growth and permanent settlements will see less perfectly healthy and more "normal" people within the crews, adding various health problems. Physiological trends on Earth, such as the expansion of the average lifespan, may be broken. Humans deciding to permanently settle on Mars will be exposed to many hazards with unforeseen consequences. However, one cannot rule out positive effects. Mars's 0.38G may be rather comfortable to live in after all, putting less strain on our bodies as we age, preventing our spines from bending, decreasing the risk of frequent falls and supporting the cardiovascular system in its job to get blood up to the brain (as less gravity means less fluid gets pulled downward)—and through all this, perhaps turning ageing into a more comfortable process.

The question of how 0.38G will affect human physiology remains crucial. If we cannot live, thrive, and reproduce in Martian gravity, building permanent multigeneration settlements will be impossible. We can protect ourselves from radiation and overcome psychological hardships—but the gravity of a planet we cannot change.

This section is mostly a thought experiment, a highlight of the fact that if we are to proceed, if humans are eventually going to venture out without a return ticket to permanently settle Mars, we really do need more research into the risks—especially those concerning a group of people who cannot yet advocate for themselves.

8.3.1 Making Martians

When talking about permanent long-term settlements on Mars, the effects of the environment on human reproduction must be considered. Is a multiple-generation development even possible? The trouble is, space and Mars have potential negative effects in every step of the way. Amongst the more urgent questions to be answered are the effects of spaceflight (and therefore radiation) on reproductive organs (and respective sex differences), dangers of a pregnancy off-Earth, and the development of a foetus and child in partial gravity.

[3] This section is authored by Carmen Possnig.

To date, 644 astronauts have lived and worked in space. Of these, 73, around 11%, were female. Reflecting on these numbers makes it clear that, investigating sex differences, we are once again faced with a lack of data.

The overall adaptation to microgravity for both physiology and psychology is similar for female and male astronauts. While subtle sex-specific differences have been found, there is a lot less data for female astronauts and interpretation therefore difficult. However, the reproductive system is entirely different between males and females and is expected to react dissimilar to space travel. Certainly, challenges for reproduction in a Martian settlement will be very different for female and male settlers.

8.3.1.1 Fertility

At the moment, there is limited knowledge on how reproductive organs react to space travel and the associated stressors. Microgravity, radiation, sleep disturbance, stress and anxiety, isolation and confinement can all have potential effects on their functionality. Although there is a paragraph in the Outer Space Treaty (Article VIII), stating that "a State Party to the Treaty on whose registry an object launched into outer space is carried shall retain jurisdiction and control over such object, and over any personnel thereof, while in outer space or on a celestial body", meaning that children born in outer space or in the constructed objects (e.g., space settlement) on a celestial body will not be stateless but will have citizenship of the nation that controls the object, pregnancies in space are forbidden by most space agencies, as they pose too high a risk for mother and child.

It is not possible to say with today's data whether fertility is impacted by spaceflight. Female astronauts do return from space and bear children afterwards. Data from female astronauts who flew during the Shuttle era suggest that pregnancy rates and associated complication rates are equivalent to ground-based, age-matched controls. As most of these astronauts postponed getting pregnant until after they had completed training, or flown one or two missions, the mean age for giving birth tended to be rather high: 42.5 years for females in a cohort of 30 NASA astronauts, and 44.5 years for their male counterparts ($N = 171$). Use of infertility services or assisted reproductive technology is common, but more likely a consequence of advanced maternal or paternal age rather than related to spaceflight. The occurrence of pregnancies ending in spontaneous abortions is not different from the rest of the population (Jennings & Baker, 2019).

However, astronauts on 6-month missions on the ISS are still relatively well protected from radiation. Travelling to Mars and settling there will be a different matter in the light of reproduction. On Earth, increased radiation, social isolation or confinement, impaired sleep and dietary changes, and psychological stress can all impair reproduction. It is not unlikely that adding effects of partial gravity will exacerbate these issues (Jain et al., 2023).

A wide range of challenges will have to be overcome if, in the scope of a permanent settlement on Mars, reproduction becomes the goal and pregnancy something

to strive for. As mentioned above, fertility rates at least seem not affected by LEO spaceflight. As most female astronauts suppress menstruation with the use of a combined contraceptive pill, whether spaceflight induces changes in the endometrial or ovarian functions remains unknown. However, various secondary pathways can affect the reproductive system: For instance, the immune system undergoes changes in microgravity, which might affect immune cell populations in the endometrium (the tissue lining the uterus). Blood flow and blood vessels themselves may be affected as well, which would subject the astronaut to abnormal bleeding patterns and thus affect fertility (Kennedy et al., 2014; Mishra & Luderer, 2019).

The most obvious challenge for fertility will be exposure to radiation. The first challenge will be getting pregnant: As is known from patients receiving radiotherapy, oocytes are very sensitive to radiation. Independently of age, increased exposure to radiation can damage oocytes and lead to an early onset of menopause. A female human's oocytes are not renewed with time—in fact, females are born with the complete set of egg cells within their ovaries. The quantity of these cells is determined during the time spent in utero, and subsequently both number and quality diminish with age (Donnez & Dolmans, 2017; Jennings & Baker, 2019).

Male astronauts might not be spared from the infertility risk, but studies show diverging results. Sperm cells exposed to low doses of radiation can easily become damaged or get killed, resulting in sterility or the passing on of birth defects—yet some studies do show that stem cells in the testes are fairly resistant to radiation, ensuring that the production of sperm cells recovers after exposure is ceased. Additionally, in long-term stays in low Earth orbit as well as in simulation studies on Earth, a decrease in formation of sperm cells alongside a decrease in testosterone levels was seen (Mishra & Luderer, 2019). If the challenges for preserving fertility can be overcome, settlers envisioning reproduction will be faced with the next one:

8.3.1.2 Pregnancy

Once the first Martian babies have been conceived, their development will be a battle. Embryos are sensitive to chemical and physical environmental stress, as well as to viral infections. Any of these may induce malformations or congenital abnormalities.

Spaceflight can also cause increased oxidative stress. In addition to having detrimental effects on the immune system, oxidative stress can interfere with the placenta. Effects can include pre-eclampsia (a potentially life-threatening situation for mother and foetus), but also cause growth restrictions in the baby, increase the risk for an early birth and pregnancy-induced diabetes (the risk for which is already high, as spaceflight also increases insulin sensitivity).

Sheltering from radiation is of the greatest importance also for brain development of the foetus: Unborn children of atomic bomb survivors of Hiroshima and Nagasaki later showed a high rate of brain malformations, linked with a decreased intelligence quotient. These effects were seen especially when the

radiation exposure happened during the first trimester of pregnancy, a critical period of brain development. Pregnant mice exposed to radiation gave birth to pups with small brains who showed abnormal behaviour. A study computing the effects of radiation doses equivalent to a total dose during a 3-year Mars mission found that in human embryos, similar malformations would occur, including brain development defects and neural tube defects, possibly resulting in low IQ and mental health impairments. Interestingly, in a study where folic acid was used as a supplement for pregnant mice, it seemed to counteract radiation effects by significantly reducing the rate of malformations induced by radiation during early organ development (Jain et al., 2023).

Radiation exposure during pregnancy also increases the risk of later childhood cancers, aside from the fact that the baby might be born sterile: Observations from studies with (nonhuman) primates show that relatively low doses are sufficient to damage egg cells even inside an unborn foetus.

In short, while radiation exposure at early stages of pregnancy will increase the risk for miscarriage, brain malformation, and mental health issues, exposure during late pregnancy may lead to the baby being born sterile.

The lack of terrestrial gravity can be neglected, some argue, as a foetus basically lives inside a neutral buoyancy tank. We cannot be sure whether a certain downward tug plays a role in the development some point during pregnancy, or has some influence on the birthing process. In addition, cardiovascular alterations may impair blood supply to the uterus and placenta, possibly leading to birth defects or miscarriage.

Indeed, to overcome both the radiation and the gravity issue, researchers have suggested building an artificial gravity ring underground, rotating to create terrestrial gravity levels, where mothers can spend pregnancies—or kids their childhood. The psychological effects of such a confinement have not been considered in depth, and in the end, if we venture to settle Mars with the goal of living in rotating underground tunnels, there better be a very urgent reason for us to go.

8.3.1.3 Birth and Childhood

Should the pregnancy have gone well, labour and delivery will be the next hurdle to overcome. Adequate medical care will have to be available on site to prevent life-threatening situations for mother and child. Giving birth is not without risks on Earth, but on Mars, we add a considerable number of challenges. The decreased bone density may make the mother's pelvis susceptible to fractures during the birth process, which would put both lives in danger. Caesarean sections or blood transfusions might be needed, and neonatal intensive care units must be available.

The first 6 weeks after a successful birth are critical both to the mother and to the child for recovery, and to ensure a safe start into life on Mars. The next problem this new Martian will be facing is that in order to preserve our cardiovascular, bone, and muscle health, humans will most likely need to engage in some form of regular countermeasures. At the moment, the best countermeasure available against

deconditioning is physical exercise. Martian partial gravity likely will still mean some form of regular exercise schedule is required, especially if an eventual return to Earth is envisioned. It will probably be challenging to explain this to a 4-month-old infant. A onesie with added weight might be an option, and in the far future, efficient drugs might exist to preserve at least bone health (but whether we want to test these on children is another matter). How low gravity affects the development of a child's anatomy is difficult to compute by itself. It is important to consider long-term effects however: It is entirely possible that, without the right amount and type of countermeasures, a return to Earth would be dangerous or even impossible for Martian children.

Hormonal changes will influence the development of Martian children. Decreased levels of testosterone have been seen in male astronauts during low Earth orbit missions. This has been reproduced in small vertebrates as well and might simply be an effect of a stressful, high-pressure working environment, but the triggering factor is not known. Should this occur also in children, it might affect a range of factors in the development of boys. The already mentioned effect of perchlorates (which make up around 1% of Martian soil) on thyroid hormones can easily have disruptive changes, as a balance of thyroid hormones is needed for the development of foetuses and children (Davila et al., 2013).

In addition to these open questions, all data we currently have on life in space come from fully grown humans. We have no idea what micro- or partial gravity would do to the cardiovascular system of a teenage girl experiencing a growth spurt. There are certainly a lot of unknowns surrounding reproduction outside Earth. Some researchers wave these aside with the argument that, in the fifties, we were not even sure whether our hearts would be able to pump blood and keep us alive in microgravity. Today, we know that this, at least, works quite well. However, back in the fifties, there was the option of sending cats and dogs and monkeys to space and observe their reactions. While we try our best with pregnant urchins, fish, and rats at the moment, the main problem is the immeasurable number of things that can go wrong. If women on Mars are not able to get pregnant, or if future Martian babies have major health issues, it will be extremely difficult to tell what exactly creates the problem. Is the culprit hormonal imbalances? Is it the lack of gravity impeding development of the heart? Do we have radiation to blame? Or some gas escaping from a new kind of material? Did the problem arise during the father's space travel to Mars, or sometime in utero, or after birth?

Furthermore, what happens when an abnormally high number of babies are born with physical or cognitive disabilities? Will there be adequate care available for them? Will we plan to have resources on site to care for these vulnerable populations? Mothers and babies will be pioneers, they will be part of an experiment—where only half of them can give their consent. Much research on site will be needed before we can go forward with a clear conscience, ensuring we endanger neither the mothers during pregnancy, nor experiment with the lives of future Martian generations.

8.3.2 Being Martian

The environment we live in matters for development of appearance and personality. Just as identical twins that are separated at birth look less alike with time, humans living on Mars will likely change in appearance. Light exposure, altered gravity levels, and predominantly living indoors will all elicit subtle changes. This will certainly be the case for babies born on Mars, but changes may also be visible in adults who spent previous decades of their lives on Earth.

Contrary to what is often suggested within popular science books, it is unlikely that humans will change appearance drastically once settling on Mars. Darwinian evolution-driven changes in anatomy would take tens of thousands of years, and only happen if they are indeed selected for—if people with that change have a reproductive advantage. However, there are several changes that may happen due to living conditions on the red planet.

A life on Mars will mean a life spent mostly inside a habitat with few faraway horizons to gaze at. This might mean that an uncommonly high number of infants become near-sighted, as is the case with children on Earth who rarely go outside (Rose et al., 2008).

Skin tone may change as well. Settlers on Mars will live in habitats which they exit wearing suits, with no direct sunlight ever coming into contact with their skin. It is thus more likely that they would get paler in complexion, just like humans on Earth who are confined to inside spaces. After a year spent in Antarctica, where even in the summer months, the station is exited only with protective gear, crew typically have very pale complexion. Skin tone may even turn orange due to nutrition. Even on Earth, a diet rich in foods such as carrots, pumpkins, and sweet potatoes can turn skin orange due to them containing carotenoids. Astronauts' meals are likely to be supplemented by carotenoids, as they protect against radiation damage to a certain amount. As a side effect, these pigments would accumulate in the blood stream, giving skin an orange glow.

The human microbiome, an estimated 500–1000 species of bacteria living in harmony on our skin, in the gut, and other places, is likely to also change with the new environment. The microbiome supports the immune system, possibly influences mood, interacts with hormonal and neural systems, and probably has many other functions we do not yet understand. On Earth, changes in the microbiome are linked to various illnesses, among them major depressive disorder, certain types of cancer, and bowel diseases (Gilbert et al., 2018). Once more, the sterile Martian environment, in combination with microbe-poor food, and being surrounded with the ever-same people, might change the microbiome with unpredictable consequences. Changes in the microbiome may make us thinner, or more prone to obesity. It will certainly have effects on kids born on Mars, as the formation of the individual microbiome takes place mostly in the first year of life.

In any case, if we are to settle on Mars and build a multigeneration human presence, ideally we would want thousands of pioneers to start with—for diversity of skills and knowledge, but also for diversification of the gene pool. The Amish

religious community in Pennsylvania is almost exclusively descendant from the first hundred families that settled in the region. This limited gene pool combined with their preference to marry within the group has resulted in a high incidence of rare genetic diseases, among them dwarfism and numerous cardiac and nervous diseases (Strauss & Puffenberger, 2009).

8.3.3 Returning to Earth: Mission Impossible?

Whether a return to Earth will be possible for people who spent years or decades on Mars is a tough question. Should Martian gravity levels not be enough to sustain muscle, bone, and cardiovascular health to a satisfactory level (i.e. avoiding deconditioning), constant physical exercise will be needed to uphold a level of performance in physiology that makes a return and healthy life on Earth possible. Child-friendly countermeasures will have to be invented.

If countermeasures are not used, a new homeostasis may develop, similar to deconditioning with age on Earth. On Earth, the cardiovascular system especially suffers from a sedentary lifestyle over time (even if gravity exercises it to some extent), the heart and vessels getting stiffer, less stretchy and less compliant with age. For a person never having performed regular exercise during their youth, it is difficult to gain muscle and aerobic endurance in later age (Lazarus et al., 2019). However, it is not impossible. Life may be hard at the beginning, but provided adequate medical care, perhaps it would be possible to revert Martian changes and return to terrestrial gravity even after years.

Another obstacle will be the immune system. Effects may be visible already after a short-term mission. The immune system is happiest when facing regular challenges. A spacecraft or habitat will be as sterile as possible and contact to new people—and their microbes—will be rare. In this regard, a larger settlement on Mars with crews exchanging on a regular basis may have protective effects. Still, constant inputs are needed for the immune cells to be working well. Spending a year in Antarctica, where the environment is as sterile as it gets on Earth, has detrimental effects and puts immune cells into a state of hibernation. Perhaps related, more than half of people wintering over report the occurrence of new allergies after returning from the ice. Children born and growing up on Mars may never develop an immune system strong enough to withstand the armies of mostly harmless microbes waiting for it on Earth, and adults spending years off-Earth may well lose the ability to fight them off.

For children born on Mars, the complete picture may look different in several ways. Depending on their individual adaptation to the Martian environment, their bones might be too weak to withstand gravity, the muscles of the heart not strong enough to pump blood to the brain against 1G, and the blood pressure regulation inefficient for upright life on Earth. By giving birth off-planet, we may be banning future generations from access to Earth, leaving them forever confined to the magnificent desolation of outer space.

8.3.4 An Outlook: Humans on Mars

Whether we venture out on short-term missions, spend a few years on Mars, or plan on permanently settling the planet, there will always be some toll on health. Until we have invented adequate countermeasures, people will likely travel to Mars for exploration, not settlement. Parallels can be drawn with Antarctica. Early explorers were faced with the extreme environment, suffered from frostbite and the inability to return for months to years. Therefore, they travelled to the continent to do science, advance knowledge, to explore or to be heroes upon their return. Nowadays, we have found ways to make life in Antarctic stations a lot more comfortable, eliminating many of the earlier challenges. Yet still, hardly anyone would move to the ice wanting to settle with their family and stay for the remainder of their days. The exploration of Mars may well take a similar path: certain challenges can be overcome, health issues can be endured, but until our knowledge is expanded and safety can be ensured, exploration ought to be the main focus of these bold space endeavours.

8.4 Considerations for a Settlement up to 1000 Workers

8.4.1 Space Resources: Exploitation, Ownership, and Governance[4]

8.4.1.1 Space Resource Exploitation and Ownership

In recent years, several countries with space capacities have been working on technologies and systems to mine resources in space. In the future, these potential resources could serve as a supply for further space activities, and even substitute some precious minerals needed for production on the Earth. Companies are kicking off efforts to create a complete infrastructure to support these activities, from telecommunications networks to specialised facilities for the study and processing of resources obtained from celestial bodies. As an example, operators are designing and building rovers that can explore the surfaces of asteroids and the Moon. It can be said that space resource-related activities go beyond extracting and owning resources: they can be understood as a chain of activities including economic aspects.

Numerous companies and start-ups are considering space mining activities as a rationale to establish permanent installations on the Moon. The main reason for this is that space resources, such as regolith (lunar soil), water (in the form of ice), and metals, can be used for various purposes like construction, energy, and propellant production. This utilisation of space resources, known as “in situ space resources

[4] This section is authored by Philippe Clerc, Mahulena Hofmann, and Laetitia Cesari.

utilization" (ISRU), may eventually expand into large-scale industrial exploitation for extensive space missions.

From a legal standpoint, the space resource ecosystem involves the participation not only of space resources companies but various other stakeholders across the entire supply chain. Diverse entities can be engaged in various stages of the supply chain across the world, including resource exploration, extraction, processing, transportation, and utilisation. Each of these stages has its own set of legal considerations and implications.

8.4.1.2 Space Resource Governance

From a chronological perspective, the prospection of space resource would start when states and/or operators under their jurisdiction send missions to investigate the areas that hold potential resources and identify the zones of value. Once these resources have been collected, they would undergo transformation processes to make them suitable for specific purposes. For example, they may be converted into oxygen for long-term human habitation in space or used as propellant for robotic missions and launch systems.

The main source of the legal norms of exploration and use of outer space is the United Nations Outer Space Treaty. Adopted in 1967, it could not envisage targeted space resources activities. Yet, it adopted two important principles, the freedom of the exploration and use of outer space (Article I), and the principle of non-appropriation of outer space and celestial bodies (Article II). According to Article II: "*Outer space, including the Moon and other celestial bodies, is not subject to national appropriation by claim of sovereignty, by means of use or occupation, or by any other means*". This non-appropriation principle was established to prevent undue territorial claims. In view of the planned projects on space resources, the non-appropriation principle raises important questions about the limits of resource extraction, as for example no whole celestial body such as an asteroid may be consumed by resources extraction.

However, before states can proceed with their space mining plans, they must first identify the locations of valuable resources. From a legal perspective, the exploration of outer space does not raise any legal questions, if it respects the space environment. It could be different if a single operator, more technologically advanced or having invested significant resources, gained exclusive control over an area on a celestial body without any consultation or considerations on an international level. The control of an area and the exhaustion of its resources could be perceived as a means of de facto ownership.

In addition, the planned existence of technical *safety zones* (defined in the Artemis Accords) which are envisaged by some operators to protect their mining areas could raise questions of compliance with the non-appropriation principle and the freedom to explore. The Outer Space Treaty prohibits any occupation of space and its territories. Therefore, most probably, the legality of safety zones will depend on the length of time for which they will be established, the grade of permanency in

which they will be built, and the readiness to share the area with other countries or to leave the area in a manner which would not compromise the space environment.

According to the US led Artemis Accords wording, exclusive zones of exploitation are intended to prevent harmful interference among operators and may only apply to parties engaged in the same activities, such as NASA's partners under the Artemis Accords. Artemis Accords pertains to the utilisation of in situ resources, and introduces a concept of safety zones to govern commercial space activities. The system consists, for the operator responsible for the extraction or processing of extra-terrestrial resources, in formally declaring, in a reasonable manner, the area requiring specific security and restricting access or circulation of other parties or any activity or anomalous event that could cause *harmful interference*. The question remains open whether the concept of safety zones includes also future installation set-up for space resources activities, or whether these installations must remain open to representatives of other States in line with Article XII of The Outer Space Treaty.

From the first reading of the Artemis Accord, this safety zone or ZoI is not limited in width, depth, height, and time and is declared such, up to the moment the declaring body decides not to do anything in this ZoI. There are some doubts about the alignment of that agreement with the Article II (prohibiting the appropriation by means of use or occupation) and it is in contradiction with article I while it is prohibiting, de facto, the free exploration. Interestingly, such a declaration appears to grant operators the privileges of use and set up installation without necessitating any formal claims, aligning with the non-appropriation principle of Article II of the Outer Space Treaty.

These zones are also proposed as areas for notification and coordination, aiming to enhance transparency and trust among all stakeholders without hindering the freedom of movement for any operator. The discussions surrounding these issues seek to strike a balance between ensuring the responsible use of space resources and fostering cooperation and trust among states and other relevant stakeholders.

However, at present, it seems that there is no interest of the operators in having long-term territorial claims: these rather seem interested in the ability to extract valuable materials from a given area before moving on to another location of interest. However, the commercialisation of space resources may open another legal Pandora box: Not all UN Members consider space resources activities legal and, should the resource be commercialised on their territory, may threaten with legal consequences.

To address these challenges and facilitate international cooperation, debates are being held, particularly within the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS). In the 2022 session, the Legal Subcommittee (LSC) of the COPUOS established a Working Group specifically dedicated to the Legal Aspects of Space Resource Activities.

This Working Group was granted a 5-year mandate to gather information, examine the existing legal framework, and evaluate the advantages of advancing a comprehensive framework for space resource activities, potentially through the creation of additional international governance instruments. The purpose of this Working

Group is to foster collaboration and knowledge-sharing among participating states. By studying the current legal framework, the Working Group aims to identify areas that require further development and explore potential avenues for enhancing international governance in space resource activities.

The intention is to gather comprehensive information on the subject, assess the benefits and implications of different approaches, and propose recommendations for the future. This initiative highlights the recognition among states that addressing the legal aspects of space resource activities necessitates a collective effort. Through these multilateral discussions and the establishment of the Working Group, COPUOS seeks to facilitate an inclusive and transparent process to better understand the legal implications and potential benefits associated with space resource utilisation. To effectively coordinate their national activities, states must come to a consensus on fundamental rules governing these activities.

Another fundamental principle of the Outer Space Treaty, which structures any operational space activity, is the obligation of its parties to authorise and supervise national space activities, whether conducted by government or non-government entities (Article VI). This can be done by licensing space resources activities within their own jurisdictions based on the domestic space or other applicable law.

8.4.1.3 Government Initiatives Towards Laws on Space Resources

Several states have already implemented domestic regulations that govern space resource activities. By introducing authorisation regimes with well-defined rights and obligations, governments have sent strong signals to companies and investors, demonstrating their interest in, and support of, these operations.

As per 2023, four states adopted a domestic legal framework applicable to activities related to space resources: the USA, Luxembourg, the UAE, and Japan. These national legislations enable private entities to engage in the exploration, extraction, and utilisation of different space resources found in outer space, including the Moon and other celestial bodies, knowing that these jurisdictions consider these activities legal.

The laws enumerate necessary requirements the operators must fulfil to obtain mining licenses and engage in related operations, and they aim also to facilitate the supervision and monitoring of space activities.

However, these national regulations are always bound by states' compliance with their international obligations and in particular the principles of liability, responsibility, non-appropriation of land and planetary protection deriving from the Outer Space Treaty.

8.4.1.4 Preliminary Rules for Space Resource Usage

Future space activities conducted on celestial bodies not only involve resources extraction and ownership but also all the logistics and chain of activities supporting the operations. The increasing involvement of private industry and commercial actors requires better coordination between all stakeholders, including governmental entities. This is particularly true if the utilisation of space resources in situ expands further. In this context, multilateral discussions can serve to find points of convergence. Therefore, the rules currently applicable to these activities will need to be interpreted to mitigate risks, including those of collisions and harmful interference, favour information-sharing mechanisms, and set up rights and obligations on governmental entities and, by extension, private operators, based on existing treaties, including the Outer Space Treaty, the Liability Convention and the Registration Convention.

8.4.2 Legal Instruments for the Protection of Investments and Facilities[5]

8.4.2.1 Intangible, Intellectual, and Information Rights

Data policy in future Martian settlements will be driven by the types of settlements that arise and the relationship that those settlements maintain with each other and with their terrestrial sponsors. How these actors envision the nature and purpose of their settlements will dictate the way they understand the protection of their data. The relationship to data and information of a scientific outpost will differ significantly from that of a commercial outpost. International space law gives a starting point for such considerations but leaves much to be determined at the national and bilateral levels.

A core function of the Outer Space Treaty is to structure information sharing among state actors. The treaty requires some information sharing and encourages it at a more general level. For instance, Article IX requests that states share information that is necessary to help prevent harmful interference in their use and exploration of outer space. However, the Outer Space Treaty only dictates a de minimis level of information sharing. Many provisions of the treaty encourage broader information sharing, though they do not make it a hard legal requirement. For instance, Article XI requests that states share information with the United Nations Secretary General about their activities in space and phenomena they encounter.

Data issues for Martian settlements will be complex as there are several considerations that need to be taken into account when classifying data for sharing purposes. Whether such information impacts safety of operations, security of

[5] This section is authored by Philippe Clerc, Mahulena Hofmann, and Laetitia Cesari.

settlements, commercially valuable data, or scientific discoveries will influence the applicable data policy.

As a baseline, international space law attaches great importance on sharing data and information that impacts the safety of operations, and particularly the safety of lives, in the space domain. This can be seen in Articles V and VIII of the Outer Space Treaty, as well as in the Rescue and Return Agreement and the Registration Convention. The establishment of multiple settlements on the Martian surface, or on the surface of any other celestial body, will require those settlements to share data that protects the respective operations and the lives of any individuals within those settlements. Such data could refer to specific phenomena found naturally on the celestial body, for instance weather events, or could refer to the coordination of specific operations aimed at avoiding harmful interference. The coordination of operations for the prevention of harmful interference would, at least initially, be linked to the consultation provisions found in Article IX of the Outer Space Treaty.

Closely related to the safety of operations is the security of operations. Security, herein, refers to protection from external threats that emerge from the militarily or criminally aggressive activities of others. Security issues are distinguished from threats that emerge from natural phenomena or from the activities of other actors that lack an aggressive intent. In international law, international controls on national security information are generally rejected unless there is a specific agreement for the sharing of such information. For instance, bilateral disarmament agreements often facilitate the sharing of national security information in specific circumstances. In the case of Martian settlements, if there were two or more non-cooperative settlements, then it is likely that these settlements would guard security information pertaining to their respective infrastructure and interests. It should be noted that some states extend their security to encompass a number of areas including economic interests and environmental interests, which will both have significant impact on future Martian settlements. To some extent, this is why the Outer Space Treaty only encourages some types of information sharing, with the hope that an open information environment will reduce the chance of conflict.

If Martian settlements are sponsored by, or have significant stakeholders in, the commercial realm, then commercial needs for information security will also play a prominent role. Specifically, discoveries one wants to protect, out of commercial interest, as a trade secret or as a patent, will raise questions on how much data about the Martian environment should be shared. If industry is seen as a critical partner in Martian exploration, then those actors will want an assurance that their investments will pay off. To this end, commercial actors will seek to protect commercially valuable data using a variety of private law mechanisms, such as non-disclosure agreements. Managing the protection of such information will have to be balanced with the needs for safety and security, as well as the need for openness.

A final consideration pertains to data and information connected to scientific exploration and discovery. In the international space law regime, the sharing of information related to scientific discoveries is encouraged and there is a strong tradition of openness. As a result, a number of civil space agencies that focus on science and exploration maintain open policies on scientific data. For example, deep

space astronomy images taken by telescopes such as the James Webb Space Telescope are openly disseminated within a set amount of time after the data is captured. The issue will lie in distinguishing scientific data that is subject to such sharing from protected data categories such as security and commercially valuable data.

Of course, these categories of information are not neatly or easily divisible. For instance, data and information concerning the discovery of a resource, such as a large water reservoir, on the Martian surface could have impacts within each of these categories. Such a resource, as a critical element of life support, would fit within the category of information related to safety of life. At the same time such a resource could be seen as critical to the security of a discrete settlement as it impacts long-term viability. This places tension on how such data should be protected. This is further complicated by the fact that the exploitation of such a resource could have significant economic impacts, and a commercial enterprise might seek to keep such data proprietary and secret. At the same time, any large reservoir of water on the Martian surface would also constitute a significant scientific discovery, thereby placing tension on the principle of transparency found in the Outer Space Treaty. The categorisation of such data will be linked to the conceptualisation of the settlement, and to its goals and purposes

Considering the competing interests vested in data on, and produced, by Martian settlements will be critical to establishing data policies that best serve the distinct stakeholders. Any such policy, though, will need to be coordinated in cooperation amongst stakeholders and most importantly, amongst the various settlements that may emerge.

8.4.2.2 Legal Protection Derived from "Civil" or "Tort" Liability

Terrestrial property rights for land, movable property rights for resources, or industrial property rights for inventions and creations through patents have not been designed and are proving ill-suited to protecting investments and work in the activities on, and on the way to, Mars. They are not conducive to large-scale cooperative ventures, which are the only way to gather the financial and technical capacities required for these activities. Indeed, a claim to exclusive ownership is always a source of lasting tension, both between the various parties involved in a given project, and towards those who are excluded, including future generations. Even today, in the context of the privatisation of these activities, it is easy to understand why the founding treaty of space law prohibits the appropriation of territories and remains neutral on the ownership of resources.

However, space law—as promoted by COPUOS, the International Telecommunication Union and other operational intergovernmental organisations—has already found solutions other than appropriation or ownership of assets to protect public and private investment, or to prevent reservation conflicts over limited space resources, without enshrining the right of "first come, first served".

Since the 1960s, states have adhered to freedom of exploration and utilisation of outer space as a fundamental principle (Outer Space Treaty, Article I). While space activities often occur within shared orbits, each is distinctly and independently conducted by its respective operators. Entities such as the Space Services Department of the International Telecommunications Union have played an important role in coordinating these efforts, ensuring coordinated distribution of orbits and radio frequencies to minimise potential interference (ITU Constitution, Article 1). However, as space activities grow both in scope and scale and are accompanied by an increasing number of objects being launched into orbit and onto celestial bodies, discussions about the protection of these operations and objects have intensified (United Nations Office of Outer Space Affairs, 2019).

These discussions encompass multiple facets of protection. First, they emphasise states' responsibility (Outer Space Treaty, Article VI) and liability (Outer Space Treaty, Article VII) and their obligation to exercise due diligence when conducting their space operations, ensuring they do not infringe upon the activities of other operators (Outer Space Treaty, Article IX). Second, they relate to states' environmental responsibility, especially towards commons (based on the "polluters pay" principle that stems from customary international law) for managing space debris (Larsen, 2018; United Nations, 1938) and the potential hazards of specific objects, especially those with nuclear power sources (Harvey, 2020; United Nations, 1938).

Furthermore, protection extends to ensure that space operations remain unaffected by external interference. It is however worth noting that the protective measures adopted by certain space entities can occasionally interfere with the rights of others, notably their access to specific orbital and celestial locations (Schingler, 2020).

In response, several national efforts, such as the Artemis Accords, may also enable the operator to request the help of the police to put an end to "*abnormal neighbourhood disturbances*", by analogy with the civil code, or its equivalent in common law, enforced in many countries. Conversely, it obliges the operator to take responsibility for any damage caused by its activities and installations to third parties or to the global environment, and of course to national or intergovernmental authorities with legal jurisdiction.

The "safety zone" concept has also been transposed to the security and protection of the vicinity of satellites and other in-orbit infrastructure against unfriendly approaches from other devices or systems (espionage, jamming, neutralisation). This is particularly true of France's space defence strategy, as formalised by Armed Forces Minister Florence Parly on July 25, 2019 at the Lyon Mont-Verdun air force base. The notion of territorial ownership in-orbit has no practical or legal meaning in areas that move continuously at a rate of at about eight kilometres per second! The protection extends to a defined moving zone of space which encompasses a volume of space centred on the object to be protected

The notion of "safety zone", when justified by legitimate safety and investment protection on the part of responsible private operators duly authorised by their state, may prove to be an easier, more effective, and a more proportional legal tool than a claim to an absolute and permanent ownership of land or property, which cannot be

approved according to the most widespread interpretation of space law derived from the Outer Space Treaty.

It also complements other instruments that propose similar mechanisms for different purposes, such as the protection of historic sites and artefacts, and of specific zones to deconflict activities for extraction purposes on celestial bodies, or for other types of in-orbit activities (for example, the COSPAR in 1964, with Project West Ford and Starfish Prime, the 2011 NASA historical protection recommendations, the 2013 HR 2617 Apollo Lunar Landing Legacy Act, the 2019 Hague Space Resources Building Blocks, and the 2020 One Small Step Act).

Finally, private players can obtain *specific rights* from governments or governmental organisations in compliance with the Outer Space Treaty. *Concessions, delegations, and emphyteutic leases* may be less absolute than ownership rights, but are sufficient to grant that their investments are protected in terms of duration and area of operation.

In this respect, one may recall the precedent of the two-headed organisations set up at the end of the last century to operate commercial systems (Intelsat, Inmarsat, Intersputnik, Eutelsat...) for access to frequencies and domestic markets or public facilities. It should also be remembered that the new forms of public–private partnership governance models recommended in Sect. 5.1.2 could be inspired by such organisations.

8.4.2.3 Way Forward

Various initiatives, such as the US led Artemis Accords, China's Moon-mining endeavours, and the Hague Building Blocks, contribute to the ongoing international discourse concerning the first human settlements on Mars, and the extraction and management of resources.

While the legal status of celestial bodies and their resources is a crucial aspect, equal importance lies in addressing the challenges associated with movements of people, housing, and interaction during projects on space resources, regardless of whether individuals are part of the same mission or not. Additionally, contingency plans and rescue protocols must be established to ensure the safety and security of crewed operations in space. Achieving these objectives necessitates robust international coordination among the stakeholders to foster collaboration, establish common standards, and effectively respond to potential emergencies.

In international locations, such as the Antarctic, the high seas, and outer space, states always opted for a collaborative approach. They might have varying levels of development and thus rely on each other's support. Additionally, in the event of accidents, cooperation becomes crucial as activities in rough environments can be hazardous. There is hope in the rationality of the potential space mining actors and their interest in operation in an interference-free environment. An international system of coordination drafted by the UN COPUOS and based on the experience of other international coordination structures, such as the International Telecommunication Union, would be a solution.

8.4.3 *Ethical, Societal, and Political Aspects (1000 People)*[6]

It is assumed that the first crewed missions and permanent science outpost would be mostly or entirely operated by space professionals. Thus, we can assume that their code of conduct as well their moral status could be most suitably assessed from the perspective of professional ethics, not unlike that of military or health care professions'. However, in this section, the mission has grown into a settlement of a thousand people. This scale of a Mars settlement is probably not a fully independent or self-sustaining human society yet, but there are a few important differences from the smaller scale outpost. Most importantly, with 1000 people it is safe to assume that not all inhabitants are astronauts, scientists, or engineers, but that there are also maintenance people and providers of different services. In short, the settlement is now also inhabited by the so-called ordinary people, although in very extraordinary circumstances.

This ordinariness does not imply that "ordinary people" on Mars do any less significant work, but rather it refers to their moral status as people who are governed by ordinary morality, which is a system of ethics that applies to most people in most circumstances. Thus, the standard moral theoretical constraints apply to them. With this, we see another system of ethics introduced to Mars, as ordinary morality appears alongside professional ethics. One of the implications of this is that there is a need to consider the needs and wellbeing of people from a broader perspective. Recall that a professional ethic can allow greater sacrifices and more limited pleasures of life. Ordinary morality does not as readily require or allow these kinds of sacrifices and limitations (Puumala, 2023). A risk that is acceptable for astronauts may not be acceptable for maintenance personnel. For a settlement to be good and just, it must take the needs, wellbeing, and safety of individuals better into account.

This change in ethics also changes the rules of moral theorising. Things that are morally permissible, forbidden, or required for specific professionals may not be so for "ordinary people". Also, the rights and responsibilities of "ordinary people" may be different from professionals during their duty time. This immediately affects individual-level ethical questions, but also broader political and societal aspects of the collective level. For instance, the settlement must defend the basic rights of the settlers: if these cannot be satisfied, for instance in terms of guaranteed life support, it is not morally justified to establish such a settlement (Schwartz, 2022).

This is an important challenge for space engineering and habitat design. The moral acceptability of a Martian settlement requires overcoming a series of technological challenges related to the safety and wellbeing of its inhabitants. This is also related to the political and legal issue of distributing resources. As some people have better access to and control over crucial technology (such as oxygen production), there is a heightened risk of tyranny. In the space ethical literature, it has been

[6] This section is authored by Mikko Puumala, Oskari Sivula, Barbara Gonçalves, Maria Hedlund, and Morten Tønnessen.

suggested that space settlements should indeed be designed in a way that mitigates the risk of tyranny, an approach called "freedom engineering" (Cockell, 2019).

8.4.3.1 Civil Liberties vs. Security

At least initially, the biological needs of humans on Mars will remain the same as they are on Earth today. Basic needs for humans, beyond access to vital resources (water, oxygen…), include nourishment, shelter from environmental conditions, protection from enemies, courtship and sexual reproduction, cultural and social needs. On all these accounts, life on Mars in an early settlement stage would likely be very different from what we are used to on Earth. The available habitable infrastructure and the environment should satisfy basic biological needs and viability of the community from the outset. Peoples' behaviour must also adapt to the prevailing conditions. With a population of only 1000 people, the settlement's continued existence would be at risk if too many were maladapted to the new living conditions, especially if the maladaptation of some would affect the majority's experience and behaviour. Mediating such risks and unpredictability could be a reason for restricting individual freedoms regarding, e.g., courtship, sexual reproduction, and family relations (on liberty in space, see, e.g., Cockell, 2013, 2015, 2022).

The issue is that to ensure the safety of a group on Mars, it becomes necessary to impose restrictions on individual liberties. The harsh environment combined with limited resources and the interdependence of the community requires stringent measures, but how much do we have to sacrifice individual freedom to survive? The first arrivals, probably a smaller crew of, say, five to ten astronauts, each selected for their specific expertise, can be governed by an appointed mission commander (Schmidt & Bohacek, 2021). A hierarchical system in which group members give up their individual freedom and subject themselves to the orders of the commander may work well in the short run, but for long-term extra-terrestrial settlements, survival depends on a balancing of the constraints to individual liberties and the required measures to secure survival. Charles Cockell (2013) discusses this balancing act in terms of negative and positive liberties.

Negative liberty pertains to the freedom from interference by other people, often understood as the reduction of governmental restrictions in individual lives, such as in the freedom to choose what to do, think, and say. While one can never be completely free in this regard even on Earth, on Mars, negative liberty is necessarily constrained by the lethal environmental conditions: a very thin atmosphere of mainly carbon dioxide, no running water, mean annual temperature below –60 °C, higher dose rates of ultraviolet and cosmic radiation than on Earth, and recurrent dust storms. These conditions require a high level of technological advancement and make individuals highly dependent on a well-functioning infrastructure that can provide oxygen, water, food, pressure suits, and other essentials for human survival.

The protection of the safety of the individuals and the group justifies constraints on negative liberty, but it also enables positive liberty. Positive liberty refers to the freedom to actively pursue one's own objectives and is often understood in terms of

having access to necessary resources to pursue these objectives, such as money or education. On Mars, industrial provision of oxygen, water, pressure, radiation protection, and so on is crucial for survival, without which no objectives whatsoever could be pursued.

However, a key argument of Cockell is that extra-terrestrial societies always run the risk of tyranny. In contrast to life on Earth, in which people can rebel or escape, the safety concerns of an extra-terrestrial settlement mean that its members have to comply with the ruler. Take oxygen production: the authority that controls an oxygen supply can effectively control dissenters by threatening to restrict or modify their oxygen delivery. This will remind them who is in control of their survival, and through fear reduce the challenge to collective authority. In an environment in which a failing oxygen supply implies death, the individual is likely to refrain from protest. If applied across many areas, the Martian society will end up as a "colony of automatons" (Cockell, 2013, p. 29). While there are similar means to control people on Earth, like threatening their lives, these means are "inbuilt" in the Martian environment, requiring additional consideration of both habitat design and power dynamics in a Martian society.

However, survival alone is not sufficient. To be sustainable, and not develop into tyranny, the Martian society will have to ensure not only the physical but also the mental wellbeing of people. As the extra-terrestrial society grows, it must secure individual liberties both for the sake of individual happiness and for the thriving of the society itself. A culture of liberty must be fostered. It must be possible to question those in power. Power holders need to be legitimate. That is, aspects that are important in democracies on Earth are also important on Mars. Where to strike the balance between liberty and security is a tricky issue. Moreover, these issues may be difficult to determine by a top-down approach from Earth. Instead, close attention needs to be paid to the everyday experiences of the settlers to find sustainable solutions that enhance both the wellbeing of the inhabitants and the overall safety of the settlement. In solving this issue we could then learn (in a perhaps a bit far-fetched manner) from *the local-turn* (see, e.g., Mac Ginty & Richmond, 2013), in peace and conflict studies, that puts focus on local peacebuilding.

8.4.3.2 Worker's Rights and the Exploitation of Workforce

When new inhabitants settle in a territory, the entire legal system, including citizens' rights, is to be established. This is all the truer when it comes to imigrating in uninhabited land, since the first settlers do not necessarily come from the same state and are therefore not all subject to the same legal rules. The first settlements will probably be technical or scientific installations made possible by the financial investments of large companies.

Since the first inhabitants will also be the first workers, initially settled on Mars to establish a scientific or commercial (e.g., mining) base before building a first Martian community, it may be envisaged that the rights of these settlers are partly established by the companies or other institutions that financed their installation.

This possibility was considered by Erik Persson (2015), but he also quickly pointed out its limitations. It could, of course, encourage companies to develop their investments off-planet, allow the new inhabitants to mark their independence with the different countries from which they originate, and allow something new to be rebuilt. But it would also likely result in economic and commercial interests being placed ahead of workers' rights and freedoms and would thus ultimately be an unsatisfactory solution from the point of view of democracy and the protection of human rights.

8.4.4 Cost of a Permanent Martian Settlement[7]

Having established the first scientific bases on Mars we can start to review the opportunities for larger-scale settlement. In this section, we look at how such a settlement programme could be funded.

Elon Musk, in his discussion of a Martian Space City, has outlined the means by which a settlement could be made. SpaceX would use the Starship design to transport the settlers. Creating a stainless steel (producing the problem of secondary radiation in space conditions) rocket, fully reusable, with enough pressurised cabin space to comfortably hold around 100 people on a trip to Mars lasting 6-8 months. The Starship itself measures 160 ft (about 49 metres), but when paired with the Super Heavy booster the entire construction measures 383 ft (about 117 metres). It is designed to take over 100 tons of payload as far as Mars, assuming SpaceX can solve the issue of adding more fuel in orbit. Two uncrewed Starships would first land, then around 2 years later, when the Earth and Mars are close again, two crewed and two uncrewed ships would be sent in a "Martian fleet". The crews would be tasked with setting up a propellant depot and refuelling the ship with liquid oxygen and methane to return home (Heldmann et al., 2022).

Over the course of ten convoys, flying when the Earth and Mars are closest, Musk claimed it would be possible to establish a settlement, the first Mars city. Principal Mars development engineer for SpaceX Paul Wooster explained in September 2018 that the first inhabitants would have to create landing pads, liveable habitats, greenhouses, etc., in order to bring some self-sustainability to the enterprise. This vision in many ways replicates the historical example of the first European colonies in North America, Australia, and New Zealand. The Jamestown settlement in the Colony of Virginia was the first permanent English settlement in the Americas and grew from the first expedition of 105 men and boys and 39 crew members in 1607 to around 1000 in 1624. However, establishing the colony was hard and required regular supply convoys, and even then of the 6000 people who came to the settlement between 1608 and 1624, only 3400 survived. Similar patterns are recorded for other North American settlements. In contrast, the

[7] This section is authored by Nigel J. Mason.

settlement of Australia and New Zealand had a lower mortality rate. The first European settlement in Australia established at Sydney in January 1788, consisted of 730 convicts (570 men and 160 women), 250 marines, and 300 officers and ships' crew in the "First Fleet" of 9 transport ships accompanied by 2 small warships. Despite initial hardships, with the support of supply convoys within a decade the colony was established. The first European settlement in New Zealand (150 settlers establishing Wellington in 1840) was better organised and established a sustainable settlement in only a few years.

Therefore, there is a precedent for establishing settlements in inhospitable environments with an initial population of 100 growing to a few thousand to sustain the necessary infrastructure necessary to make any settlement viable. Indeed according to Impey (2015) a population of at least 5000 is required to ensure long-term survival of an extra-terrestrial settlement. The difference to Mars being that the environment is far more inhospitable than any of the continents on Earth.

How would such a settlement be funded? Again, we may look at the examples of European colonisation for several models. Nation-state-initiated and funded enterprises are probably the most likely mechanisms for the first habitable bases on Mars and may be akin to the scientific bases in the Antarctic. Today there are around 66 scientific bases in Antarctica representing 29 countries, of which about 37 are occupied year-round, the remainder are open during the summer and closed down for winter. These are populated by about 4000 people through the summer months and about 1000 overwinter each year. The cost of operating these bases was estimated at $470 million in 2019–2020 and includes everything from infrastructure and logistics to scientific research and environmental protection. The majority of this funding comes from the United States, followed by Japan, Germany, Italy, and Australia. Similar to Antarctica initially all supplies to Mars would have to be imported, but as the bases develop, as discussed above, local in situ resources can be utilised and even exploited to realise a profitable return for any investor willing to "grub-stake" settlers. Indeed, this was the objective of the entrepreneurs who funded the establishment of North American colonies—The Virginia Company of London funding Jamestown, and the New Zealand Company Wellington, New Zealand. In the Americas, the company paid all the costs of establishing each colony, and in return controlled all land and resources there, requiring all settlers to work for the company. In exchange for 7 years of labour for the company, the company provided passage, food, protection, and land ownership (if the worker survived). Another alternative to companies would be for a settlement to be established by a self-interest group mimicking the Pilgrim Fathers, the settlers of Plymouth, Massachusetts in 1620. There are thousands of cults worldwide with an estimated income of many billions; for example, The Church of Jesus Christ of Latter-day Saints (the Mormons) has an income of up to $200 billion; the Sree Venkateswara Swamy Temple (Hindu) has $35 billion and the Seventh-day Adventist Church has assets up to $20 billion, all are therefore capable of funding a Martian settlement.

Thus, we may envisage early stages of Martian settlement to be led by nations, or as discussed above, by an alliance of nations or even a global initiative. Still, the long-term development of sustainable settlements is likely to involve other actors,

as was the case for European colonial settlement in many parts of the world. As discussed elsewhere in this book, such settlement should be controlled by ethics and legislation (see Sect. 7.4.1, perhaps akin to the Antarctic Treaty but the question remains as to how this would be policed once settlers are resident on the planet. It should also be noted that there is a risk in any private enterprise since they may go bankrupt if the financial model fails or the funder simply pulls out. Historical examples of settlement schemes that failed include the Darien scheme led by the Company of Scotland, backed largely by investors of the Kingdom of Scotland, to gain wealth and influence by establishing New Caledonia, a colony in the Darién Gap on the Isthmus of Panama, in the late 1690s. As the Company of Scotland was backed by approximately 20% of all the money circulating in Scotland, its failure left the entire Scottish Lowlands in financial ruin and is believed to have played a major role in Scotland signing the Act of Union with England (1707). More recently, the failure of the first space launch by Virgin Orbit in January 2023 led to the company being unable to secure additional financing and its suspension of operations in March 2023. Should such a private initiative fail, marooning the settlers, who would assume responsibility and the costs? If we accept current space law the final responsibility for such settlers would still be the Nation-state(s) from which they and the company originate.

8.5 Establishing a Permanent Settlement of 100,000 and More

8.5.1 Governance Models for Large Settlements

The establishment of permanent Antarctic bases regulated by the Antarctic Treaty of 1 December 1959, the International Space Station resulting from the Washington Agreement of 29 January 1998, or the contemporary space exploration projects on the Moon and then Mars provided for in the Artemis Accords led by the United States since 2020, could constitute a model for the first international governance of human settlement on Mars.

The main challenge remains to involve economic players in these intergovernmental cooperation agreements, using the public–private partnership (PPP) solutions evoked in Sect. 7.5. These players of various nationalities or economic sectors, all aspire to take part in the decisions and economic return commensurate with the investment and added value they bring and the risks they assume. However, such associations can flourish around motivated partners, when they are built in "project" mode, i.e. within a well-defined timetable and area of cooperation, with a clear sharing of responsibilities and budgetary, human, logistical, technological, or other contributions between the parties.

A new challenge arises as soon as the goal would be to perpetuate, without any time limit, one or more large autonomous settlements on Mars, with a significant population ranging from 1000 to 100,000 or more.

This development can be illustrated historically by looking at the experience of the first European settlements in America in the fifteenth century, followed by the trading posts or establishments in Asia from the sixteenth century granted for the East India Companies of the Netherlands, the United Kingdom, and France. Authorities, managers, workers and their families are first seconded from their native country to remote, little explored areas to build and operate a permanent establishment there. They are endowed with diplomatic, administrative, and commercial powers, with the aim of providing a link with the local authorities and their sovereign and managing the supplies needed to export goods and services to the home country.

This transitional situation generally only lasts a few generations. The expatriates either eventually return home, rich or ruined, or they settle there permanently because this new world, even if hostile, refocuses their family, their social and economic relationships and can offer them opportunities they could not have dreamt of in their social condition and country of origin. Gradually, this new population frees itself from the control of the country of origin, although it retains the relationships of economic utility and the link of nationality.

It is likely that some level of autonomy would be rapidly achieved on Mars as soon as the first large-scale habitats are installed (full material autonomy and sustainability will take longer time to achieve). It should be remembered that the remoteness of this planet means that there can be no real-time communication with Earth, unlike the human space activities we currently experience in Earth orbit or on the Moon. It takes, *at a minimum*, between about three to twenty-one minutes to send, by radio, voice or image to Mars and the same amount of time to receive a reply. In the event of distress, it is not possible to get out of the situation with the famous "Houston, we have a problem" phrase, as was the case with the Apollo XIII lunar mission in 1970.

The physical, geographical, and social remoteness of Mars in relation to Earth makes it necessary to establish an authority on Mars that is fully empowered to take any useful decision at local level without having to refer to the Earth first. We are familiar with such a geographical division, at the level of each state on Earth, between the executive, regulatory, and judicial powers at local level, in towns, districts, departments, regions, provinces, or states, and the President, Prime Minister, government, parliament, and high courts at central or federal level. In some countries, this dissociation is accentuated between the mainland and the overseas territories, as in France with the "two-headed" administration of the Terres Australes et Antartiques Françaises (TAAF), which governs the French subantarctic islands and Antarctic bases.

On Mars, this decentralisation of powers in relation to Earth should enable the creation of one or more semi-autonomous communities, fully responsible for administering their city, population, territories, public facilities and services, and the entire local economy, while guaranteeing the safety of goods and people. Each

community should also have the power to administer justice at its own level. These communities and their leaders may be accountable to a higher authority and justice system on Earth.

In particular, this governance will have to deal with the sensitive issue of occupation and management of local territories and natural resources between the various interested parties: administration, economy, and citizens. The local mission will be responsible for authorising and controlling settlement and operating permits within a more general legal framework, still defined by intergovernmental governance on Earth, to avoid any import of conflict generated by the distant planet. To this end, a master plan or urban development plan may have to be drawn up in advance, in co-decision or consensus between Earth and Mars, to organise all future settlements. This organisation will have to be careful to grant only concession rights for well-defined durations and activities, to avoid any claim to property rights likely to undermine the principle of territorial non-appropriation instituted by the 1967 Space Treaty.

Fortunately, unlike the history of all terrestrial colonisation, in the current state of our knowledge, no settlement on Mars is likely to have an impact on the existence of an indigenous population or extra-terrestrial "manufacturing" species by creating a dominant-dominated or exploiting-exploited relationship. The most serious risk in this respect will be the contamination or pollution of a planetary environment previously untouched by any human presence or economic activity, with a potentially irreversible impact on future scientific research useful to future generations, to humankind, and to our knowledge of the Universe. This risk will have to be managed by the communities located there, who will have to report to the competent authorities on Earth, in accordance with Articles VI (responsibility) and IX (planetary protection) of the 1967 Outer Space Treaty.

The next foreseeable stage in the longer term, or through crises, would be the acquisition of independence by these Martian communities from their terrestrial authority. Historically, such a movement began on Earth at the end of the eighteenth century between the Americas and Europe or in the twentieth, after the two world wars, in many Asian and African countries.

An independent Mars would raise new legal challenges (Clerc, 2023).The entity on Mars, recognised as independent of Earth, will in turn be able to establish its own sovereign rights and internal institutions. It will also be able to negotiate or renegotiate any bilateral or multilateral treaty with the states on Earth. Such commitments will go beyond the international or intergovernmental legal framework known on Earth. This would create a new law with an *interplanetary dimension*. In this context, will the Outer Space Treaty devised by Earthlings in 1967 remain as a reference for these new Martian institutions and citizens, who are still human but have become independent, and who now regard Earth as their *outer space*?

8.5.2 Growth of Self-Sustaining and Profitable Communities[8]

In contrast to the Moon, Mars is rich in carbon, hydrogen and oxygen, all in biologically readily accessible forms such as carbon dioxide gas, and water ice. Nitrogen is also available in scarce amounts in minerals and in the atmosphere. The Moon is deficient in about half the metals of interest to developing an industrial society (copper, for example), as well as many other elements of interest such as sulphur and phosphorus, whereas Mars has these elements in abundance. Moreover, on Mars, as on Earth, hydrologic and volcanic processes have occurred that may have consolidated various elements into local concentrations of high-grade mineral ore. You can generate power on either the Moon or Mars with solar panels, and while the Moon has the advantage of clearer skies and closer proximity to the Sun this is offset by the Moon's 28-day light-dark cycle. Furthermore, if you wish to manufacture solar panels in situ, only Mars possesses the large supplies of carbon and hydrogen needed to produce the pure silicon required for producing photovoltaic panels and other electronics. In addition, Mars has the potential for wind-generated power while the Moon does not. Mars may enjoy a power-rich economy based upon the exploitation of its large domestic resources of deuterium fuel for fusion reactors. Deuterium is five times more common on Mars than it is on Earth, and tens of thousands of times more common on Mars than on the Moon. However, the biggest problem with the Moon, as with all other airless planetary bodies is that sunlight is not available in a form useful for growing crops because plants won't grow in a light/dark cycle lasting 28 days and the surface is exposed to solar flares. On Mars the atmosphere is also too thin to protect crops grown on the surface from ultraviolet light (UV), solar flares, and the galactic cosmic particle radiation. Thick-walled inflatable greenhouses protected by pressurised UV-resistant domes could be used to create cropland on the Martian surface, and the strong greenhouse effect that could be created inside such domes could produce a temperate climate inside. Such domes up to 50 m in diameter are light enough to be transported from Earth initially, and later on they could be manufactured on Mars out of indigenous materials. Hence it is possible to envisage a more self-sustaining Martian settlement exploiting the planet's richer in situ resources, than what is possible on the Moon.

Following models in human history, we can expect that more than one settlement will develop on Mars, each gradually developing its own identity and philosophy. Whether they will collaborate or compete with one another is likely to depend on the way in which they are formed and funded. A set of settlements established across the Martian surface by a single Nation-state or alliance of states may be expected to collaborate whilst those funded for commercial profit are likely to see others as competitors. This is akin to the European trading settlements in India, which saw not only the then "super-powers" Britain and France, but also smaller nations (Holland, Portugal, and Denmark) establish trading companies in these

[8] This section is authored by Nigel J. Mason.

regions. Each sought to profit by bringing goods and materials to Europe that could be sold with large mark-ups.

The primary question in establishing Martian settlements is their economic viability. In recent years, the idea of sustainable space economy where nations and private enterprises may derive financial benefits from the extraction and utilisation of extra-terrestrial material and energy resources has been discussed. The proposed activities for Martian settlements range from mining asteroids to space tourism and the development of large-scale on-orbit platforms that could offer a range of technical capabilities. However, many of these economic models are just as valid for the Moon as for Mars with the Moon, lacking an atmosphere and lower gravity, having some advantages in the fabrication of materials and drugs. Nevertheless, there have been speculations by Mars colonisation enthusiasts, such as (Walker & Zubrin, 2016) that it may be possible for Mars colony to become profitable by exploiting vast domestic resources of deuterium, which can be used as fuel for fusion reactors. Yet others, including Musk, (Nair, 2012), argue that it is unlikely that Mars would offer anything material that would be financially viable to export to Earth. Perhaps the most viable resource that could be exploited and without the ethical and environmental debates that may restrict mining on the Martian surface would be to mine Mars's two moons—Demos and Phobos—believed to be captured asteroids. The possibility of mining Phobos and Deimos for their natural resources has been suggested for two reasons: (1) extracted minerals might be more easily returned to Earth or Mars or (2) latent materials could be used to build space stations or used as fuel (Ferus et al., 2022; Poggiali et al., 2022). In an example of Space 4.0 public/private exploration, Honeybee Robotics has partnered with NASA and the Japanese Aerospace Exploration Agency (JAXA) to study the chemical composition of Phobos and Deimos. The Martian Moons eXploration (MMX) mission, led by JAXA, aims to determine the origin of Phobos and Deimos. Honeybee Robotics designed and fabricated a Pneumatic Sampler, or P-Sampler, that will capture surface material on Phobos (Kuramoto et al., 2022).

The most likely mining method on these two moons would be open-cast mining removing any surface regolith and tunnelling into eventual veins of specific substances. Due to the very low gravity of these moons, much of the ore will fly off, and a large canopy might be used to collect it. However, the lack of gravity is an advantage in moving mined material around without having to use much power. Rocket fuel for ferrying the mined material to be sent to either Earth or a Martian settlement, or to a space colony, could be produced by breaking down water to form hydrogen and oxygen on the moons. Mining machinery will have to be lightweight and likely be solar-powered, to reduce the need for fuel that would have to be taken to Phobos and Deimos by spacecraft. Mining is likely to be largely robotic to limit the personnel needed to carry out the mining project as this would reduce the amount of supplies, like food, required for a crewed mission. Transport of the miners to and from a settlement on the Martian surface would be akin to travel to and from oil rigs with staff having set shifts on the moons. A space elevator has been considered as being more practical for travel between Mars and its moons than from the Earth to the Moon (Aslanov & Neryadovskaya, 2023).

Mars may also ultimately be the gateway to further interplanetary travel. The interplanetary supply chain may include orbits and locations in the solar system (e.g., on Mars, the Moon, or cislunar space) that serve as sources of propellant and propellant depots. Terrestrial enablers include both physical infrastructure systems and socio-economic "systems" with the Earth being the source of settlers through immigration for a considerable amount of time following the initial establishment of the settlement. Shishko et al. (2017) provide an economic model based on extraction, storage, delivery and processing of water and land, and found that although the commercial viability of mining water on Mars is far from guaranteed it could be met. Similar models may be developed and adopted for other economic opportunities.

Martian Identity and Independence

With the growth of Martian settlements the desire for local governance structures is to be expected. Indeed, strong local leadership will be essential in order to address undoubted challenges and emergencies that are likely to arise during the establishment of structures in the hostile and remote environment of Mars even if, unlike the early North American colonies, communications with Earth and the funding agency are constant. The isolation of the first settlements will also require a local community and collective approach. Thus, in time, even if much of the workforce is rotated, an *esprit de corps* and identity of those spending their lives on Mars can be expected to grow. With it, a desire to have their wishes and ideas heared for the development and conduct of the society and the leadership within the settlement will grow. This identity will only be strengthened if families are part of the settlement, and children are born as part of the Martian society.

Following the historical parallels of European colonies and settlements on Earth there may then come a time when a Martian society will seek to change its relationship with Earth and seek its "independence". It should be remembered that the 13 British North American colonies secured their independence less than 200 years after the first settlers arrived. However, political independence may only come with economic autonomy and this may be the ultimate barrier for the Martian settlements thus, as discussed above, Martian independence and autonomy from Earth may not ever be feasible. Nevertheless, the establishment of a human society operating independently of the Earth would surely be a landmark in human history.

8.5.3 Ethical, Societal, and Political Aspects (100,000 and More People)[9]

At this stage, the settlement will likely inherit many of the ethical, societal, and political problems of Earth. Erika Nesvold's *Off-Earth: Ethical Questions and Quandaries for Living in Outer Space* (2023) explores many of these issues, from worker's rights to dealing with unemployment and crime. These are very human

[9] This section is authored by Mikko Puumala, Oskari Sivula, Ondřej Ditrych, Natuschka Lee, Erik Persson, Nikola Schmidt, Stefan Selke, and Morten Tønnessen.

problems, so it is not unlikely that wherever people go they will be encountered in one form or another. On the other hand, some have argued that as space opens a new page in the history of humanity, the settlements should be designed so that old Earth-problems will not be repeated on other planets. The idea is that we should do better in space.

A sustainable, 100,000-people settlement on Mars requires a constant inflow of new workforce. It is not clear whether human reproduction is possible or safe in Mars conditions (see Sect. 8.3), but both shipping workforce from Earth and producing new workforce on Mars bring about their own problems. What is the legal, political, and social status of people migrating to Mars? What kind of political entity is Mars, if there are no born Martians? On the other hand, if reproduction is possible and safe, there is a need to plan for a full human life cycle from cradle to grave. Martian settlements inherit issues like worker's rights and the full spectrum of political, societal, and ethical questions involved with human life on Earth, but some problems seem to be more pressing or unique on the rather different conditions of Mars. Again, some of the problems are unique to such a large-scale space settlement, and our focus will be on them.

8.5.3.1 Demography

The demography of Mars settlements would likely play out in three phases:

- A first phase where settlers are recruited, and therefore likely to be well-trained professionals with a quite narrow range of ages dominated by people in early/middle adulthood (35–44 years) (cf. Smith et al., 2020)
- A second phase where settlers start to establish families, and some grow old, eventually resulting in an age structure covering all ages
- A third phase where the age structure of the Martian population resembles the age structure found on Earth

In effect, the first phase will be exceptional from a population perspective, whereas the second phase will involve a gradual demographic transition from the initial population profile towards the third, permanent phase. Transitioning to the second phase with establishment of families may require that arriving newcomers get younger over time to facilitate reproduction at this stage. The demographic transition will involve a gradually increasing dependency ratio, with a growing part of the population depending on the labour of the working-age adults. The young, the old, and the sick will have to be cared and provided for, and this will take up more and more resources as the settlements mature. However, the different circumstances on Mars might lead to a new understanding of what labour and working-age amount to, and what is expected of different inhabitants.

The demographic transition that can be predicted on Mars as settlements are established and reach more mature stages, as described above, will be different from the demographic transitions known from most countries on Earth. These have been characterised by a changing balance between births and deaths, starting with longer

life expectancy and thus a lower death rate, and ending with falling birth rates, with rapid population growth in the intermediate period (on demographic transitions on Earth, see, e.g, Roser, 2019). The exact development of the birth rate and the death rate on Mars is hard to predict. However, any successful and self-sustaining settlement of Mars presupposes a sustained period of population growth. This can in principle be achieved either by immigration from Earth, or by a surplus of births relative to deaths. If immigration from Earth continues indefinitely, this could lead to population growth even if death rates were high (and life expectancy short). However, population growth would be more sustainable, if it was after an initial period of immigration-driven population growth mainly based on a surplus of local births relative to local deaths. A precondition for achieving this is a well-functioning healthcare system. While a period of population growth is a prerequisite for successful settlement of Mars, any prospect of overpopulation relative to the practicable carrying capacity of the Martian environment would result in a risk of societal collapse. The population development would therefore have to be balanced and always take into account the availability of resources.

A decisive question in the context of demography and individual liberties is to what extent family planning in Martian settlements would be left to individual choices, or would be a matter of Martian governance. Moreover, it is questionable whether having children in space settlements is morally defensible at all, at least in the early phases of settling Mars. This is because the conditions for living and opportunities for a good life will likely be limited in the early settlements. Thus, perhaps the size of the settlements should first be increased by migration and only later by reproduction when possibilities for a good enough life can be guaranteed for the offspring as suggested by Balistreri and Umbrello (2022). They argue that there is a duty to assure a sufficiently good life for newborns and that this applies in space also. According to them, this means that "[a]stronauts who choose to leave for space have the right to decide to make significant sacrifices, but we shouldn't impose these same sacrifices on other people" (Balistreri & Umbrello, 2022, 3). After all, we do not even know whether people born on Mars can ever migrate back to Earth because their bodies, muscles, and skeletons will develop under lower gravitational conditions (for various health concerns in reproduction biology (see Sects. 6.4, 7.4, and 8.3)).

8.5.3.2 Social Problems

Settling Mars has by some been regarded as a "cultural duty of humanity" (Puttkamer, 2012, 242), although some perspectives still appear naïve and immature (e.g. Kaku, 2018). This applies to many different aspects, such as various health risks and endurance, technical and economic challenges, but also to *social* (i.e. non-technical) risks and problems.

The social dimension is a "blind spot" in space research. This is despite the fact that the NASA publication *Living Aloft* (Conors, 1985) already pointed out the need to address the opportunities and risks of peoples' psychological and social

adaptation to space within a newly established interdisciplinary field of research. However, the state of knowledge at that time ended with critical group processes such as individually different reactions to dangers, the scapegoating syndrome, or forms of destructive shaming of team members.

Basic works on the subject of space are still predominantly technology oriented. For example, the introduction to the handbook *Human spaceflight: mission analysis and design* (2000) only mentions "space-tolerant human physiology" as a non-technical challenge (Larson & Pranke, 2000, 15). The human "environment" is reduced exclusively to the physical environment. The idea of a "social context" remains a gap, apart from references to psychological risks such as spatial confinement, workload, and contingent stress scenarios. The handbook *Space Safety and Human Performance (2018)* also focuses more on medical and cognitive aspects as well as measures to increase psychological resilience (Kanki et al., 2018). Since recently, a new space research field has developed, space psychology, where this aspect is considered from a deeper perspective (see Sects. 6.4, 7.4, and 8.3)

This state of research can be only insufficiently transferred to the design of more complex extra-terrestrial societies. If some day the first Mars settlement with more than one hundred thousand inhabitants exists, it can be assumed that the technical context (life-support systems, protection, security, mobility between Earth and Mars, etc.) will be fundamentally taken care of. Nevertheless, *social problems* will arise that cannot be solved technically. Rather, they will require a comprehensive understanding of society, culture, and civilisation. Potential problems are presented in an overview in Table 8.4 and briefly explained below.

At the *micro level*, identity crises or disruptions can occur in the settlement because the Martian environment and the life there have an impact on the social system. The chronology created by pioneers will lead to idiosyncratic collective formation. From real-utopian projects on Earth (e.g. "Auroville" in India) it can be learned that different cohorts (pioneers, early/late groups, latecomers, etc.) develop different forms of "chronological communitisation" (Selke, 2022, 5–7). Furthermore, the associated role in dynamic group processes in the context of space exploration and space settlement has been discussed only superficially (Gleason, 2012, 36–7). The type of identity formation on Mars can be outlined to some extent with the term "resistance identity" (Venet et al., 2012, 14), because individual and collective identity will develop as a social form of resistance against exogenous influences and endogenous challenges.

Table 8.4 Social problems on Mars

Micro level	Meso level	Macro level
• Identity disruptions and crises • Fragile reproduction of social relationships • Adhesion instead of cohesion • Discrimination	• Ambivalence of heterogeneity • Narrative disintegration • Conflicting motives • Multiple alienation	• Inappropriate understanding of the "social" • Conflicting aims • Mal-adaptive future design • Future poverty

On Mars, there is a risk that the social relationships (as the core of a social system) will prove to be too fragile, due to the inadequate understanding of social roles. In addition, the distribution of roles may be unclear. The so-called boundary roles (Conors, 1985, 288) will become particularly important. These will be performed by people who act as an "interface" between Earth and Mars, as well as between different settlement cohorts and interest groups on Mars. Earthly real-utopian civilisation experiments have shown that although this type of project requires highly confident individuals to initiate it, they quickly generate conflicts among themselves and with the equally necessary followers. This leads to an increase in competition and a decrease in cooperation (Selke, 2022, 371).

Under these conditions, social processes are more likely to be based on competencies typical for Mars, and no longer on hierarchies or privileges typical for Earth. What sounds emancipatory at first, also entails problems, as the social basis can be more of a functional liability (or in extreme cases even manipulative dependency) instead of a life-serving (convivial) connection based on a voluntary basis (fundamental: Illich, 2009). In this context, the role of the so-called shadow work, which takes place in the background, remains completely unexplained. As a result, the decline in social cohesion and the dominance of technocratic adhesion can be expected to lead to a gratification crisis among the settlers.

The problem of discrimination through AI-assisted decision-making is particularly striking. Forms of biometric surveillance are already expanding on Earth. Metric colonisation (Ajana, 2018) is leading to numerous demarcations (e.g. political disciplining through scoring) as well as to new thinking and power structures. The biological, social, and political interactions will be renegotiated. Against this background, the increasing role of artificial intelligence (AI) ranges from an assisting "co-acting technology" to a social partner that supports decision-making. The need for autonomous decision-making is emphasised in the context of space exploration (Nesnas et al., 2021). AI is establishing itself as a problem solver that operates independently of human prompts, and its importance as a "social object" is constantly increasing (Williams & Braddock, 2019). Automated reasoning is considered a key technology for enabling error management on Mars in the first place (Soroka & Kurkova, 2019). People will become "numerical objects" whose biometric profile will be increasingly linked to (local) opportunities. Although this process appears to be objective and rational, it is actually opaque and manipulative. Traditional sociological typologies of power must therefore be supplemented by the phenomenon of *metric power* (Beer, 2016). The question remains as to whether Mars settlers are prepared for the consequences of the transfer of sovereignty from humans to AI (Simanowski, 2021).

Most problems occurring at the *meso level* result from the fact that it will take a long time for generally accepted institutions or institutionalised processes to develop on Mars. Thus there will be a lack of social conventions that would serve as the logic of coordination and reduce complexity (Diaz-Bone, 2017). Mars pioneers are likely to originate from heterogeneous and diverse groups. Although positively connoted characteristics of teams bring advantages, there are disadvantages. Heterogeneity makes it difficult to define situations together, increases the chance

of value disagreements, and brings the risk that no "social centre of gravity" can be developed.

The larger and more complex the Martian settlement becomes, the more interactions between "multiagency participants" will occur. To prevent the heterogeneous actors from falling apart, a socially binding definition of the situation must therefore be created. This requires narrative description and integration at all levels. The greatest risk in this context is an incomplete or even missing "deep story" that convincingly presents the "eternal gains" of the settlement. A "deep story" is a (positive) socio-cultural narrative of a civilisation about itself, on which the community defines itself and distinguishes itself from others (El Ouassil & Karig, 2023).

As long as earthbound narratives dominate, there is a danger of narrative disintegration on Mars through incoherent "deep stories" and misleading motifs. Space therefore needs new stories. "Space is not empty. Space is filled with imagination, visions, ideas and ideologies" (Venet et al., 2012) (see Chap. 10). These visions, ideas, and ideologies must be fundamentally restructured during the settlement of Mars.

The "Charta of the European Astronaut Corps", which served as the basic definition of vision, mission, and values, can serve as a narrative (European Space Agency, 2024).[10] In this (or a similar) way, conflicting motives could be avoided. These could result from the dominance of technology-driven and instrumental-rational motifs over meaningful and value-rational frames of reference. A risk is that the technical means move to the foreground and the meaningful (cultural) goals to the background in the motive stories of the Martian community.

In extreme cases, multiple alienation processes can lead to an "ET culture" (Battaglia, 2009, 220), whereby the "ET effect" is not caused by the encounter with aliens. In this case, the "aliens" are the former terrestrial inhabitants of Mars. This alienation effect will range from latent scepticism and prejudice to manifest in conflicts over resources.

Finally, at the *macro level*, there is the problem of a misunderstanding of the "social" that is inappropriate to the new environment. A new social theory of Mars is needed, especially considering the division between humans and AI that has already been outlined. This also applies to social subsystems such as politics, business, media, and culture.

Therefore, the "social" must be reconstructed in order to avoid conflicting objectives. These arise as a result of the double contingency (expectations of expectations) between Earth and Mars, i.e. between two increasingly loosely coupled social systems. This raises the question of which goals should be the focus of Mars settlements in the long term. The novel "White Mars" (Aldiss & Penrose, 2000) provides a literary illustration of this problem. If the focus were solely on technological development or the exploitation of resources ("red Mars"), this would result in a conflict with the political-normative ideal of space research with the presence of

[10] https://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/European_Astronaut_Selection_2008/European_astronaut_charter

humans on Mars ("white Mars"). In essence, the overall aim can be only about the expansion of the human sphere, the liberation from previous boundaries, and the path to a polycentric world or cosmology.

A permanent human civilisation on Mars means designing a new world. At its core, this is not a technical task, but a task of political and public design with many prerequisites (Borries, 2016). In order to achieve this awakening, "utopian capital" is needed (Selke, 2022, 457–59) which then leads to a transformation "by design" and not "by disaster". If not properly designed, the crucial social problem of settling Mars would be a mal-adaptive future based solely on fear-driven adaptation narratives. Instead of "future euphoria", structural resignation would then arise in the long term (Selke, 2025). The reason for this is an inadequate connection between cognitive future designs and emotional images of the future. At worst, there is a risk of a "giving up–given up"-syndrome in the next generation, with the catastrophic effect of social anomie.

On Mars, too, the greatest challenge will be to transform human existence into a meaningful life. In order to adequately counter obstructive social problems and to make constructive proposals, it is helpful to remove the "blind spot" of social issues in the debate on space exploration and space settlement, and furthermore, to take seriously and strengthen the role of sociological knowledge in the future space exploration.

8.5.3.3 Safety and Governance

The histories of past human societies on Earth may be informative with regard to some of the requirements for successful governance on Mars. As Jared Diamond (2011) stresses in his book *Collapse: How Societies Choose to Fail or Succeed*, many past civilisations have gone through steep decline quite suddenly, not long after their peak power or complexity. Key factors in explaining why societies collapse include environmental fragility and mismanagement of resources, hostile relations with other societies, and the mal-adaptive development of political institutions and culture. In Diamond's view, mitigating the risk of societal collapse requires long-term planning, anticipation of emerging problems, avoidance of prioritising short-term interests, and a willingness to accept cultural change and reconsidering the core values of society as history unfolds.

Settlements could be run and organised in different ways. Schwartz (2022) argues that the demanding nature of space environments should oblige any space society to provide its citizens with guaranteed access to life support. She also argues that space settlement projects that have a high risk of life-support insecurity should not be pursued. Cockell (2009) suggests that any extra-terrestrial state must vivify the sense of individualism in the state's population and resist the temptation to serve special interests, which could easily lead to tyranny.

In terms of governance models, unified governance for all settlements has some clear advantages, but also results in vulnerabilities and risks. Particularly, a settlement system with unified governance is very vulnerable to takeover by rogue actors,

since it is much easier to assume control over a centralised, unified system than a more diversified system. For the sake of the planned survival and growth of Mars settlements, it might be safer to apply settlements that are organised in several smaller, self-reliant units. With such an organisation, rogue actors would be less likely to be able to take over all settlements. It might be possible to balance centralised and decentralised organisation within one and the same settlement design. For instance, Lordos and Lordos (2019) outline an urban design where self-reliant villages are connected to jointly make up a city. Concerning the choice of a governance model for a Mars settlement, they recommend a participatory democracy inspired by ancient Athens' direct democracy for citizens. If the governing council governs the entire city, as they outline, governance would be unified. Having a governing council for each village would make the villages even more self-reliant and would also allow for more diversity over time.

Related to this, one interesting question is whether all settlements would be planned, for instance by applying urban planning (Hollander, 2023), or whether there would additionally be more spontaneous settlements, as a result of societal developments. If governance in established settlements broke down or lost authority, it is conceivable that breakaway settlements could emerge, which might perhaps resemble favela-style settlements characterised by criminal gangs and parasitic exploitation of key resources such as oxygen, energy, and water. Such improvised settlements could potentially be established by some individuals in human-made structures that were not constructed for habitation but that could still secure the survival of these individuals. This would deprive planned settlements of some of their resources and make them less efficient, and perhaps less functional than planned. However, such scenarios might be unlikely considering the harsh environment of Mars. After all, the governing authority can stop supplying goods necessary for survival or stop protecting the rogue individuals from the environmental horrors of Mars. The rogue actors would have to manage the production of essential goods and to improvise adequate and sustainable shelter (cf. Morales, 2022)—something which is close to impossible on Mars.

Nonetheless, something similar could occur if rogue actors took over some but not all of the established settlements. Conceivably, such a rogue actor could be a contracted private actor with its own agenda (think of a private but state-funded military company such as the Russian Wagner group) or a public unit run by someone with a personal agenda. Seizure of settlements could be motivated by private or commercial gain, or various political aims ranging from changing Earth politics to changing policies impacting the living conditions of settlers. The aim of the rogue actor could be to use the seizure of settlements to negotiate from a position of strength. If so, then a governing entity might possibly end the seizure and regain control over all settlements on negotiated terms. However, if the rogue actor's demands were too unreasonable or were deemed to be too costly, a governing entity may prefer combat to negotiation. However, combat may be deadly for all parties taken the environmental realities. Thus, societies on Mars may be extremely prone to collapse unless strong democracies take root there (Morales, 2022). On the

relation between private companies and sovereign states in the context of space law, see Paladini and Castellucci (2022).

Moreover, if the rogue actor's aim was to end human settlement on Mars, a seizure of settlements could easily become even more devastating, for one thing, because it might imply an attempt by this actor to take over all settlements on Mars. Risks would be heightened further if the seizure of settlements was part of a suicide mission where the involved actors were willing to lose their lives for the cause of the rogue actor. Centrally controlled provision systems would be particularly vulnerable to this kind of relentless sabotage. Conceivably, applying such a strategy could be considered, e.g., by a Great Power on Earth if its relations were hostile with another, enemy Great Power, who monopolised Mars settlement and utilisation of Mars resources. Similarly, a (terrorist) faction, e.g., with strong political or ideological convictions within a Great Power might also consider applying such a strategy to get its way. Several of these risks would be alleviated by maintaining peaceful relations between and within Great Powers on Earth, and by having a cooperative, inclusive approach to settlements of Mars.

The risk of rogue actors interfering with plans or operations related to the establishment or administration of settlements raises the question of what kind of criminal justice system a governing entity would apply and operate on Mars. Rogue actors could be resourceful and organised and have powerful supporters, but rogue actions could also start out with one disobedient individual. If the circumstances allow this individual to gather increasing support, even the actions of one person could ultimately threaten the whole settlement. After all, it is much easier for an average individual to cause untold harm on Mars compared to Earth since the surrounding environment on the red planet is so hostile; a simple improvised explosive device could kill everyone on a settlement if it were to destroy essential life support (cf. Huttunen & Sivula, 2023; Persson & Savulescu, 2012). Besides the existential risk posed by a potential rogue actor, there would also be a risk of various crimes that are morally intolerable or harmful to social cohesion.

The workings of a criminal justice system on Mars should preferably be transparent, predictable, and be perceived as fair. This might be easiest to achieve if Mars settlement is arranged by a broad international coalition, even though cultural differences in perception of fairness and justice will be a challenge even for a consensus-based coalition. Imprisonment of convicted criminals will take up resources that are limited. Thus, fines or withholdment of valuable resources could be the most common type of punishment but it is conceivable that we could see other forms of punishment, such as corporal punishment, take place in Martian societies. Given the settlers' dependence on the provision of air, water, energy, etc., banishment from a settlement might in effect be a death penalty—unless the banished criminal could practically join another settlement or establish a spontaneous, parasitic settlement. In the latter case, even banishments would be costly for the settlement as a whole. Any criminal fugitives from imprisonment systems would raise similar issues. Deportation back to Earth would be extremely costly and would rarely be chosen as the preferred course of action. If the behaviour of criminals could be reformed, so as to be more compliant or considerate, that would certainly

be in the settlements' interests. In the future even biomedical means for such ends could be used, especially if biomedical human enhancement is common among Martians (see Sect. 7.7.1 on human enhancement). Overall, space settlements may force us to entirely rethink punishment and hence in the future there may be more and more voices calling for a reform to our practices of punishment—even abolishment.

It is hard to predict how strict punishments a criminal justice system on Mars would operate with. While a strict regime might be deemed necessary by some, given the need for order, solidarity, and predictability, a strict regime would most likely be more prone to abuse by rogue actors and create discontent than a softer, more humane one. Hence, a delicate societal balance must be found for the settlements to be stable. Otherwise, dissent (and potential rebellion) among people may rise. Furthermore, as already noted, moral and social norms might develop differently among Mars settlers than on Earth.

The risk of rogue actors emerging in the Martian setting, the risk of military or other conflicts between Great Powers involved in establishing settlements on Mars, and the risk of everyday and more serious crimes, all lead to a need for security systems. However, monopolising of security systems by any one actor could prove to be counter-productive, as it might heighten the risk of conflicts. Actual—not forced—unity would mitigate both the risk of war and the risk of rogue actors more generally (cf. Morales, 2022). Given the cultural and political diversity among countries and humans in general, unity among humans can only be achieved by cultivating a culture of deliberation, trust, transparency, and tolerance for diversity. As Cockell (2009) argues, planning for and stimulating a culture of liberty among settlers is necessary to minimise the risk of tyranny. A politically free society would require tolerance for heterodox ideas, including those that contradict the state's views, and avoidance of any dominating state-sponsored system or ideology. In Cockell's view, the culture of liberty in the extra-terrestrial state should include values stressing equality of opportunities and individualism. On the other hand, he argues that some economic inequality is the price to pay for a maximally free society, which would otherwise benefit the settlement.

What is also needed is a diversity of skills. Multiple long-term risks and adversities will affect the survival and wellbeing in the Martian settlements, including for instance the technical failure of life- support systems of its habitats, or of the maintenance supplies of communities. Thus, in the long term, the shortage of intellectual capabilities and practical skills may be problematic (Elvis, 2022). Without accommodating diversity, the settlement risks collapse. Lordos and Lordos (2019) suggest designing a Mars settlement with cultural diversity and social cohesion in mind. They recommend a physical configuration involving a central hub and a number of villages, each based on a complex system of tunnels and self-sufficient with regard to power generation and life-support systems. At the same time, each village would contribute uniquely to the settlement's infrastructure by taking care of specialised tasks with the workers for relevant professions. In addition to contributing to the maintenance of the settlement's physical infrastructure, each resident would choose an ancillary profession, and spend some time, e.g., as an educator, scientist, artist,

sports coach, chef, gardener, interior designer, or fashion designer. This design of the settlement, they argue, would provide the settlement inhabitants with healthy, fulfilling human experiences while simultaneously encouraging a diverse society and multi-layered identities.

8.5.3.4 Mars–Earth Relations, Geopolitics, and Conflicts

The future relations of human settlements on Mars and policies on Earth will depend primarily on the design of the settlements, together with the character of their *fundatores terrani*—i.e. the collective associations on Earth, whether public or private, which act in legal and factual terms as founders of the space settlements. In general terms, the governing of the space settlements—and/or the critical traffic corridors and infrastructure—has been discussed in relation to planetary sovereignty (Haqq-Misra, 2023), extension of liberty beyond the Earth (e.g. Cockell, 2015), technological and environmental challenges, extra-terrestrial governance (e.g. Cockell, 2015; Szocik et al., 2016), interplanetary relations (Cockell, 2022), government/industry partnership in settling space (Brown, 2016), and to space expansionism´s ethical quandaries (e.g. Billings, 2017). These complex relations between stakeholders and subsequent complex infrastructures are not limited to flat plots on the Earth's surface, but are spread to open space through various orbital paths based on various concepts of transfer orbits (Miele & Wang, 1999) or circlers useful for cargo (Pelle et al., 2019). They will all have a profound effect on the establishment of stable political relations. The direct dependency on Earth of any settlement in space, given the comparably vast and cheap (though depleting) resources Earth possesses, will also have profound effects on the cooperative political model if we accept that *feudatory* relation is normatively and practically unacceptable.

It is likely that, irrespective of the nature of the *fundatores* and inscribed political designs, settlements will over time develop a certain degree of autonomy and develop their own identities, interests, and divergent governance designs, not mimicking those on Earth, that can produce frictions and conflicts both with regard to the *fundatores* and among themselves. A transnational authority may limit these frictions, but also to become the very site and object of contestation. The brighter side of this problem could be the emergence of a new *transplanetary* political entity governing first relations of the planets and later the planets themselves, whose decisions are binding to both political entities. Currently we know such a model from the relations between the European Commission and the EU member states.

The geopolitical rationality extended to Mars is a likely challenge to the universalist, technocratic, and depoliticised vision of space exploration, given the currently intensified Great Power competition in global politics. It represents the controversies outlined above and would be affected through territorialisation and militarisation of both settlements and the key access lines (e.g. the Hohmann transfer orbit) and points. (An imperfect historical analogy would be the Atlantic Ocean in the early modernity, featuring an assemblage of state, privateer, and pirate actors pursuing their interests along the navigation lines to the "new world".) Conflicts or

tension between the settlements on Mars can be the direct extension of geopolitics on Earth. It can also be a gradual process in which settlements established by different *fundatores terrani* can develop conflicts among themselves due to the competition for resources on Mars, or as agents of further settling of the solar system. (Again, an imperfect historical analogy featuring a conflict of settlements involving their *fundatores* and so becoming a systemic war would be the Peloponnesian War.) Yet another scenario would be a conflict between confederated settlements on Mars and those on Earth ("Blue on Red") structured around governance, identity, or resources issues and stimulated by degrading capacity of earthly *fundatores* to exert power and influence.

As settlements scale up and the Martian population increases, the question of sovereignty emerges. Haqq-Misra (2023) has made the case for making Mars independent as a "juridical peer to Earth" from the beginning. This is an unlikely scenario unless settlements are established by private entities with both the will to create new political entities (as illustrated by Elon Musk's public propositions) and capacities to withstand the earthly states' predictable opposition. More likely, Mars can become gradually emancipated from the Earth and therefore "sovereign", including as a result of military conflict (see above). Such a pathway to independence may or may not involve establishing of a supranational authority tasked with governing the settlement(s) but under the control of earthly powers as "principals". Sovereignty would, however, assume a high degree of self-sustainability.

An astonishing large part of science fiction narratives (literature, books) are built on wars in space, be it that Earth is attacked by hostile aliens, or that different, alien civilisations somewhere far out in deep space fight over power, resources, or survival. The classic, mythological fight between the good and the evil on Earth has simply been moved out to space. In each of these narratives, some form of military, or fighting/defending heroes are involved. While most of this is regarded as pure fantasy, these narratives do reflect, from a psychological point of view, humankind's unconscious fear of its own annihilation and the unknown in space. Thus, it is not surprising that the military played a significant role during the early space age, especially as they were also in charge of, for instance, suitable flight vehicles and monitoring instruments. After all, some of the masterminds of the first successful spacecraft had previously been working for the military during the Second World War. Fortunately, the focus of attention moved stepwise away from military operations to research, collaboration, and knowledge for the benefit of mankind. Nowadays, military activities in space seem almost like a taboo. As Daniel Deudney has noted:

> while it is universally acknowledged that military activities have played a very large role in actual space expansion, prospective military activities and scenarios for large-scale violence largely disappear in nearly all visionary schemes for the industrial development and colonization of space near the Earth, as well as for space expansion across the solar system (Deudney, 2020, 27–8).

Bleddyn E. Bowen (2022) has recently claimed that the original sin of space technologies is that they were developed not for the collective benefit of humankind

but for military use. Indeed, elaborate organisations and instruments or weapons with military purpose (either for monitoring, defence or for attack) have nevertheless been set up, ranging from military units to military satellites, military communication, military spaceplanes, to different types of weapons in space. These units are in fact being expanded all the time, especially since new countries join the space race and start to plan for their own space missions and space bases. Fortunately, different kinds of treaties have been formed, such as the Outer Space Treaty, the Moon Treaty, limited test ban treaty, and the Prevention of an Arms Rate in Outer Space (PAROS).

However, considering mankind's own history, wars have always been prevalent throughout time up to the present day. How likely is it that wars or at least conflicts can be avoided on Mars or between Mars and Earth? Due to such geopolitical risks related to space activities and space settlements in particular some scholars, such as Ian Crawford argue for strengthening international institutions up to the level of world government or statehood. If such fully fledged cosmopolitan solutions are unrealistic or unwanted, at least new global institutions such as "world space agency" under the UN auspices could be desirable to enhance peace and security in space (Crawford, 2021, 2022).

8.5.3.5 Ethical Considerations of Non-humans on Mars

Human settlers would almost certainly bring along plants and animals for social needs and to improve mental and physical health. That the settlers would bring traditional livestock animals to Mars, or even raising animals e.g., from embryos, for purposes of nourishment is improbable since nourishment could in principle be met with a vegetarian diet. Such a diet would only necessitate cultivating plants, microbes, and fungi (including yeast) indoors. However, insects could conceivably be part of the "Martian diet" because they could provide animal protein and it is presumably easier to grow insects on Mars compared to livestock. Keeping of insects could also perhaps provide pollination and other ecosystem services for food production. According to the Cambridge Declaration on Consciousness (Low, 2012), there is very strong evidence to support that insects possess the neurological elements of consciousness. Moreover, the New York Declaration on Animal Consciousness (Andrews et al., 2024) states that if an animal is likely to have conscious experience, we have a responsibility to consider welfare risks and how our actions affect the animal. This makes insects morally considerable, but most people will have a gradualistic approach to how much their welfare should matter compared with the welfare of cognitively complex beings such as humans, other mammals, and birds. If insects have a lower capacity for welfare compared to typical livestock animals, then farming them would be less problematic from an ethical perspective. Lab-grown meat, which would involve animal tissue but not animal individuals, and thus no suffering, is also an option if producing it ever becomes adequately cost-efficient. Of course, if insects or lab-grown meat is added to the diet, it would not be purely vegetarian anymore. The issue with livestock is that, even small

sized ones like chicken need space and resources in form of animal feed and waste recycling. In terms of feed conversion ratios, keeping laying hens for egg production would be more economic than keeping any animal for meat production, but even egg production would require at least twice as much feed by weight as the food produced (Fernyhough et al., 2020). Companion animals might be an option, but they would also have to be accustomed or adaptable to a contained environment. However, they might be very valuable asset to promote the wellbeing of the humans.

From an animal ethics perspective, it has to be questioned, whether, how, and under which conditions it should be allowed to bring and/or raise animals on Mars. In moral terms, whether or not a good life for the animal is attainable on Mars is decisive. It will also matter to such assessments whether the presence of animals is useful for humans, or beneficial for human quality of life. If the human–animal coexistence is experienced as mutually valuable for humans and animals alike, this can also play into our assessment of animal quality of life.

"Blind passengers" of various species would likewise be present, if for no other reason, then because humans, livestock, and companion animals all carry with them microbiomes that involve multiple microbial life forms, and indeed, they cannot thrive without them (Knight et al., 2017). The human settlers alone would therefore already make the settlement multi-species.

The human settlers would not have any natural enemies of other animal species. Apart from the risks posed by microbes, larger blind passengers such as insects and maybe even rodents could pose serious threats to the food supply and agriculture, and maybe even other life-support systems. Rodents, for instance, are known for chewing on cables and digging through structures. As is well-known from Earth, dealing with invasive species is very difficult, and almost impossible once they have established themselves. Pest control might therefore be treated in a similar way as planetary protection or become an integral part of it. It may also call for very strict border controls for transports between Earth and Mars

8.6 Take-Home Message

Several private entities have stated their goal of creating a permanent settlement on Mars. Individual motivations for relocating there are diverse: to serve as a member of the scientific, engineering, or maintenance staff, to establish an ideological or artistic community, or to become engaged in profitable industries.

Some economical visions for such settlements are based on the idea that space and our neighbouring celestial bodies would offer possibilities for establishing profitable entrepreneurship, perhaps based on a hydrogen fuel production economy or the mining of deuterium, or by using it as a home base for the exploitation of the Martian moons Phobos and Deimos, or even the asteroid belt.

The most prominent project has been announced by Elon Musk, CEO of SpaceX. His vision includes a community of a million inhabitants on Mars, established within a hundred years, a local economy based on tourism, on the exchange

of consumables and services between entrepreneurs, and on interplanetary economic exchange. For such a permanent and economical human settlement to emerge, extensive experience and a wealth of novel technologies would need to be gained during Moon and Mars missions of a smaller scale. As an obvious example, the interplanetary journey and landing on Mars would need to become cheaper and safer. Permanent landing and launch facilities may, for instance, be needed on the surface, with spaceport facilities featuring air-lock access to pressurised vehicles or perhaps trains to move the passengers to the habitats. Additionally, for such settlements to be feasible, adequate in situ resources (water, all necessary minerals, and locally produced food) should be available to allow a self-sustaining existence. Efficient systems for recycling all consumable materials would need to be established. Durable construction designs and methods should be used to extend the habitats and infrastructure to cover the needs of the increasing population.

If people are aiming to stay permanently on Mars, and to reproduce and raise families there, the maintenance of their physical and psychological health becomes all the more challenging. Contrary to short-term missions, where only extremely fit, healthy, and trained astronauts are likely to be onboard, large-scale settlements would provide opportunities for a more diverse population to arrive on Mars. With them, they may bring various new health concerns and needs. In addition, once settlers come to stay, entire lifespans will eventually be spent on Mars, adding challenges that arise from the normal ageing process. Ageing may also be enhanced by the Martian environment.

A further problem would be reproduction biology. Whether pregnancies, embryo and foetus development, and childbirth would proceed normally in the Martian environment is currently unknown, as is the answer to the questions of whether children would develop normally in these conditions, and whether they will ever be able to visit the Earth.

In addition to specialised health services, a permanent human settlement on Mars will face needs related to the wellbeing of the community. Education, societal, social, and cultural services must be provided. Constructing the social structure of the community will further increase the size of the settlement. Settlements would also require a legal code and governance that are adjusted to local circumstances, and regulate the relations of the settlements with each other and with their terrestrial sponsors, and the rights to use local resources without the appropriation of the land, etc. These newly emerging regulations may be established in the form of new international treaties and agreements, such as the Artemis Accords, which must be compatible with the existing international space law, i.e. the Outer Space Treaty and the national laws of the operator(s). They must promote the safety and security of the settlements and investments and respect the rights of all humanity, including future generations.

The emergence of larger settlements and communities on Mars would also generate a multitude of questions related to the ethical, political, and societal status of people migrating to Mars and possibly staying there for the rest of their life.

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Chapter 9
Mars as a Planet B?



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9.1 Terraforming Mars: Planetary Issues[1]

The surface of Mars is hostile to all forms of life that we know and in particular to human beings. In order to transform Mars into a planet with properties closer to those on Earth, more suitable for habitation by living organisms and conceivably humans, it has been speculated that the entire planet and its climate could be altered by the means of a planetary-scale engineering, a process that is referred to as "terraforming".

The concept of terraforming a planet has been developed in works of science fiction since the middle of the twentieth century (see Sect. 10.1) and in various speculative scientific studies starting in the 1960s. Nowadays, terraforming Mars is a widely known concept that has been popularized in novels (e.g. "The Sand of Mars" by Arthur C. Clarke in 1951, or the "Mars Trilogy" by Kim Stanley Robinson, 1992–1996), movies (e.g. "Total Recall", 1990), video games and board games. Elon Musk is famous for advertising terraforming Mars. At Space X's headquarters in Hawthorne, California, next to Musk's office, a wall is decorated with two giant twin images of Mars: one with Mars as it is today, reddish and barren, and the other showing a blue Mars covered with seas and rivers, terraformed by engineers.

In practice, terraforming Mars can correspond to different definitions, goals, and requirements. In line with the previous chapters, we can distinguish:

(i) Increase the atmospheric pressure to allow human beings to perform outdoor activities on Mars with an oxygen mask only and no pressure suit (this implies no requirements on temperatures nor presence of liquid water).
(ii) Transform the environment to allow terrestrial organisms, possibly genetically modified, to survive and develop.
(iii) Create an Earthlike atmosphere breathable by humans, other animals, and all terrestrial plants.

Are such modifications of Mars possible? After all, humans have been able to significantly modify the Earth's climate by releasing massive amounts of CO_2 into the atmosphere. In this section, we discuss the different definitions of terraforming, their requirements, review the various strategies that have been proposed, and evaluate their feasibility. Spoiler alert: we conclude that terraforming Mars is nearly impossible, and certainly several orders of magnitude more difficult than what is described in the pop culture or in the many pseudo-scientific articles that can be found on the web.

[1] This section is authored by François Forget.

9.1.1 Thickening the Atmosphere

9.1.1.1 Requirements for Human Beings to Live on Mars Without a Pressure Suit

With a mean surface pressure of 6.1 mbar and always less than 14 mbar, the Martian atmosphere is too tenuous for humans to survive without a pressure suit. Even in the deepest valley, the boiling point of water, and therefore of blood or saliva, is less than a few degrees Celsius, well below body temperature. To avoid water boiling at 37 °C, an absolute atmospheric pressure larger than 65 mbar (boiling point) is necessary. However, such a pressure would still not be high enough for humans to get rid of a pressure suit, because we need a minimum partial pressure of oxygen to avoid the various problems related to hypoxia (our body is mostly sensitive to the partial pressure of gases). An ultimate limit is given by the partial pressure of O_2 at the top of Mount Everest (80 mbar), where a few well-acclimatized alpinists have been able to survive for a few hours. In reality, to work efficiently, without risks, and without long-term health issues, humans need to live below the equivalent of about 5000 m of altitude on the Earth, corresponding to a partial pressure of oxygen P_{O2} = 120 mbar. Therefore, we suggest taking 120 mbar as the minimum atmospheric surface pressure (whatever the atmospheric composition) that would allow humans to work and walk on Mars without a pressure suit, just breathing pure oxygen at 120 mbar or more in a mask (and probably wearing warm clothes). In comparison, the NASA Exploration Atmospheres Working Group (NASA EAWG final report, 2010) recommended that long-duration Mars surface habitats should be able to operate at P_{O2} = 155 mbar (32% O_2 at 483 mb absolute pressure). ISS astronauts performing extra-vehicular activity (EVA) using the NASA Extravehicular Mobility Unit (EMU) spacesuit breathe 100% O_2 at 300 mbar. However, the main reason a lower O_2 pressure is not used in spite of the fact that it would improve suit mobility is because that would result in a higher risk of decompression sickness when leaving the ISS 1-bar Earthlike air. On the ISS, 4 h of breathing pure oxygen is required before an EVA to purge the tissues of nitrogen. It would take more time with a lower O_2 pressure in the spacesuit.

Whilst an atmospheric pressure of 120 mbar would be sufficient to get rid of pressure suits, it would still require using pressurized long-duration habitats, greenhouses, or domes because only pure oxygen can be breathed at such low pressure over the long term. This is acceptable in a spacesuit, but this is now considered to be too dangerous in a full habitat because of the risk of fire, like the one that killed three astronauts on Apollo 1. A buffer gas (typically N_2) is needed to limit the flammability of the oxygen-rich environment. There are no clear constraints on the minimum amount of buffer gas that is acceptable, as it depends on the choice of material and technologies used in the facility. The NASA EAWG recommends more than 60% buffer gas for upcoming missions, but this is of course conservative. A good reference is the NASA Skylab missions which employed an oxygen-rich atmosphere containing up to 74% O_2 (with 26% N_2) without fire issues.

We can thus conclude that to allow outdoor activities on Mars without a spacesuit and only an oxygen mask the minimum absolute surface pressure is about 120 mbar (without regard to the atmospheric composition), and to avoid the need for pressurized habitats the minimum pressure is about 120/0.74 = 160 mbar.

9.1.1.2 Increasing Mars Surface Pressure from Adsorbed and Frozen CO_2: Why It Does Not Work

A Runaway CO_2 Greenhouse Effect Scenario

After a few short speculative studies published in the scientific literature in the 1970s and 1980s (e.g. Sagan 1973), terraforming Mars became a notorious and imaginable project following the publication of the impressive study entitled "Making Mars Habitable" led by NASA scientists Christopher P. Mckay, Owen B. Toon (then both at NASA Ames Research Center) and Penn State University professor James F. Kasting. This reference study made the cover of the journal *Nature* which was published as a long review article in August 1991. It also made headlines around the world and remains today the reference study regarding terraforming Mars. The McKay et al. (1991) article discusses many aspects of terraforming, but it is remembered for proposing a scenario to restore the early Mars atmosphere based on the idea that if Mars could be warmed in order to raise the temperature by ~20 K, some of the CO_2 frozen in the polar caps and adsorbed in the regolith would be released, increasing the pressure to 100 mbar. From there, the authors infer that "If there were large regolith and polar CO_2 reservoirs the pressure would continue to rise on its own". The idea that initial warming can be amplified by sublimation of CO_2, adding to the warming and subliming more CO_2 in a feedback loop was called "runaway CO_2 greenhouse effect". With enough CO_2 available, it could create a thick CO_2 atmosphere with a greenhouse effect strong enough to enable a plant-habitable environment (see below) within a 100–100,000 year timescale. Contrary to a popular idea, this atmosphere would then hold to Mars since the current escape rates from Mars are very low (Jakosky et al., 2018) despite the lack of global magnetic field.

How to warm Mars to "kick start" terraforming? Several ways have been mentioned to initiate the CO_2 outgassing, including warming the poles with giant or multiple mirrors (Birch, 1992; Salazar & Winter, 2019; Zubrin & McKay, 1993) or spreading black soot over the polar caps (already discussed in Sagan, 1973). With his slogan "Nuke Mars", Elon Musk has popularized the idea that terraforming Mars could be triggered by nuclear explosions that would vaporize Mars' ice caps. As explained in McKay et al. (1991), Gerstell et al. (2001), or Marinova et al. (2005), a more efficient way to warm Mars would be to industrially produce artificial greenhouse, fluorine-based gases like C_3F_8. A fraction of a Pa (a few ppm in an Earthlike atmosphere) would be sufficient (Marinova et al., 2005).

Why It Does Not Work

Since 1991, a flotilla of orbiters, landers, and rovers have revolutionized our knowledge of planet Mars and we now understand that the amount of subsurface CO_2 that would be available on Mars to sublime and desorb is very small, not sufficient to significantly thicken the atmosphere (Jakosky & Edwards, 2018).

Extensive radar soundings have shown that although some CO_2 ice is buried at the south pole (Phillips et al., 2011), it corresponds to an equivalent of 12 mbar if emplaced into the atmosphere (Bierson et al., 2016).

More CO_2 could be hidden in the form of H_2O–CO_2 clathrates (Dobrovolskis & Ingersoll, 1975) in which the H_2O molecules form a "cage" that can hold CO_2. If the full volume of polar ice deposits consisted of H_2O–CO_2 clathrate, they could contain up to the equivalent of about 150 mbar of CO_2. However, there is no evidence that clathrates are actually present, and it is extremely unlikely that the entire polar deposit could have formed in a way that allowed them to be fully filled with CO_2 (Jakosky & Edwards, 2018).

The amount of CO_2 that could be desorbed from the subsurface of Mars if suddenly warmed has been found to be much more limited than suggested in McKay et al. (1991). At high- and mid-latitudes the pores of the near surface are filled with water ice. It can be estimated that the equivalent pressure of 40 mbar of CO_2 may be adsorbed in the first 100 m of regolith but that only a small fraction would be released by heating this material (Jakosky & Edwards, 2018) (Fig. 9.1).

9.1.1.3 Alternative: Making a CO_2 Atmosphere from Carbonate Rocks

As also discussed in McKay et al. (1991) and previously in Fogg (1989), an alternative source of CO_2 is carbon-bearing minerals such as carbonate rocks (either Ca-, Mg-, or Fe-CO_3). In theory, carbonate rocks release CO_2 when heated to more than 300 °C.

On the Earth, very large amounts of carbonate rocks (limestone) can be found, the equivalent of tens of bars of CO_2. They are the ultimate product of the dissolution of CO_2 into liquid water throughout Earth's History. It has been speculated that similarly, a large amount of CO_2 could also have been trapped on Mars at the time when liquid water was flowing under a thick CO_2 atmosphere. However, no widespread global deposits of carbonates have been identified: Carbonates were first observed as Mg-rich carbonate linked to the alteration of olivine-rich bedrock in the *Nili Fossae* region (Ehlmann et al., 2008). Local outcrops of carbonates have also been reported from central peaks of impact craters (Wray et al., 2016), but, at a global scale, the number of detections of carbonates on Mars is limited. This paucity may be linked to the limited extent of olivine-rich bedrock because only the alteration of the latter can lead to the high water pH favourable to carbonate formation (Gil-Lozano et al., 2024). From orbital observations, it has been concluded that the carbonates detected can only explain a small fraction of the missing CO_2 suspected to have sustained a warmer past climate (Edwards & Ehlmann, 2015). An upper

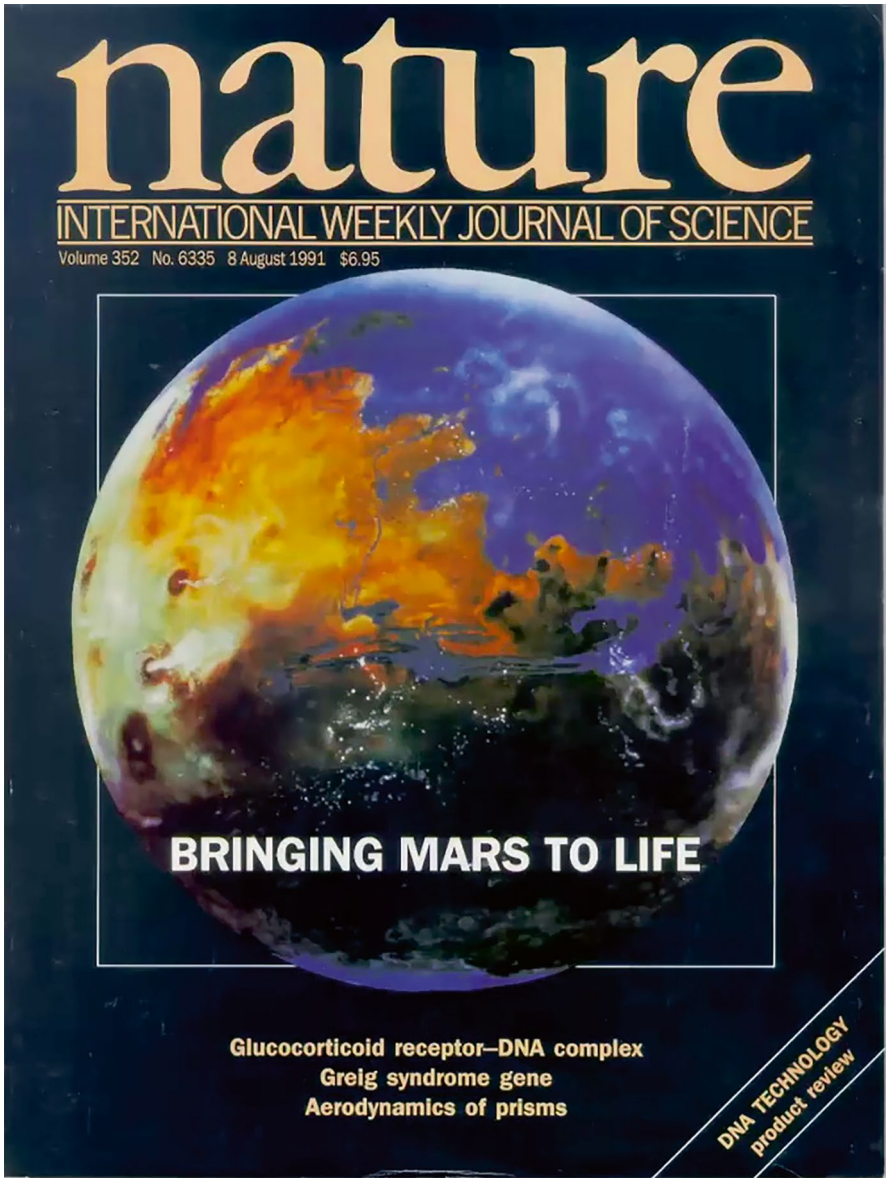


Fig. 9.1 The cover of the 1991 Nature journal that published the reference article on terraforming Mars by McKay, Toon, and Kasting, entitled "Making Mars Habitable"

bound of several 100 mbar of equivalent CO_2 gas trapped in these carbonates has been proposed for the whole planet (Hu et al., 2015).

At a local scale, Fe-carbonates have been detected on the Columbia Hills by the Spirit rover (Morris et al., 2010) and at Gale crater where they are mixed with sulphates (Tutolo et al., 2024). The Perseverance rover has detected Mg-carbonates that

are linked to the olivine-rich rocks of the Jezero crater (Clavé et al., 2023). These recent findings increase the potential storage of carbonates in Mars's crust, which is of strong importance for the understanding of past Mars climate (Tutolo et al., 2024). Yet, most of these carbonates are in relatively low proportion in the rocks analyzed. For instance, they are estimated at ~10% in volume of the rock at Gale crater (Tutolo et al., 2024). At Jezero crater, carbonates may be linked to the alteration of the local rocks, which are largely preserved in place. No pure carbonate sinks exist on Mars in contrast with Earth where huge km-thick carbonate reservoirs exist.

Could We Create a Dense CO_2 Atmosphere from Carbonates?
The limited regional extent and related reservoirs observed at a global scale, and the relatively low abundance observed in situ within rocks containing carbonates, are strong limitations to the usage of carbonates as a source of CO_2 for the atmosphere. If we limited such processing to the Nili Fossae deposits (the only significant reservoir detectable from orbit), large-scale strip-mining would probably produce less than 15 mbar (Jakosky & Edwards, 2018). Even if hidden carbonates were abundant somewhere, the amount of work and energy to extract CO_2 from them is beyond our imagination. For instance, Fogg (1989) suggested that the most practical way to volatize carbonate-bearing minerals on Mars would be through the use of buried thermonuclear explosives. However, he estimated that at least ten million such explosives, in the multi-megaton range, buried at depths of hundreds of metres would be required.

The same conclusion can be reached regarding other gases that could be released from processing rocks. In theory, nitrates could be used to inject nitrogen into the atmosphere, but they are certainly very rare (Stern et al., 2015) and difficult to vaporize.

9.1.1.4 Bringing Volatiles from Elsewhere

If there is not enough material on Mars today to make a thicker atmosphere, one can wonder if it could be possible to bring volatiles from elsewhere. As we are dealing with planetary-scale amounts, it is easy to show that the scale of the transport is such that it is beyond the scope of our technologies and even our imagination. The mass of a 120-mbar atmosphere on Mars would be 4.66×10^{17} kg. This corresponds to the payload of 25,000 billion Ariane rockets. McKay et al. (1991) mentioned the possibility of obtaining volatiles by moving large asteroids and comets into collision courses with Mars but calculated that it would require more than one million comets of 1 km radius to provide, very hypothetically, the mass equivalent of a 1-bar atmosphere on Mars.

9.1.2 Developing a Biosphere on Mars

Terraforming Mars can also designate the planetary environmental engineering project that would allow some terrestrial organisms to survive, develop, and ultimately modify the Martian environment.

9.1.2.1 Requirements for Life

The key requirement for any kind of Earth's life is the availability of liquid water at or near the surface, where photosynthetic organisms could use atmospheric CO_2 to create biomass. However, defining what must be changed to allow surface liquid water is not straightforward. On Mars today, whilst there are locations where afternoon temperatures and pressure are compatible with liquid water, it is never available, for fundamental reasons: Water tends to condense and stay in cold traps, not in warm zones. If some water ice is present in a region where temperature is increasing up to the melting point, this ice sublimes extremely efficiently well before melting unless the atmospheric partial pressure of water reaches the triple-point pressure, which is of the same order as the present-day absolute pressure! In such conditions, also because the inventory of water is limited, water on Mars ultimately accumulates only in the coldest regions of the planet. In order to allow liquid water to be present at least regionally and seasonally on the planet, it is the mean temperature of these coldest regions on the planet that must be raised up to the melting point. This corresponds to a considerable increase in temperatures on Mars (50–100 K) and certainly a significant increase in surface pressure.

If water is available along with some nutrients in the soil and a small amount of CO_2 in the atmosphere, some terrestrial microorganisms may be able to adapt to all kinds of atmospheres. In particular, oxygen is not required for anaerobic species. Plants need more than 1 mb of O_2 for aerobic mitochondrial respiration, more than 0.15 mb of CO_2 for photosynthesis and at least 10 mb of N_2 for biological nitrogen fixation (McKay et al., 1991).

9.1.2.2 Can the Martian Soil Be Used to Grow Plants, Algae or Fungi?

As we do not have access to real Martian soil, only "simulants" derived from terrestrial soils can be tested. Nevertheless, it is already clear that the most accurate of these simulants are not capable of supporting plant growth in the absence of nutrient supplementation (e.g. Eichler et al., 2021). Even with nutrients, highly alkaline (pH > 9.0) Martian soil and the presence of perchlorates (present at many locations on Mars, Glavin et al., 2013; Hecht et al., 2009; Navarro-Gonzalez et al., 2010) may prevent the growth of most terrestrial plants (Eichler et al., 2021) and possibly algae.

9.1.2.3 Adapting Life to Mars If the Atmosphere Could Be Thickened

Assuming that a thick enough atmosphere could be created (which is almost impossible, as explained above), climate models suggest that at least 1 bar of CO_2 would be required to create a warm-enough climate to allow liquid water on the surface (e.g. Forget et al., 2013; Richardson & Mischna, 2005). However, a thinner CO_2 atmosphere would be sufficient if enriched in super-greenhouse gases produced industrially (Marinova et al., 2005).

What kind of life could adapt to a CO_2-dominated atmosphere is discussed in, e.g. McKay and Marinova (2001). Amongst macroorganisms, photosynthetic algae have a great potential for thriving under a pure CO_2 atmosphere with very low levels of O_2 as well as producing O_2 that could later be useful to plants. As mentioned above many organisms require a significant amount of nitrogen in the air, and it would be extremely challenging to extract nitrogen from the soil or bring it to Mars etc.

9.1.2.4 Building a Biosphere Without a Thick Atmosphere

If significantly thickening the atmosphere of Mars is impossible because of the lack of available volatile, would it be possible to create a biosphere with the present atmosphere or with the 20–40 mb CO_2 atmosphere that may be obtained by sublimation and desorption from the caps and regolith? The limit of life in presence of liquid water but at very low pressure is not well known (e.g. Verseux, 2020) although some bacteria can grow under 700 Pa (Schuerger and Nicholson, 2016). In any case, a real challenge is to maintain an aqueous environment suitable for life despite the low pressure. One can speculate that this may be possible using an optimized mix of greenhouse gases (Marinova et al., 2005) or possibly creating artificial aerosols designed to maximize the scattering greenhouse effect (Forget & Pierrehumbert, 1997) and in theory able to warm Mars much more efficiently than the best greenhouse gases (Ansari et al., 2024). A low pressure, this will be particularly challenging because the horizontal temperature contrast remains significant: water will only be stable in the coldest part of the planet.

Alternatively, Wordsworth et al. (2019) proposed to artificially warm the Martian regolith by coating small regions with silica aerogel in order to melt the shallow subsurface ice currently present at mid and high latitudes. This Silica aerogel would be transparent to visible wavelengths, opaque in the infrared, with a very low thermal conductivity. These combined properties make silica aerogels an excellent material to induce a solid-state greenhouse effect. With such a method Mars would not be terraformed, but Wordsworth et al. (2019) claimed that it could allow for photosynthetic life to survive there with minimal subsequent intervention: they concluded that "This regional approach to making Mars habitable is much more achievable than global atmospheric modification".

9.1.3 Giving Mars a Breathable Atmosphere for Humans?

9.1.3.1 Requirements

The ultimate form of terraforming would be to create an atmosphere suitable for humans to breathe without any respiratory mask, in which terrestrial plants and animals would thrive as well. The requirement for oxygen is the same as discussed before, with a minimum partial pressure of O_2 of 120 mb. To avoid spontaneous combustion, O_2 must be diluted in at least a few tens of mb of a neutral buffer gas like nitrogen, argon, or helium. All gases must be kept below their toxicity level: less than 10 mb for CO_2 (which is, by coincidence the partial pressure of CO_2 on Mars today), 0.1 mb of CO etc. Even O_2 and N_2 must be limited in order to prevent the long-term oxygen toxicity that appears for O_2 partial pressure above 300 mbar, and nitrogen narcosis, which typically starts for partial pressure of N_2 above 4000 mb.

9.1.3.2 Feasibility

Much more than thickening the atmosphere and developing a biosphere on Mars, the project of creating a breathable atmosphere on Mars seems out of reach. Assuming that the creation of a thick CO_2 atmosphere (as discussed above) was possible, the only mechanism that seems capable of changing the bulk composition of a planetary atmosphere is planetary-scale biology which would produce O_2 via photosynthesis. McKay et al. (1991) estimated that for typical Earth photosynthetic ecosystems, the production of a breathable atmosphere would require over 100,000 years, although using specially developped organisms could strongly accelerate this. They also noted that the limiting step in the production of any net O_2 on Mars may not be the efficiency of photosynthesis but the necessity of sequestering the organic material in places (presumably deep sediments) where it is not re-oxidized.

As discussed above, in addition to O_2 a buffer gas would be necessary to avoid spontaneous combustion and hyperoxia. It is hard to imagine anything else than N_2, and even harder to imagine how to extract enough nitrogen from Martian reservoirs (nitrate).

To allow the presence of plants and liquid water, a hypothetical O_2-N_2 atmosphere would have to be completed with enough super-greenhouse gases that should be maintained with a dedicated industry (Gerstell et al., 2001).

9.2 Humanizing Space: Mars as Planet B, Outside the Earth's Jurisdiction[2]

The idea of inhabiting the cosmos has made futurology a topical issue. The United States has set its sights on a human return to the Moon as part of the Artemis program. SpaceX, for its part, is aiming for Mars and beyond, in the hope of giving rise to a multi-planetary humanity.

Meanwhile, the sponsors of another concept, the Asgardia project are working to create the first space state in Earth orbit (Sergey & Sergey, 2019). The idea behind the project lies in establishing a human colony within orbital structures located in the circum-terrestrial area. Asgardia purports its station is an autonomous legal framework detached from terrestrial laws and aims at establishing itself as the first space state in history.

These settlement projects have different legal implications. Mars is not the Moon, and the respective distance of these celestial bodies from Earth is directly proportional to the degree of autonomy a colony would require. In other words, whilst a settlement established in deep space may eventually become autonomous and govern itself according to its own standards, a community established in a circum-terrestrial area will fall under Earth's law. It is, therefore, necessary to distinguish between the areas corresponding to Earth's gravity well, also known as "Greater Earth", and deep cosmic space or far celestial bodies.

9.2.1 A Thought Experiment: Settling Greater Earth

The Greater Earth area corresponds to a spherical region of space centred on Earth, where the gravitational influence of our planet dominates the movements of any object. It extends over a radius of 1.5 million kilometres from the centre of the Earth to the L1 Lagrange point, where the Earth's gravitational field meets the gravitational influence of the Sun. Within this area, space activities can be carried out without excessive energy expenditure, with fast radio connection and fast transport between different locations, thus allowing continuity in trade with earthbound stations. Thus, a human community located in this area will remain in constant contact with terrestrial support in terms of supplies, communications, and crisis management.

Greater Earth could be defined physically as the natural perimeter of Earth and legally as the common heritage of Earth's inhabitants. Each state is the caretaker and guardian of this heritage within the scope of its jurisdiction. This area is the seat of Earth's law and corresponds to the scope of international and transnational space law. In terms of human habitation, this raises the following legal question: Can a colony established within this area claim autonomous nation-state status, along the lines of Asgardia?

[2] This section is authored by Perrine Barthomeuf.

9.2.1.1 No State Without Territory

Article II of the Space Treaty prohibits any form of appropriation of outer space, including celestial bodies, by anyone (be they government or private entities) and in any manner whatsoever. As a result, Asgardia cannot claim territorial title to any part of outer space. Moreover, the Asgardian space station is, from a legal point of view, a space object, and as such cannot constitute, or even be assimilated to, a territory. The Asgardian community (or rather, its investors) only have title to the station. Consequently, in the absence of any territory, Asgardia cannot claim statehood.

9.2.1.2 No State Without Effective Government

Article VIII of the Space Treaty provides that any space object located in space, as well as the community on board, is subject to the control and jurisdiction of the terrestrial state of registration. This means that the Asgardian station, and the colony within it, will be subject to the laws of the state of registration. More generally, life in orbit will be governed by the national law of the terrestrial state that registered the space object. In the absence of an effective autonomous government, Asgardia once again fails to achieve statehood.

This case study is a good illustration of the power of the Outer Space Treaty to act as a bulwark against the ambitions of a few to establish themselves as autonomous, sovereign communities within circum-terrestrial space, on an equal footing with earthbound states. The question is then: can a terrestrial state extend its sovereignty over a celestial body as part of the Artemis project?

The crewed Artemis space program, initiated by the USA, consists of bilateral agreements signed by the USA and various partner countries, establishing a governance framework for the exploration and settlement of the Moon, and later Mars. Although the Artemis agreements reaffirm the principle of non-appropriation, they contain a whole string of provisions of uncertain scope, enabling the USA, in agreement with their partners, after simply informing the Secretary General of the United Nations, to unilaterally issue for themselves temporary titles of occupation covering parts of the space domain known as “safety zones”. Within these zones, vital installations and bases will be duly registered and placed under American jurisdiction within the meaning of Article VIII of the Outer Space Treaty. As a result, these so-called “safety zones”, as well as the equipment and personnel located therein, will be subject to the law of the state of registration, which will undoubtedly be the USA.

The space-faring states thus manage to circumvent the principle of non-territorialization of space by extra-territorializing their law, which ultimately enables them to extend their sphere of sovereignty in space and over in situ resources. This method inaugurates a new form of imperialism, in space.

It is important to note, however, that within Greater Earth, states are not so much seeking to extend their territorial sovereignty in space as to maintain economic leadership through intensive exploitation of circum-terrestrial space. The aim is to

attract private investors through a favourable regulatory regime. The race for space is multipolar, and adaptation to international regulatory systems appears to provide an effective brake on imperialist ambitions.

9.2.2 Settling Deep Space

What would happen, should a colony venture beyond Earth's gravitational field?

A settlement on Mars would involve sending people over 55 million kilometres from Earth on a 7–8 month-long journey, on a potentially one-way mission. The communication time is directed by the speed of propagation of radio waves between Mars and the Earth (the speed of light). The transmission times vary from, roughly, 3 minutes when the planets are at the closest approach to 21 minutes when they are at the farthest. There is a period of blackout when the Sun is precisely between the Earth and Mars. In the future, such a deep-space colony could (hypothetically) be totally independent of terrestrial life support systems and could be responsible for its own sustenance and protection using in situ means of production. No control or continuous monitoring of the inhabitants would be possible from Earth. Consequently, Article VIII of the Treaty, which provides that the state of registration retains jurisdiction and control over the space object and the personnel on board, becomes ineffective. Similarly, the principle of non-appropriation becomes meaningless insofar as the survival of the colony will require the exercise of full sovereignty over the space resources available within its location. The colony's survival will depend on its ability to act on its own, to make the right decisions at the right time and to adopt its own code of conduct.

9.2.3 The Rise and Multiplication of Autonomous Space States

In theory, the human settlement of space could take two fictional forms:

- So-called horizontal human settlement, which consists in the pure and simple dispersal of the human species throughout the cosmos. This human settlement model, inspired by transhumanist schools of thought, might lead, whilst totally ignoring the Darwinian law of evolution, after allopatric speciation, to the formation of new "human species" (*Homo spatialis*, *Homo alterio spatialis*, or Posthumanity) in which each taxon organizes itself into an autonomous, independent community.
- Vertical human settlement, inspired by Cosmism, is part of a new awareness of the universe. As humans ascend to the cosmos, they become aware that they are one and the same, that they belong to the same humanity.

There arise different legal implications, depending on the human settlement model adopted: either the colony claims independence from Terran authority and

asserts itself as an autonomous Martian state; or the colony remains part of the continuity of the Terran system and, and completing it, achieves the unity of the "species" within the same humanity.

It is of interest to discuss the legal considerations that would be involved in the most inventive ideas that circulate amongst certain groups of people. Some groups are considering or even promoting an expansion of more or less autonomous, more or less independent human colonies, both on celestial bodies and in deep space. These theoretical exercises are based on declarations of intent which are not supported by any current solid technical and scientific basis.

9.3 Mars as a Planet B: Ethical, Societal, and Political Concerns[3]

Discussions regarding space ethics began to take shape in the 1980s, largely in response to studies exploring the viability of terraforming Mars (Schwartz & Milligan, 2021). The obvious emerging question was (Haynes, 1990; McKay, 1990): if we have the capability to render Mars habitable, is it also something that we *should* do? Terraforming, also known as planetary ecosynthesis, is especially interesting from the perspective of environmental philosophy and environmental ethics. Many of the terraforming-related questions echo traditional debates within the terrestrial context, but when applied to the process of engineering an entire planet and transferring lifeforms from one world to another these "traditional" issues become amplified, more extreme, akin to environmental ethics on steroids.

In addition to environmental ethical issues, terraforming raises interesting questions about the future of humanity and interplanetary geopolitics. This section will delve into one specific facet: terraforming as a strategy to mitigate the risk of human extinction. Above all, terraforming is a fruitful thought experiment that, regardless of its actual feasibility, will undoubtedly continue to feature prominently in the writings of not only science fiction authors, but also academic scholars who explore societal, ethical, and political issues related to outer space.

9.3.1 Terraforming as a Thought Experiment

As has already been pointed out, terraforming may not be possible. Even so, it may be fruitful to discuss as a thought experiment. This is already done in science fiction literature (Kim Stanley Robinson's Mars trilogy is a well-known example of this).

Fogg (1993) suggests that studying terraforming as a thought experiment will have a large range of benefits in education, research, understanding the habitability

[3] This section is authored by Oskari Sivula, Erik Persson, Morten Tønnessen, and Natuschka Lee.

of Earth in the past, present and future, planetary exploration, engaging the public, planning for the future, and for debating, for instance, new issues in technology and environmental ethics.

In fact, if terraforming of Mars never happens, this entire Sect. 9.3 can be seen as a thought experiment through which we have had the chance to penetrate many questions in areas ranging from planetary science via technology, to politics and ethics. If we have to conclude that terraforming is impossible in practice, that too is a lesson learned that may also facilitate a change in attitude towards our own planet by showing the "uniqueness and cosmic value of life and Earth" (Haynes & McKay, 1992).

Pantropy, the alternative to terraforming, is a process that hypothesizes around how to modify humans to adapt better to new environments in space. Even if we can manage to adapt the human body to some extent to the conditions of a new planet, we can hardly modify a whole human body that has adapted to the conditions on Earth during millions of years. Moreover, pantropy raises deep ethical questions around how far we are allowed to modify the human body as discussed in Sect. 7.7.1. Since neither terraforming nor pantropy seem like fully feasible solutions, would it instead be possible to combine terraforming and pantropy for a more fruitful survival on Mars (cf. Jebari, 2024)?

9.3.2 Existential Risks

For many, one of the central motivations for building large societies off-Earth and eventually terraforming other planets is to minimize the risk of an existential catastrophe. As defined by Toby Ord (2020, p. 37), existential catastrophe is "the destruction of humanity's long term potential", that is, an event that wipes humanity out of existence. In addition to these sorts of extinction risks, the idea of an existential catastrophe captures irreversible events that are as bad as human extinction. An example of this could be a future where climate change and ecological collapse cause the demise of most of the human population, with only a tiny portion surviving with rudimentary technology and modest life quality, or a future where artificial superintelligence has enslaved humanity, especially when no recovery from such grim scenarios is possible.

So, why are existential risks a concern, and how can settling in space help us with them? Various scholars argue that at present the risk of human extinction is relatively high (Ord, 2020; Rees, 2004). This perceived increase in risk is largely attributed to humanity's technological advancements; humanity has found itself in a novel position where it poses a threat to its own existence. Before, only natural existential risks such as comet or asteroid impacts, stellar explosions, or supervolcanic eruptions posed threats to humankind. Now humans have added anthropogenic risks to the list of existential risks which include catastrophes such as nuclear war, climate change and other environmental damage, natural and engineered

pandemics, rogue artificial intelligence, and other unforeseen anthropogenic risks (Ord, 2020).

This is troubling, particularly considering humanity's relatively young age. Our species *Homo sapiens* is about 300,000 years old (Snyder-Beattie et al., 2019), a short lifespan compared to other Earth species. The average lifespan of a mammalian species has been estimated to be roughly 1 million years, and our predecessor *Homo erectus* persisted for about 1.7 million years (Ord, 2020). Moreover, our planet will remain habitable for humans for at least 500 million years more before the Sun gets too bright (MacAskill, 2022). If we settle other places in the solar system or beyond, perhaps humanity's future trajectory could be even more impressive. However, a question that arises in the long term, if today's humans succeed in settling beyond Earth, is whether this would lead to speciation events. If it does, what will this do with our concept of humanity, in other words, whether the various new species that may emerge following adaptation to radically new environments will still be regarded as human? A further question is, who will be the authority to determine this, and what does the answer imply? The descendent species may prove to be distinct from us, but it should have as much of a right to exist as we do—and also, to represent the next stage of the human lineage, in the same way as we do in comparison to the *Homo erectus*.

Because the stakes are so high—the existence of our species, or our descendants more loosely, as just noted—significant efforts to mitigate existential risks are called for. The ultimate solution to achieving a greater level of existential security is to settle other planets such as Mars because, as Stephen Hawking has aptly said: "[t]here are too many accidents that can befall life on a single planet" (Highfield, 2001). The rationale behind this is that if an existential catastrophe occurred on one planet, the fire of humanity would still be carried by those who live elsewhere (Green, 2019; Huttunen & Sivula, 2023; Musk, 2017; Rees, 2004).

Whilst the logic of this argument is apparent, certain factors nevertheless significantly undercut its strength. Firstly, not all existential risks are independent between planets. Indeed, some are likely correlated across different locations. This means that some risks such as rogue AI, war, and pandemics are more probable to affect all planets and settlements if they affect any (Ord, 2020, 194). This implies that settling Mars would not lower the level of total existential risk as substantially as one might initially assume.

Secondly, most likely there are more cost-effective ways to mitigate the risk of human extinction than settling and terraforming Mars (Baum, 2009; Baum et al., 2015; Matheny, 2007; Ord, 2020). Examples of this would be to enhance world peace mitigation systems, build refuges in remote parts of the Earth, invest in AI safety, improve the ability to respond to highly infectious diseases, enhance food security, and develop a robust capability to detect and deflect large asteroids and comets. Also, Earth will undoubtedly remain the home for the lion's share of humans even after settling on Mars. Hence, building settlements or terraforming Mars should not undermine efforts to decrease the risk of global catastrophes on Earth (Schwartz et al., 2021). However, the money for space settlements does not necessarily come from a fixed budget that would diminish the funding for other risk

reduction. Instead, it may come from totally different sources since many consider settling space such an inspirational project (Ord, 2020).

Thirdly, for an off-world settlement to safeguard against human annihilation it must be sufficiently sustainable and self-sustaining (Puumala et al., 2023). Otherwise, it may run into trouble when Earth is struck by a global catastrophe. Terraforming could potentially counter this argument, as it could allow Martian communities to become sustainable and self-sufficient more easily, possibly supporting a larger population. Consequently, existential risks could provide a justification for such extreme efforts as planetary engineering. However, terraforming is not feasible with our current knowledge and technology, as discussed in Sect. 9.1.

9.3.3 Environmental Ethics and Terraforming

Terraforming has been objected to on various grounds. One of the most straightforward arguments against planetary ecosynthesis from an environmental ethical perspective is that if there is indigenous life on Mars, we should leave it be. As put by Carl Sagan:

> If there is life on Mars, I believe we should do nothing with Mars. Mars then belongs to the Martians, even if the Martians are only microbes. The existence of an independent biology on a nearby planet is a treasure beyond assessing, and the preservation of that life must, I think, supersede any other possible use of Mars (Sagan, 1985, 130).

According to this view, terraforming should be out of the question until we have ruled out the possibility of native life on Mars (for a discussion on the challenges of deciding that a world is uninhabited with sufficient certainty to allow terraforming, see Persson 2014). However, many scholars think that we should not terraform Mars even if it was unequivocally confirmed to be lifeless. These arguments against terraforming generally fall into three categories: (1) those invoking the value of abiotic environments (McMahon, 2016; Rolston, 1986; Schwartz, 2020), (2) those emphasizing the value of naturalness and wilderness (Lee, 1994), and (3) those centred on what terraforming shows about the moral character (Sparrow, 1999).

In its untouched state, Mars may have significant value that could be compromised through terraforming. This value can be scientific, aesthetic, or intrinsic in nature. Schwartz (2020) has advanced arguments emphasizing the value of science in space exploration. Even without life, pristine Mars holds immense value for scientific inquiry, with unanswered questions pertaining to its climate, geology, and other domains that terraforming could potentially preclude. Thus, the scientific value of untouched Mars can call for at least a temporary ban on terraforming. Nonetheless, it should be noted that terraforming Mars would also have scientific value, that is, there is much to learn from trying to make a planet habitable (Schwartz, 2013). So, from the perspective of scientific value, eventually terraforming could be desirable.

Some contend that the aesthetic attributes of Mars present compelling reasons against planetary ecosynthesis. This argument has been made notably by Sean McMahon (2016), according to whom terraforming would likely result in the loss of aesthetic treasures and unique beauty. McMahon claims that this argument may become stronger the more humans start to appreciate the aesthetic merits of Mars, including its dunes, valleys, mountains, craters, hillsides, and features that are undisturbed by biology. However, one might convincingly argue that a terraformed Mars would likewise be filled with aesthetic wonders and beauty. Therefore, terraforming might not result in a substantial loss of beauty but rather generate different forms of it. In the eyes of some people, terraforming may even enhance the aesthetic allure of the planet.

Finally, there are those who posit that Mars holds intrinsic value, which planetary engineering would destroy. Intrinsic value is a notoriously ambiguous concept. Erik Persson (2019) has investigated the potential intrinsic value of abiotic Mars and identified three ways it may be understood in the context of uninhabited planets. According to Persson, Mars can either have end-value, that is, non-instrumental or final value, either in an objective or in a subjective sense, or Mars might be assigned moral standing.

Objective end-value refers to the idea that something has value for its own sake and is independent of whether anyone values it. A considerable challenge with objective value is that it is hard to determine what has it and why (ibid.). Subjective end-value, conversely, is less mystical. Something has subjective end-value if there are agents who value it non-instrumentally, appreciating it as it is. Many presumably value Mars in its current state for its own sake, suggesting that Mars certainly can possess subjective end-value in its untouched condition. The problem with subjective end-value and Mars is that equally some may value planets with life, and hence terraformed Mars would also have subjective end-value. This could be the case if, for example, one values the diversity of life since spreading life to Mars would increase diversity. This may mean that subjective-end value does not give clear reasons for or against terraforming, if this conflict of values is not solved.

Lastly, moral standing is another way of saying that something should have a special status in moral decision-making. If something confers moral duties apart from the effects it has, it is considered to have moral standing. This is about taking the interest of someone or something into account for their own sake, typically because the thing or person is considered to have intrinsic value. However, if this is the case, then we may find ourselves grappling with the aforementioned challenges related to objective and subjective end-value. Proponents of Mars having intrinsic value include philosophers such as Holmes Rolston (1986), Keekok Lee (1994), and Michael Lindquist (2022).

Terraforming can also be objected to by appealing to considerations of naturalness and wilderness. Numerous environmental philosophers believe that the value of nature partly derives from its naturalness, from the fact that it is an independent other—separate from humans (Elliot, 1982; Katz, 1992; Lee, 1999). As per this view, engineered environments such as plantation forests or human-made lakes are less valuable than natural environments whose origin and history are not

significantly tampered with human hands. Along these lines, one can question the value of terraforming since "[t]he project embodies the ultimate philosophy of transforming Nature into Artefact" (Lee, 1994, p. 94).

Oskari Sivula (2024) has analyzed the extent to which a terraformed Mars and its biosphere would be unnatural (another notoriously ambiguous concept), and whether this unnaturalness diminishes the value of the human-made biosphere, thus presenting a reason to abstain from terraforming extraterrestrial environments. Sivula concludes that the unnaturalness of the Martian biosphere alone cannot strongly speak against terraforming because it would not necessarily remarkably discount its value. That said, considerations about naturalness and wilderness can play a role amongst others in the ethical deliberation about terraforming, even though they may not provide a definitive argument against it.

Turning to arguments based on moral character, the previous two lines of argumentation have suggested that terraforming leads to a loss of value or that what is created by terraforming is of little or no value. Arguments about moral character take another route. They focus on the virtuousness or viciousness of actions. Robert Sparrow has argued, drawing on virtue ethics, that terraforming is wrong because it demonstrates vicious character, especially two kinds of vices: aesthetic insensitivity and hubris. Concerning aesthetic insensitivity, he claims that "[d]estroying the unique natural landscape of an entire planet to turn it to our own purposes reveals us to be vandals and brutes" (Sparrow, 1999, 233). With regard to hubris, he offers two interpretations. Actions commit the sin of hubris when they reveal our ambitions as arrogant and futile, or when we overstep the proper place of humans, which according to Sparrow (1999, p. 238) would be a place "in which one can flourish without too much of struggle". Indeed, terraforming Mars is a mammoth undertaking in the face of which humility may be appropriate. For a critical discussion of Sparrow's views, see, for example Schwartz (2013). A general problem with arguments based on virtue, that is also visible in the quotations above, is the difficulty in establishing that, in this case, terraforming really constitutes destruction or disaster or that the mentioned human characters are necessarily bad, without a thorough discussion of what has value or moral status, thus referring to any of the theories mentioned above.

This all shows that there is a myriad of considerations that need to be weighed when deliberating on the prospect of terraforming an uninhabited Mars. Even if one thinks that the reasons outlined above are not strong enough to prohibit terraforming, considering them nonetheless deepens our understanding of the ethics of abiotic environments. These discussions serve to underscore the point that inanimate environments—whether here on Earth or in outer space—are not short of value and immune to ethical consideration.

9.3.4 The Ethical Challenges of Creating Novel Ecosystems

Terraforming our neighbour planet would make it possible to populate Mars with Earthly or Earthlike life, that is, bringing more or less modified Earth life to Mars. On Earth, the ecosystems have had a long time to develop to reach the desirable state, where various organisms, from microbes to higher plants, animals, and humans, interact in mutual ways. This is well reflected in the concept of ecosystem services, which describe the many benefits, such as clean water, breathable air, nutrient cycles, and recreation, that humans obtain from ecosystems. These services are dependent on a certain minimum level of biodiversity. Consequently, any loss of biodiversity or ecosystem degradation will have grave disadvantages both from an economic as well as an ethical point of view.

How much of this concept of ecosystem services can be imported to Mars? Compared to Earth, where the ecosystems evolved in a natural way over a long time, bringing organisms that evolved on Earth to Mars may allow speeding up certain developments, even though the organisms are not adapted to Mars (cf. Graham, 2004). Moreover, what are the ethical implications of this and what do environmental and animal ethics have to say about these issues?

On Earth, moving species around is a very sensitive question since it may have negative effects on the local environment and local plants and animals. In the case of Mars, this problem is discussed in connection with planetary protection and animal ethics (see earlier sections). If we get as far as to terraforming Mars, however, it means we have either come to the conclusion that Mars is uninhabited or decided to ignore the indigenous life. Planetary parks and similar solutions will not work in a terraforming scenario that has to take place on a global scale (Fogg, 1998).

Moving living organisms to a new world as a part of a terraforming project obviously implies risks and there will be losses, ranging from single individuals that cannot cope, to major setbacks due to unforeseen events in the terraforming process. When humans travel to another world there are, as we have seen, a number of ethical issues, even though human astronauts and settlers should be able to give or withhold consent. With non-human animals and other life forms, this will not be the case. This leaves us with the question, what are the ethical implications for the new life and the new ecosystems?

To answer this question, we need to recourse to more general discussions about the value and moral standing of organisms and environments. The first question that needs to be approached is whether environments and animals other than humans count morally at all. If not, we only have to think about the value (instrumental or final) these organisms or environments have to humans (e.g. Carruthers, 1992; Hart, 2010; Smith, 2009).

At the other end of the spectrum is the claim that not just living organisms, but species, ecosystems, and environments count morally (e.g. Callicott, 1980; Johnson, 1992; Leopold, 1990; Lupisella, 1999; Plumwood, 1991; Rolston, 1986). This will in turn raise questions such as “Does this newly indigenous biota have a right to its own natural, but unpredictable, evolutionary trajectory, as currently exists for

organisms on Earth"? (McKay & Haynes, 1990). One might ask though whether human-made, or at least human-seeded environments are really natural and if not do they still count? Can an environment resulting from geoengineering be considered natural or real in a morally relevant sense? Does it matter whether the organisms living there have naturally occurring relatives on Earth or are created in a lab, and where should we draw the line? Does it matter if the ecosystems are engineered and managed to suit us, as long as they are allowed to develop freely?

In between these extremes, we have different forms of biocentrism which claim that all, and only, living organisms have moral standing (Cockell, 2005; Goodpaster, 1978; Schweitzer, 1976). This means all living organisms in the new environment on the terraformed planet will count and it will not matter whether they come from Earth, have evolved on the new world or are bioengineered and to what extent.

Finally, sentientism is a theory that claims that all, and only, sentient entities (that is feeling, experiencing entities) have moral status (Bentham, 2005; Bernstein, 1998; Clark, 1977; Jamieson, 1998; O'Neil, 1997; Persson, 2008; Singer, 1979). "Entities" is a more appropriate term than "organisms" in this case because strictly speaking it does not matter according to this theory whether an object is alive as long as it is sentient. According to this theory, not all living beings have a moral status which in some sense makes things easier since we do not have to consider plants and microbes etc., and similarly to what is the case with biocentrism, it does not matter where these entities come from or whether they are "natural" in any sense of the word. One problem with this theory is that it is sometimes difficult in practice to assess whether an entity is sentient. We may therefore resort to a precautionary approach in borderline cases.

One point that is sometimes made is that Mars could be a safe haven for threatened species or environments from Earth. This raises another set of questions:

If we move a species to Mars, do the Martian individuals and their descendants still belong to the same species as their Earthly ancestors, and thus, are we really saving the Earth species or creating a new one? Are the Earth environments we move necessarily more important than the Mars environments we destroy? Moving living beings from Earth to Mars will inevitably lead to a number of them losing their lives. Is it ethically acceptable to sacrifice individuals, especially sentient individual animals, to save a species (Persson, 2023)? If wild animal suffering is a significant issue on Earth due to bad lives (disease, predation, injury, starvation), painful deaths, and reproductive strategies of sentient animals living in the wild, should we spread animals to new worlds granted that we may be multiplying suffering in our solar system by doing so (cf. O'Brien, 2024; Sivula, 2022)?

The question of whether a species we move to Mars will still be regarded as belonging to the same species also applies to our own species. A question that would be raised if Mars was successfully settled and remained populated for a long time in evolutionary terms, is whether speciation would occur at some point. This would mean that the current human evolutionary line would be divided into an Earthly human species (perhaps named *Homo sapiens tellurian*) and a Martian human species—and perhaps other human species, as well, adapted to other non-terrestrial

environments. This would reactualize ethical questions concerning human equality and dignity.

9.4 Take-Home Message

The conditions on the surface of Mars are too harsh and hostile for the survival of any known terrestrial life form without adequate means to protect against radiation, provide adequate air pressure to prevent water evaporation, and, in the case of humans, the means to provide oxygen.

Some ideas on how to terraform Mars have been investigated by scientific teams, and from these, different projects have emerged: (1) increasing the atmospheric pressure to allow human beings to perform outdoor activities with an oxygen mask only and no pressure suit; (2) transforming the environment to allow some terrestrial organisms to survive; and (3) creating an Earthlike atmosphere breathable by humans. All require a thickening of the atmosphere.

A method to do so by restoring the early Mars CO_2 atmosphere had been hypothesized in the 1990s. However, after 30 years of Mars exploration, its feasibility is strongly questioned, as there is a lack of volatiles on Mars to create any significant and viable atmosphere.

Even if not feasible on a practical level, a hypothetical human settlement of a terraformed Mars also creates multiple questions on the jurisdiction and governance of such a community outside of Earth. If this settlement claimed the status of an independent state, what would be its relationship with Earth? What would be the attitude of these separate human populations toward each others? Would such settlements have the status of envoys of humanity, and would they promote a united humanity with intensive exchanges between the terrestrial world and human space settlements?

Discussing the terraforming of our neighbouring planet also involves serious ethical considerations. Terraforming is often seen as a means to avoid the risk of extinction of the human species, which by some is seen as inevitable if we remain a single-planet species, and may be caused either by natural catastrophes or by the actions of human society itself. With this risk in mind, one might justify the mammoth undertaking needed for planetary engineering. Even so, such a manipulation of an environment and creation of an ecosystem must be questioned on ethical and philosophical grounds pertaining to the planet to be terraformed, the humans and other species to be transferred there, and the society and ecosystems of the mother planet that would have to provide the resources to accomplish this task.

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Chapter 10
Mars in Science Fiction and Our Perceptions of the Red Planet



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> *I must say Good-bye, my pupil, for I cannot longer speak;*
> *Draw the curtain back for Venus, ere my vision grows too weak:*
> *It is strange the pearly planet should look red as fiery Mars, —*
> *God will mercifully guide me on my way amongst the stars.*
>
> *— Sarah Williams (Twilight Hours: A Legacy of Verse, 1868)*

Ever since the earliest humans walked the Earth, the seemingly angry red glow of Mars gave way to myths and legends, thoughts and fancies, and even though—or more aptly *because*—we now know more than ever about Mars thanks to scientific

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exploration, it continues to fascinate us and inspire stories. Some are more rigorous from the scientific point of view, some hold little adherence to it, but one way or another, they help create the public perception of Mars and Mars research. Stories can sway opinions; create (mis)perceptions; inspire STEM careers… From the earliest stories classifiable as science fiction (further abbreviated as SF), across the first modern SF from classic authors such as H. G. Wells, all the way to contemporary SF in all forms of media, the Red Planet has been a source of interest for the stories, and vice versa, the stories have been the source of inspiration in the Red Planet. Let us take a look at the history of science fictional depictions of Mars, their role in changing public awareness, and whether we can gain any insights from exploring Mars-related topics within the sandbox of SF.

10.1 Red Planet of Our Imagination

Long before modern science fiction, SF elements such as automatons (not yet called robots), flying or diving machines, time travel, or celestial voyages regularly appeared in myths, folk tales, epic, romances, stories, and novels. Mars as a planet, sometimes inhabited by Martians, starts to appear in the works of late Renaissance and later writers speculating and fantasizing about life beyond our planet, such as Athanasius Kircher in *Itinerarium exstaticum* (Kircher, 1656) or Emanuel Swedenborg in *Earths in our Solar System* (Swedenborg, 1758), although the account in the influential *Conversations on the Plurality of Worlds* by Bernard Le Bouyer de Fontenelle (1686) somewhat understates the planet and bothers with no Martian life speculations: "I don't know that there is anything remarkable in this planet. … In short, Mars contains nothing calculated to arrest our attention."

Moving on to the roots of the modern genre of science fiction, Mary Shelley's *Frankenstein* is often considered the seminal work of modern SF (Aldiss, 1974). However, while Shelly wrote more SF stories and novels, none of them concerned Mars. To encounter the first widely known modern SF about Mars, we must turn to another writer often thought of as a founder of the genre: Herbert George Wells, whose *The War of the Worlds* was published as a serial in 1897 and published as a full-length novel a year later. He was not the first modern SF author to write about the Red Planet, but certainly the most widely read and successful one, and as far as we know the first who portrayed Martians as distinctly non-humanoid (and one of the few to portray them as violent, with the notable exception of the anonymous manuscript *A Fantastical Excursion into the Planets*, published in 1839 (Fantastical excursion 1839)).

Works preceding Wells' depicted Mars more often as a utopia, in some aspects better than the Earth and humanity, in vein of the pre-modern SF descriptions of Mars by Swedenborg (1758) in the preceding century: "Of all the spirits who come from the earths of this solar system, those of Mars are the best, being for the most part celestial men … The angelic spirits spoke with me concerning the life of the inhabitants on their earth; [saying] that they are not under forms of government …

They also said their consociations are delightful, and that they converse with each other on what passes in their societies, and especially in heaven, for many of them have open communication with the angels of heaven."

Camille Flammarion, in his 1889 novel *Urania* (Flammarion. 1889), portrays *Martials* [sic] as a far older and more advanced civilization, peaceful and scientifically minded and also "more aerial, more ethereal," unburdened by earthly suffering. His description of the graceful, winged Martials evokes the imagery of angels, and he imagines that "Passions are not the same there. Murder is unknown. … The ideas and feelings of the inhabitants of Mars are of an entirely intellectual nature."

In his 1891 novel *The Man from Mars: His Morals, Politics and Religion*, William Simpson (1891) used a vaguely similar encounter with a Martian visitor as a device to describe the Martian utopia and his ideals on how the human society should work. Mars was described as a feminist utopia in novels *Unveiling a Parallel*, published in 1893 by Alice Ilgenfritz Jones and Ella Merchant (Jones & Merchant, 1893), or *A Woman of Mars* by Mary Moore-Bentley (published 1901).

Auf zwei Planeten (*A Tale of Two Planets*) is a German science fiction novel by Kurd Lasswitz, published in 1897 (Lasswitz, 1897). Likewise, it was inspired by the observations of Giovanni Schiaparelli and claims by Percival Lowell, who believed that the canals seen on Mars by Schiaparelli had been built by an intelligent species. Lasswitz's portrayal of Martians was surprisingly layered, with their interaction with humans initially peaceful, but increasingly oppressive from the side of the technologically more advanced Martians. His novel has been said to have had an early influence on the German rocket scientist Wernher von Braun (Neufeld, 2021).

These novels coincided with important scientific debates of the (non)existence of Martian channels, or even canals, and the possibility of life on Mars. This was commonly accepted in the late nineteenth/early twentieth century, but discounted, e.g., by the co-discoverer of the theory of natural selection, Alfred Russel Wallace, in his 1907 brochure *Is Mars habitable?* (Wallace, 1907). Despite the prominence of Mars fiction in various languages at the time, *The War of The Worlds* was by far the most influential novel. Wells' work directly inspired others. American astronomer, educator, and writer Garrett Putnam Serviss was inspired by American newspapers' unauthorized, edited versions of Wells' serial (Queen, 2022; Mollmann, 2009) in writing his serialized novel *Edison's Conquest of Mars* (1898) (Serviss, 1898). In this series scientists led by Thomas Alva Edison (and including the author) devise a way to defend Earth against the Martians, should they return. The novel notably includes probably the first science fictional depictions of space suits. Unlike Wells' original, a substantial part of the sequel takes place in space, as Earth nations develop spaceships to fight the Martians on their home turf.

H. G. Wells' novel thus marks a (not complete) departure from Martian utopias to stories relying more heavily on conflict. In some cases, this conflict was based on more fantasy-like depictions of Mars, adventures departing from the scientific view of the Red Planet. In the February–July 1912 editions of the pulp magazine *All-Story Magazine*, American writer Edgar Rice Burroughs published *A Princess of Mars*, a science fantasy novel set on Mars imagined as a dying planet (Burroughs, 1912). This novel, the first of his *Barsoom* series (Mars is called Barsoom by its

inhabitants) inspired a number of twentieth-century science fiction writers, including Ray Bradbury, in whose 1950 book *The Martian Chronicles* the conflict took place on Earth among humans as well as on Mars between (and among) human colonizers and the indigenous inhabitants (Bradbury, 1950).

Occasionally, Mars and Martians could also be depicted as funny; that's the case of a comic strip *Mr. Skygack from Mars*, first published in *The Seattle Star* in 1913. In most Mars stories, comics or movies with a humoristic streak started to appear in the second half of the twentieth century.

Neither the timeline in the historical overview in Fig. 10.1 nor the description above is anywhere near exhaustive; the full account of representations of Mars in fiction would take up far more space but with little direct relevance to the theme of this book. We attempted to give a general outline of Mars SF and its themes before moving on to several topics in particular that are of relevance to the exploration and settlement questions.

In the next subchapters, we examine the role of science fiction on public perception of the Red Planet, and its potential and possibility to be used as a "sandbox" in outreach and education. Science fiction depicts multiple topics relevant to human exploration and/or settlement of Mars, such as the potential for Martian life (and the issue of planetary protection), human health on Mars, the interplay of crewed and robotic research, ethics of settling Mars, potential modes of governance of research bases and settlements, and terraforming. For readers interested more in depth in early depictions of Mars in science fiction stories, we recommend Mike Ashley's *Lost Mars: Stories from the Golden Age of the Red Planet* (2018) (Ashley, 2018) or perusing the links in the Mars entry in the SF Encyclopedia (SFE: Mars, n.d.). Essays on various aspects of Mars SF (in several cases non-Anglophone, which we only covered to little extent here) can be found in *Visions of Mars* (ed. Hendrix et al., 2011).

10.2 Mars SF in Outreach and Education

Arguably, the Golden Age of Mars science fiction started after Schiaparelli's observations of *canali* (channels, mistranslated into English as canals to a big excitement of the public), and especially Percival Lowell's popular accounts of what Mars might be like (*Mars* in 1895, *Mars and Its Canals* in 1906, *Mars as the Abode of Life* in 1908) (Lowell, 1895, 1906, 1908); see Fig. 10.2. Schiaparelli and Lowell inspired H. G. Wells and others, while Lowell himself may have been inspired by earlier science fiction stories about Mars. In addition, many early science writers were called as science fiction authors (more commonly called scientific romances those days). One example of these writers is Camille Flammarion with his 1889 novel *Urania*, where a young astronomer protagonist meets a Martial [sic; *martien* in the French original] named Spero (Flammarion, 1889).

This bond between popular fiction and popular science was not lost on the people of that era. H. G. Wells wrote in his 1894 *Nature* column (Wells, 1894): "The taste

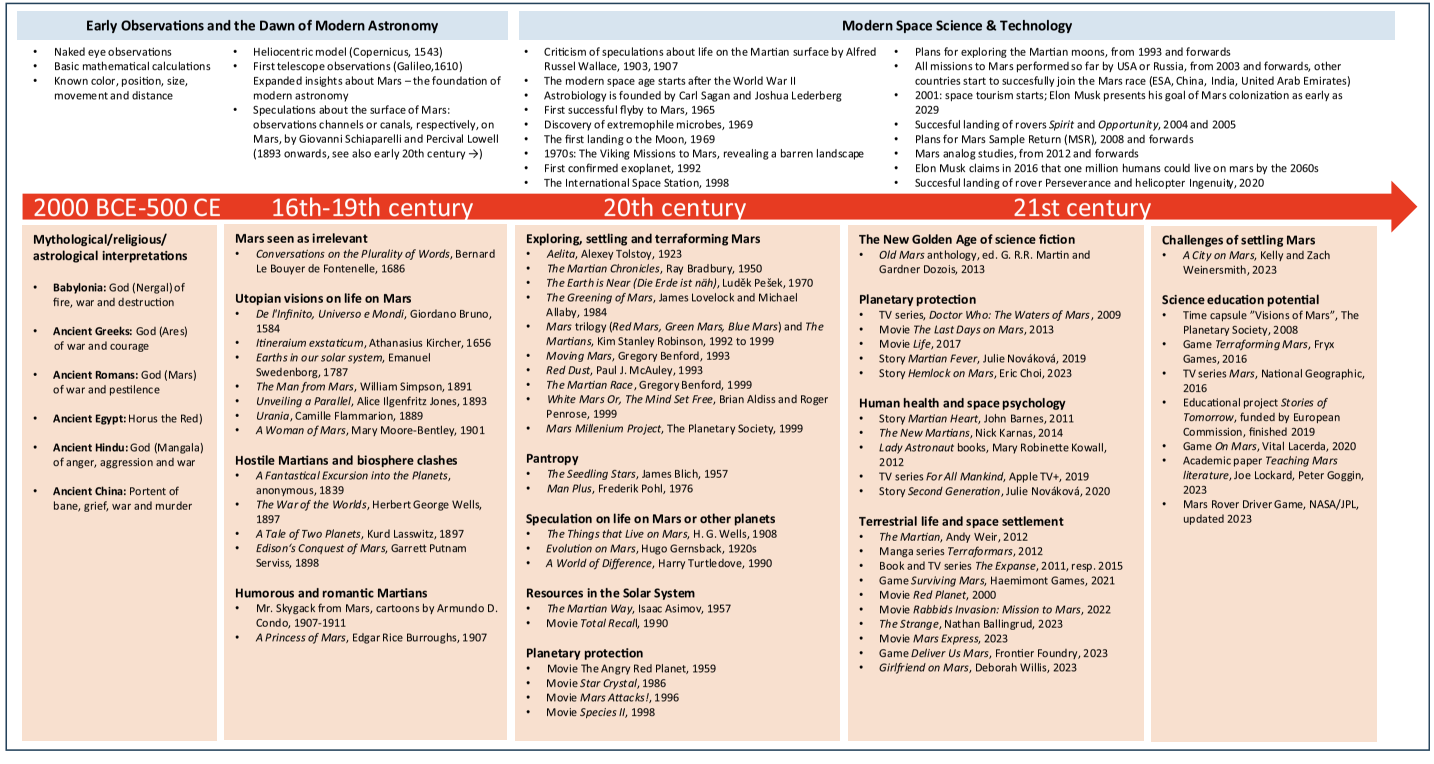
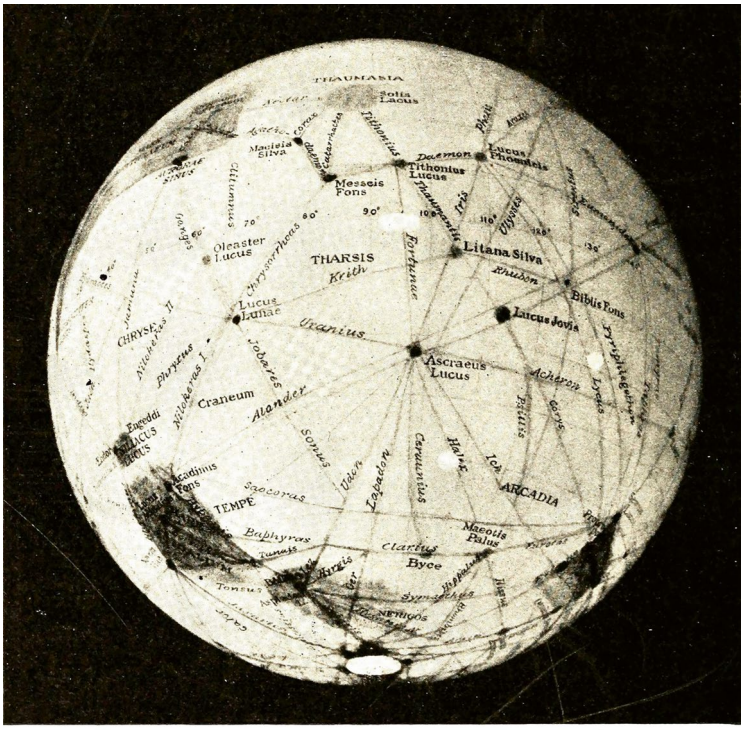


Fig. 10.1 Timeline of Mars science and science fiction. Above the arrow, you can see milestones in space sciences and exploration. Below the arrow, mythological and science fictional depictions of Mars are listed. Original figure by Natuschka Lee, 2024

for good inductive reading is very widely diffused; there is a keen pleasure in seeing a previously unexpected generalization skilfully developed. The interest should begin at its opening words, and should rise steadily to its conclusion. The fundamental principles of construction that underlie such stories as Poe's "Murders in the Rue Morgue," or Conan Doyle's *Sherlock Holmes* series, are precisely those that should guide a scientific writer. These stories show that the public delights in the ingenious unravelling of evidence," etc.

Wells was not alone in making the connection between science popularization and detective stories, later made apparent by magazines such as *Scientific Detective Monthly* or curricula using detective fiction to reinforce problem solving (Boyd 2003). After all, science is ultimately an *investigation*. Neither was Wells the only famous SF author who consistently popularized science. The chemist, author, and educator Isaac Asimov immediately come to mind. In a callback to Wells (whether intentional or not, we cannot know), he wrote an article titled *Popularizing Science* published in *Nature* (1983, nearly a century after Wells (1894), as well as countless textbooks, popular science articles, and books alongside his SF novels and short



HEMISPHERE SHOWING THE OASIS CALLED ASCRAEUS LUCUS

From this radiate many canals. Also in the upper right-hand space is shown the continuation of the Eumenides-Orcus.

Fig. 10.2 An image from Percival Lowell's (1908) book Mars as *The Abode of Life*, depicting the now-infamous network of canals

stories. Mars was depicted in them as well, such as in his 1952 novella *The Martian Way*, emphasizing the need for creativity and resourcefulness in settling space (Asimov, 1952).

These strong historical connections beg the question of whether a science fiction-inspired approach to outreach and education pertaining to Mars exploration would be of merit today. Some projects already utilized this connection: In the early 2000s, the Mars Millennium Project (MMR—The Planetary Society, n.d.) employed artists (including SF authors David Brin, Jim Kelly, and Kim Stanley Robinson) alongside scientists and engineers to stimulate students to envisage human habitation on Mars in the 2030s. Soon after, Mars science fiction comprised a key part of The Planetary Society's outreach project *Visions of Mars*, a digital time capsule that landed on Mars in 2008 aboard NASA's Phoenix lander. This trend continued: Springer's "Science & Fiction" imprint was started by a novel *The New Martians,* written by space psychologist Nick Kanas (2013) and augmented by nonfiction reading materials pertaining to the psychological issues of Mars exploration. Moreover, Mars SF is being used in the classroom to discuss both current issues on Earth and future space exploration, an approach highlighted by Lockard and Goggin (2023) of Arizona State University especially in connection to modern American politics and society (Lockard and Goggin 2023).

The use of SF in Mars-related outreach is not limited to activities in the United States. Stories of Tomorrow (n.d.), a pan-European R&D project funded by the European Commission, used a storytelling approach to let pupils and students create their own (interactive) stories about future expeditions to Mars, enabling them to learn more about space and the Red Planet in particular throughout the process. Unfortunately, Stories of Tomorrow's website has since been discontinued.

Popular board games such as *On Mars* or *Terraforming Mars* have been inspired by Mars fiction, and while these commercial games are not strictly speaking educational, they can be utilized for educational purposes, or educators can derive inspiration from the game contents and mechanics (as outlined by Cardinot & Fairfield, 2022). Primarily educational games also exist, such as NASA/JPL's Mars Rover Driver Game (NASA/JPL, accessed 2024) (Educator guide: Mars Rover driver board game, n.d.).

More research is needed to establish whether science fiction (in any form) can play an effective role in teaching and popularizing real scientific concepts (as accurately as possible given that SF, ultimately, is *fiction*) related to Mars exploration and potential settlement. One way to explore the potential of SF in this respect is to look at the common themes it contains and its development alongside scientific advances, perhaps in a similar fashion as Puranen et al. (2024) looked at exoplanet depictions in SF.

On a darker note, too direct inspiration for Mars settlements derived from science fiction may even be considered *dangerous*. Most SF does not depict in-depth all the hardships likely awaiting future astronauts on Mars (be they explorers or settlers), making them less salient in the public perception of Mars settlement. Mars science fiction directly inspired present-day "rocket barons" and their dreams of colonizing Mars, even if some of that inspiration may have been meant more as a

cautionary tale than a how-to manual. This sentiment goes through the recent popular book *A City on Mars* (Weinersmith & Weinersmith, 2023).

As Lockard and Goggin (2023) pointedly ask: "A contemporary pedagogy of Mars literature needs to engage with questions of social prioritization: why are we obsessed with landing on and settling Mars when the sustainable habitat of our own planet is in question, when species extinction may include humanity sooner rather than later? Is Mars the site of escapism from the realities of an unsustainable future, a means through which we can dream of another world when humanity has fouled its own nest on Earth? Or, taking the opposite side of debate is the exploration and settlement of Mars a vehicle for humanity to transcend the limitations of a one-planet future and adapt itself to new, radically different physical environments? Can society's have-nots share the benefits of space exploration? How might impoverished, less educated people gain empowerment through projects to reach and inhabit the Moon and Mars? Reading Mars fiction can assist students wrestle with such questions…" Indeed, it—we hope—can. We can also take a step further and employ Mars fiction as a sandbox for envisaging the complexity or tipping points of hypothetical future scenarios for the public, or even policymakers (bearing in mind the potential drawbacks of this approach—as noted above, let us not use a cautionary tale as a how-to manual).

10.3 Sandbox for the Future

More than ever nowadays, we encounter issues so new that no well-known or binding framework to deal with them has been developed. Science and technology can outpace policy and law, resulting in gaps, blank pages, and uncertainties. Even where recognized international guidelines exist, their real-world reach could often be questioned. Can we run hypothetical scenarios to try to understand the consequences of different discoveries, disputes, and decisions? Science fiction can serve as a "sandbox" to explore the question "what if?": What if we discover indigenous life on Mars? What if that happens during a crewed mission or even a settlement? What if we find that living in the Martian environment is too detrimental to long-term human health? What if we run into unexpected social problems when settling Mars? And what if we conclude too late that such a settlement is not ethical?

We can imagine wildly different scenarios with many different outcomes for each of these questions. What factors tip the scales toward one or another kind of consequence? Kim Stanley Robinson's Mars trilogy (*Red Mars, Blue Mars, Green Mars*) is a good example of this kind of sandbox (Robinson, 1992, 1993, 1996 (Mars Trilogy)). It describes different stages of settlement and terraforming and provides an ample set of examples of issues and conflicts that could occur at different stages, providing a good discussion material for these issues.

10.3.1 Martian Life

Are we alone in the universe? We can find this timeless question within myths and legends as well as the earliest science fiction, up to contemporary stories. Mars has often been part of the answer. One of the earliest imaginings of indigenous Martian life comes from H. G. Wells, both from his science fiction and popular science articles.

In his *War of the Worlds*, Wells describes the Martians as having "A big greyish rounded bulk, the size, perhaps, of a bear ... Two large dark-coloured eyes were regarding me steadfastly. The mass that framed them, the head of the thing, was rounded, and had, one might say, a face. There was a mouth under the eyes, the lipless brim of which quivered and panted, and dropped saliva. The whole creature heaved and pulsated convulsively. A lank tentacular appendage gripped the edge of the cylinder, another swayed in the air."

Wells' seminal novel had been rare in the very non-humanlike depiction of Martians. Even in the direct (if officially unsanctioned) sequel to *The War of The Worlds*, Garrett P. Serviss' *Edison's Conquest of Mars* (Serviss 1898), the Martians appear as grotesquely-rendered humanlike giants. Perhaps surprisingly, Wells himself later deviated from his own novel in popular science descriptions. In his 1908 article for *Cosmopolitan* (Wells, 1908), Wells asked: "Is it probable that evolution has gone upon exactly parallel lines on the two planets?" Immediately, he optimistically answers: "Here again we have definite facts upon which to base our answer." He points out that due to the lower Martian gravity, plant stalks and stems will be slenderer and the structural support laxer. A thinner atmosphere with infrequent rain, but possibly more frequent snow, would result in conifer-like, spiky leaves with thick cuticles to protect them from desiccation. He expected to find no fish or fishlike creatures on Mars due to only seasonal availability of large amounts of liquid water. Animals would also need to cope with the thinner air, having larger lungs and chest as a consequence, and they would be larger and slenderer in general due to the low gravity. Finally, Wells embarks upon envisaging the intelligent, technological Martians as "deep-chested, big-headed bipeds," and likely covered with fur or feathers. In the final paragraph, he gives the explanation for the striking difference of this image from that in his own *War of The Worlds*: there, Martians journeying to Earth had to prepare themselves for its higher-gravity conditions, and in order not to be crushed, augmented their bodies with mechanical arms and organs, becoming "mere bodiless brains with tentacles" (Fig. 10.3).

Aside from Wells' original Martians, only a few others imagined "alien" alien creatures rather than "dressed-up humans." "A Martian Odyssey" (1934) by Stanley G. Weinbaum featured silicon-based life (albeit depicted in such a way that would not have been scientifically feasible) and creatures thinking in ways alien to humans (Weinbaum, 1934). But Wells' later nonfiction musings resonated across the Atlantic as well, whether because of inspiration or independently: Martians constructed with a certain scientific similitude made their appearance in the first science fiction magazines developed in the 1920s by Hugo Gernsback (1924). In August 1924, the

cover of *Science and Invention* featured a strange being. Under the title "Evolution on Mars," in line with a widespread view of the time, Gernsback begins by asserting that Mars is an older world than the Earth. In his view, evolution works in a similar way on Earth and on Mars, but it is more advanced on the latter. Based on a drawing comparing the evolution of cranial capacity in man's ancestors, he postulates that the cranial capacity of Martians is considerably greater than that of modern humans. Similarly, he believes that Martians underwent a remarkable evolution in the size of their thoracic cage to compensate for the progressive thinning of the Martian atmosphere. He then conjectures that Martians must be proportionally much taller than humans by virtue of the lower gravity of the Red Planet. According to him, their limbs are slender because they have acquired such a high level of technology that they use very little their arms and legs. In fact, as a result of greater science knowledge, the Martian in the picture carries an atomic rifle. Because of the extremely thin atmosphere, sounds and smells travel poorly on Mars, so Martians have very large ears and tube-like sensory organs for detecting odors. Gernsback also conjectures that evolution has endowed them with projecting eyes, located at the end of

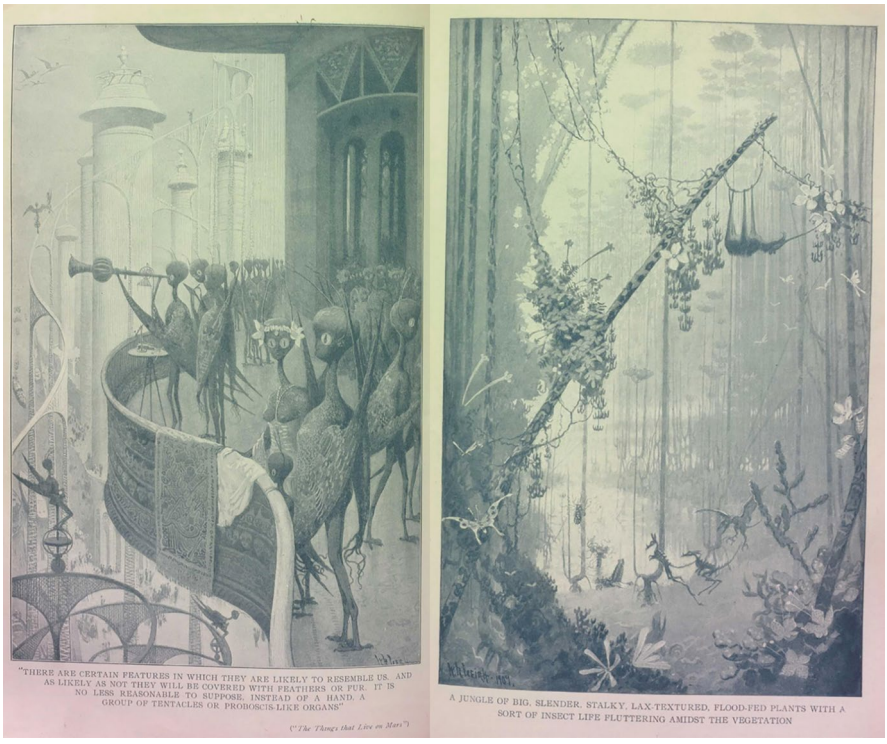


Fig. 10.3 Drawings from H. G. Wells' 1908 article for *Cosmopolitan*, titled "The Things that Live on Mars." Wells imagined Martian flora and fauna to be tall and slender given the lower gravity. Source: The Things That Live on Mars (n.d.)

appendages that form a kind of horn, in order to increase their visual agility while protecting fragile organs. The extremely low temperatures suggest that they are covered with thick fur. And finally, the ultimate in Martian evolution, they have two antennae on their foreheads, which are telepathic organs, a communication technique they have mastered to perfection.

These arguments are based on a vaguely evolutionary interpretation in which life forms are constrained by the environment, and the accumulation of the induced characteristics leads to the representation given by the artist Frank R. Paul. His Martian is a pure product of science, a rationalizing extrapolation based on a few scientific data on the planet Mars: it is not based on unbridled fantasy, but its apparent extravagance can be understood thanks to (then contemporary) scientific arguments. This illustration was reprinted several times, notably under the title "The Man From Mars," on the back cover (and p. 97) of *Fantastic Adventures* first issue, May 1939 (Fig. 10.4).

While space exploration made it hard to imagine any macroscopic life on Mars, various SF "solved" this by introducing alternate worlds. Harry Turtledove's 1990 novel *A World of Difference* (Turtledove, 1990) imagines a universe where a larger, more Earth-like planet occupies Mars' orbit, and outlines some of the issues in planetary habitability this way. The planet, called Miranda, hosts a civilization on an approximately medieval level. The appearance of Turtledove's Mirandans, who are radially symmetrical, may be a callback to Wells' vaguely octopus-like Martians.

Some of the short stories in G. R. R. Martin's and Gardner Dozois' 2013 retro SF anthology *Old Mars* (Martin, 2015) also make use of alternate worlds/histories, while others disregard the question entirely, and yet other pieces are specifically set in earlier fictional worlds of Burroughs and others. Contrasted to that, present-day more realistic *New Mars* stories often use either the idea of extinct or dormant life, or microbial life hidden deep in the subsurface—the latter is the case of Greg Bear's novel *Moving Mars* (Bear, 2014) or Gregory Benford's *The Martian Race* (Benford, 2008). These are more in line with expectations of current science, and the possibility of such a discovery leads us to the question of planetary protection. We must also face the eventuality that Mars had never harbored life and our searches will not yield anything, however, persistent; that is the theme of Czech emigrant space artist Luděk Pešek's novel *The Earth is Near* (originally published in German as *Die Erde ist nah* in 1970 (Pesek, 1975). There is no doubt that even continuously negative results would be scientifically very valuable—but the novel asks the important question: how prepared are we really to arrive at the conclusion that Mars had always been lifeless?

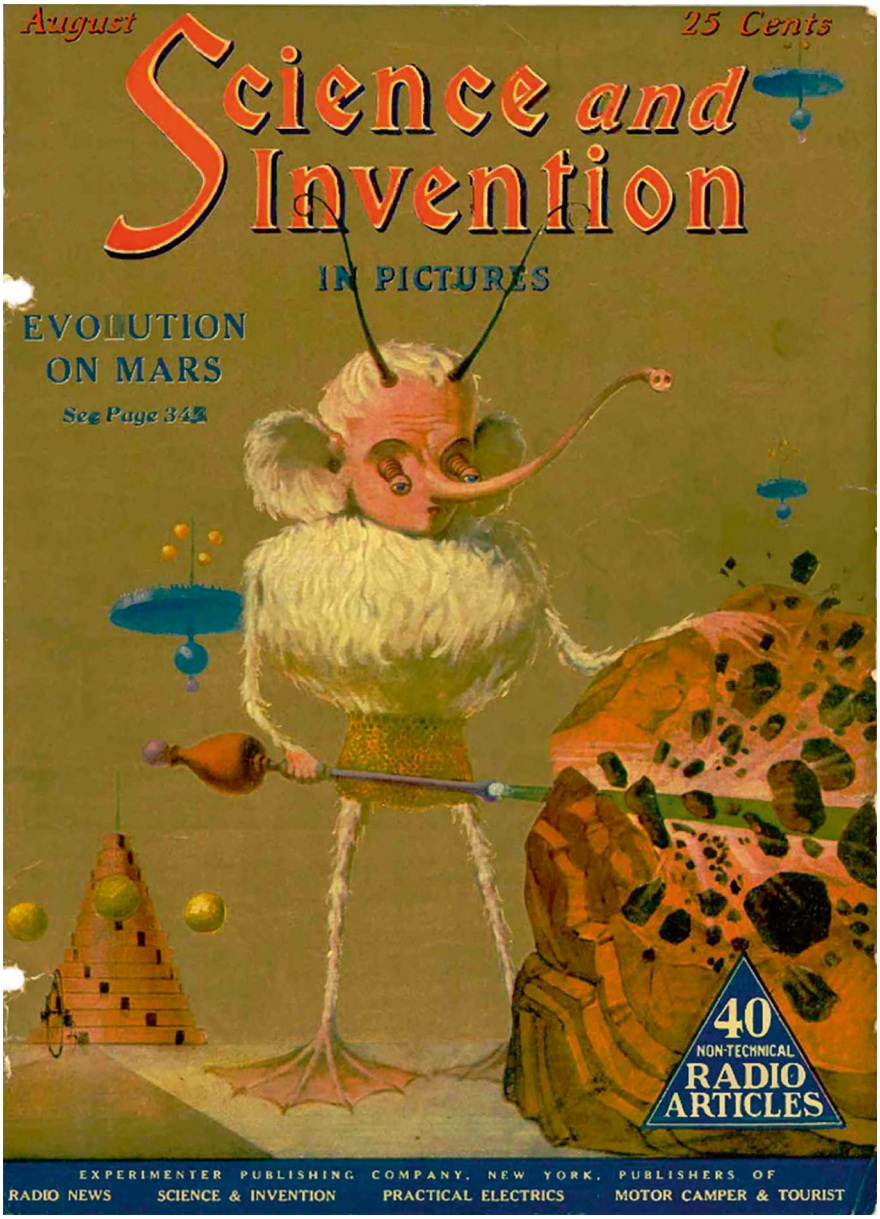


Fig. 10.4 The cover of *Science and Invention* (August 1924) with Frank R. Paul's illustration of a Martian. Source: World Radio History, accessed 2024

10.3.2 Planetary Protection and Contamination

We are faced with a timeless conundrum between exploring a new environment and keeping it pristine—for our research as well as its own sake. Antarctic research stations have left behind a legacy of pollution (Stark et al., 2023). Aggressive exploration led to the spread of new invasive species. Are we going to repeat similar mistakes on Mars?

In popular culture, the issue of planetary contamination is typically tackled in a far more dramatic fashion than we could expect to play out in the real world: The 1986 movie *Star Crystal* (Lindsay, 1986) includes bringing a Martian egg on the journey back to Earth, with disastrous consequences. *Species II*, released in 1998 (Medak, 1998), is based on the premise of a Mars exploration crew getting infected by a Martian virus from thawed regolith, and then giving rise to human-alien hybrids on Earth. In the popular series *Doctor Who*, episode *The Waters of Mars* (2009) (Harper, 2009), the crew of a Martian research base gets infected by a virus from the Martian permafrost and acts like archetypal zombies. The virus in the movie harbors intelligence and consciously wants to infect a greater population; the remaining crew destroys the rocket to ensure the infection does not spread to Earth. The 2013 movie *The Last Days on Mars* (Robinson, 2013) shares a very similar "zombie plot," along with the commander of the mission choosing death rather than risking Earth's future. Hostile intelligent life in returned Mars samples, initially in the microbial form but quickly evolving and growing, is found also in the 2017 horror movie *Life* (Espinosa, 2017). While all these portrayals are very far removed from the scientific view of potential back contamination of Earth with Martian life, they represent an exaggerated mirror of public fears that might arise when Mars sample return is realized or when humans eventually land on Mars. These fears would need to be addressed with science communication.

More realistic portrayals of planetary protection and contamination can not only mirror our sentiments, but also offer useful insights into how we would actually behave face to face with the discovery of Martian life and how policy- and decision-making under considerable uncertainty could be made (for we can expect any indigenous Martian life discoveries to remain tentative for at least some time, and suspicions of contamination of our spacecraft with Earth microbes would likewise carry a great deal of uncertainty).

In Eric Choi's short story *Hemlock on Mars* (2023) (Choi, 2023), planetary protection, including the dilemmas it can present us with, is the core of the story. A new especially hardy microbe is discovered in a cleanroom where a life-seeking lander, currently en route to Mars, was assembled. Its mission operations manager, together with the rest of the decision-makers, faces the tough decision of deciding whether to terminate the mission, into which years of painstaking work and millions of dollars have been poured or let it land on Mars with the (albeit low) risk of contaminating the Red Planet with an extremophile very resilient to the challenges of Martian conditions. While the scientists, engineers, and committees eventually reach the decision to allow the landing, the operations manager eventually bases his decision

on different weighing of the risks and benefits—and that's a problem right at the heart of planetary protection. We can try to quantify all kinds of variables, even with many unknowns and confounding factors, but it is the weighing of the options, our own societal, organizational, or personal utilities, that will tip the point toward one or the other side. These utility functions (e.g. adding greater weight to the very low, but potentially disastrous risk of harming putative indigenous life) underlie the existing and proposed protocols, as well as any maneuvering within them, and science fiction stories such as Choi's can help us become more aware of this and analyze our own opinions and decisions more objectively.

In *Martian Fever* (Nováková, 2019), human explorers become infected with Martian microorganisms, but it is far from the "perfect pathogen" of horror movie scenarios. The accidental infection is very harmful both for humans and for the indigenous microbes, who are not adapted to the environment of the human body and die very quickly—but not always before managing to multiply and strive for survival in this new, too warm, too oxygenated and, for them, chemically unfamiliar environment. When dying, the microbes' foreign metabolites unleash a storm of immune responses in the human body, with its own immune system's reactions being more lethal than any direct effects of the unfortunate contamination. The story's crew races to find a solution, while facing the prospect of becoming stranded on Mars (since return to Earth with such a high risk of back contamination is prohibited).

In Kim Stanley Robinson's novel *Red Mars* (Robinson, 1992), the question of planetary protection is staged at the beginning of the settlement when it is imagined that it is still unknown whether there is any indigenous Martian life. How to handle this leads to strong tension among the crew. This culminates in some crew members consciously seeding the planet with modified Earth life, which makes any further search for indigenous life impossible. This ends all planetary protection efforts, but also eventually drives different fractions of the settlers apart.

Such a divide is understandable since this is not a purely scientific question and the answer depends on the weight we place on things such as human expansion and comfort, or on scientific exploration and potential indigenous microbial life. As we saw in the previous chapters (and in great many novels and stories), people like to imagine Mars as theirs to settle and conform to their image. But, at the same time, many recognize the value of Mars in itself and place a much greater weight on planetary protection. It is, after all, not just for the sake of our research and keeping Mars pristine. There is a (generally considered low, but not non-existent) risk of backward contamination: bringing alien microbes into our own biosphere, whether into an enclosed Mars settlement, or to the Earth.

We have already talked about Wells' *War of the Worlds*. What happens there is an excellent example of backward contamination—from the perspective of the invading Martians. Though Wells' book in a way depicts human encounters with Mars, it depicted Martians coming to Earth, not the other way around, as is the theme of this book. Even so, it has clear relevance through its description of how the Martians eventually were defeated through their lack of immunity toward terrestrial microbes. In Wells' book, this was good, since it helped the Earthlings defeat the Martian

invaders. In a situation where it is Earthlings (humans and others) who visit Mars, terrestrial microbes will be an unintentional offensive weapon instead of the defensive weapon it was in Wells' book, and thus be a serious problem turning the human visitors or settlers into conquerors and aggressors. Wells' book can therefore be seen as predicting the modern issue of planetary protection and the question of (non)existence of a "Planet B," be it Earth for Martians or vice versa. Wells also poses the political question of the belligerents: what if the Martian civilization, technically more advanced but still not benevolent toward us, were us, toward the colonized peoples?

10.3.3 Robots and Humans on Mars

Mars today is inhabited... by our robots. Let us imagine what another species arriving on Mars would think of them? They move, are autonomous and communicate, seem intelligent... For the moment, they are the Martians.

Children's media abound with stories about Mars, perhaps thus fostering the imagination of future scientists or entrepreneurs (hello Elon). Little Nemo, Barbapapa, Mickey, Tom and Jerry, etc. visit Mars. But also, more recently, Raving Rabbits in the animated movie *Rabbids Invasion: Mission to Mars* (2022) (Kirchner, 2019) are sent to Mars because they are more resistant than humans or robots. In adult literature, Nathan Ballingrud's space western *The Strange* (2023) (Ballingrud, 2023), set in alternate 1930s on a habitable Mars, contains "Engines," thinking machines living and working there alongside humans.

In a more realistic fashion, stranded astronaut Mark Watney in Andy Weir's novel *The Martian* (Weir, 2014) and the subsequent movie adaptation (Scott, 2015) makes use of older robotic probes left on Mars and repurposing them mainly for communication. An interesting question arises: aside from life-or-death situations like Mark's, how are we going to deal with our old spacecraft if (when) humans land on Mars and perhaps even settle it? Is there going to be a Mars Heritage Site around the long-motionless *Spirit* or *Opportunity*? Are they going to be moved to a museum? Snatched by rich collectors? So far science fictional possibilities abound.

We are also seeing artificial intelligence (AI) being increasingly applied to data analysis and other purposes. It is, of course, not absent from science fiction, which frequently envisions artificial general intelligence (AGI) capable of free thought. In his 1993 novel *Moving Mars* (Bear, 1993, 2014), Greg Bear envisages "Thinkers," powerful AGIs running on quantum computers and playing a key part in a quickly escalating conflict between Earth and Mars. Earth, in turn, uses nanorobots against Martian representatives.

While we are yet to see any indications of AGI, artificial intelligence as we know it now (LLMs, neural networks, etc.) will undoubtedly play a key part in analyzing more scientific data from Mars, driving future probes (hello new robots!) and perhaps controlling station systems or advising astronauts in crewed missions, with all the advantages and potential pitfalls of AI that come with the technology.

10.3.4 Human Health on Mars

High background radiation. Low gravity. Fine dust. These are just a few of the myriads of factors that potentially threaten the health of future Mars explorers and settlers. Early SF rarely included thoughts of any adverse health effects of the journey to Mars (which, in the earliest works, was often done in balloons, aeroplanes, magical devices, or in dreams), and even during the advent of space exploration, it often just glazed over them. Modern series on Mars, in contrast, are rich on these themes: *Planet Mars explained* from *National Geographic* or *For All Mankind* (2019), for instance. They also increasingly highlight the very important role of women in projects for Mars. Mars is not reserved for men, as proved by Mary Robinette Kowal with her spatial and feminist uchrony in *Lady Astronaut* book series (Kowal, 2014, 2018). This also highlights some of the health risks of the journey toward Mars (did anyone say diarrhea in microgravity, with no evacuation possibilities?) and they apply to on the Red Planet as well.

Short stories like "Martian Heart" (Barnes, 2011, in *Life on Mars: Tales from the New Frontier*, ed. John Strahan) or "Second Generation" (Nováková, 2020, in *Future Science Fiction* 9/2020, ed. R. M. Ambrose & Alex Shvartsman) highlight insofar unknown health issues with the circulatory system and with early development that could stem from the Martian environment. *The Martian* by Andy Weir (Weir, 2014) and its 2015 movie adaptation by Ridley Scott (2015) sparked a lively debate on whether the eponymous "Martian," astronaut Mark Watney, would get cancer or not (in a nutshell, we're not sure!), or whether he would end up with lasting psychological disorders (again, we don't know, however, likely it may seem). Popular TV series such as *Mars* (2016–2018, National Geographic (*Mars*, 2016)) or *For All Mankind* (2019) also depict the potential adverse effects of spaceflight in general and Mars in particular on the human body (cataracts, cancer risk, psychological issues). So far, very little is known with certainty about the long-term effects of the Martian environment on human health; at least up to the first crewed missions. Science fictional depictions, at least, could make some of the potential problems more salient in the public's minds.

10.3.5 Science Fictional Models of Martian Society and Relationship to Earth

As we discussed in the chapter's introduction, early Mars fiction often envisaged the Red Planet as an older, wiser, utopian version of our society. This began to change in the late nineteenth and early twentieth centuries, with more hostile and unequal depictions of the (indigenous) Martian society. Alexey Tolstoy's 1923 novel *Aelita* (Tolstoy, 1923) features a duo of Russian engineers enticing a revolution on Mars, divided strictly into the ruling and ruled classes. The 1924 movie of the same name is a loose adaptation of the novel, with the revolution ending in Queen Aelita

confiscating the people's power again (and being killed for it by one of the Russian visitors, who then wakes up and finds that the whole space journey has been a dream).

While "Old Mars" stories could play with local civilizations (as, for instance, Edgar Rice Burroughs did plenty in his *Barsoom* series (Burroughs, 1912)), "New Mars" had to contend with humans. But there, too, we can find plenty of examples of both conflict and utopia.

The former is embodied by Greg Bear's *Moving Mars* (Bear, 2014) or James A. Corey's series *The Expanse* (Corey, 2011), while the latter tends to be inspired especially by the scientific communities in Antarctica. In *White Mars Or, The Mind Set Free* (Aldiss & Penrose, 1999), the exploration of Mars is decided based upon scientific priority, and any terraforming is therefore postponed. A colony is established, but corruption and financial crisis cut Mars off from Earth. The colony attempts to create a very concrete utopia so as not to repeat the errors of the Earth: no money, no weapons, priority given to science, personal and collective development, and resolution of conflicts through debate and not violence.

We would probably all love to see Mars as a new land of utopias, but if Martian resources prove interesting, the governance by capitalist corporations or terrestrial nations likely precedes over neutral scientific research. If we discover local life, especially extant, who gets access to it? Would the results be published under open science practices, or would companies try to patent insights learned from alien biochemistry? Can we keep Mars Antarctica-like, even with private companies increasingly leading the way in spaceflight?

Kim Stanley Robinson's *Mars* trilogy lands somewhere between our simplified conflict-utopia distinction, showing that attempts toward utopia creation can often stem from conflict (repeated attempts at revolution in this case, discussed in the academic literature, e.g., by Cho (2010)), and that someone's utopia may well not equal to another's utopia. In *Blue Mars*, after Terran forces are finally expelled from Mars, a new pressing question arises: What system of rule will the "Martians" adopt, and what are they going to do with the Red Planet (Robinson, 1996 (Mars Trilogy, #3))? Where lies greater value: in preserving as much as possible the Mars as-it-is, or change and terraform it for humans? Robinson does a great job showing the many agendas, worldviews, ideas, and philosophies that could clash in a multifaceted, diverse colony. From the resulting discussion and fusion of various ideas arises a new system, which could be described as an "eco-economical" (meaning trying to put non-arbitrary values arising from the new ecosystem to various kinds of jobs or goods) democratic society. Solutions could arise through inclusive, radically democratic debate, and it would not be a quick fixed process. As Burling (2005) points out, there are "self-evident" things the vast majority of the settlers could agree on despite their differences, which could serve as a groundwork to sort out the "details," a process that could take many years. Finding the "optimal" degree of centralized power is one of the key questions tackled by Robinson's characters.

We can see the desire to break free of Earth-imposed influence, or "chains," in a myriad of SF works. Many other ones are showing tensions between Earth and Mars *after* this happens, or even a full-scale war or its aftermath (such as *The Expanse*).

Martian society is frequently depicted as more egalitarian, more spartan. The budding colony in *For All Mankind* (2019), albeit not an independent one, is another good example of that, yet there are tensions and "classism" within it. Robinson's *Mars* trilogy is one of the rare examples that encompasses the *process* of gaining independence and the "birth pains" of a new society and governance system. On the pages of an entertaining SF novel, Robinson managed the monumental task of contrasting different views, ideals, and internalized assumptions, and their benefits and cons for different people (even discussing different types of ballots!). He is asking questions of (self-)rule, justice, integrity, autonomy, and freedom relevant not just for future Mars and other space settlements, but all people anywhere. In Robinson's story, the Martian model eventually becomes inspiration for the rest of humanity. We lack the space to discuss the differences between and nuances of the many proposed modes of Mars (self-)governance in science fiction, but we can refer the reader to the recent publication *A City on Mars* (Weinersmith & Weinersmith, 2023), which discusses this from the perspective of SF influences, as well as human history and academic resources. Hopefully, if Mars is ever settled by people, science fiction can serve as an inspiration (and cautionary tale?) to guide us toward equal, democratic, and even utopian societies.

10.3.6 Mars Terraforming

Although the topic of terraforming is addressed in depth in Chap. 9, let us just briefly overview the science fictional depictions of the process, the issues they highlight, and how they tie together with the underlying scientific, technological, and ethical questions.

In many of the terraforming featuring stories, the process is used as a given, with little concern over its ethical ramifications compared to the scientific and engineering challenges. A notable exception is Kim Stanley Robinson's *Mars* trilogy. The conflict between the human-centric technocratic worldview leaning toward Mars terraforming with little concern for its ethics or the planet's pristine condition, and the more environmentalist worldview warning against terraforming is central to the first novel, *Red Mars* (Robinson, 1992). This partly carries into the subsequent novels, *Green Mars* and *Blue Mars*, which depict the long-term process of terraforming alongside the multiple social, political, and economic developments partially intertwined with it (Robinson, 1993, 1996 (Mars Trilogy)).

The process of terraforming is also described in detail in James Lovelock's and Michael Allaby's novel *The Greening of Mars* (1984) (Allaby & Lovelock, 1985), a terraforming-focused future history rife with scientific and technological explanations. In the *Red Planet* movie (2000) (Hoffman, 2000), terraforming is entrusted to automatically sown algae. But a drop in oxygen production leads the humans to send a monitoring expedition. It turns out that insects eating these algae are more efficient than the algae producing oxygen.

Insects are also used for terraformation purposes in *Terra Formars* manga (2012) (Sasuga, 2014): cockroaches and lichens cover the surface of Mars and warm its atmosphere by absorbing sunlight so that the human species can live there.

The terraforming of Mars is also addressed in video games (*Surviving Mars* for example (Surviving Mars—Paradox Interactive, n.d.)) and board games, including the famous *Terraforming Mars* (n.d.) openly inspired by Robinson's Martian trilogy, and implementing all imaginable means to make the Red Planet habitable (mirrors, geothermal energy, plants, asteroid strikes, etc.).

But SF also includes examples of failed terraforming: for instance, in *Red Dust* by Paul J. McAuley (1993), Mars dies a second time after terraforming carried out by the Chinese is gradually abandoned. As such, SF addresses the ethical questions and potential cautionary scenarios of terraforming.

Conversely, if it is not possible to terraform Mars, perhaps we should "marsify" humans (see Sect. 7.7.1)? This is the concept of pantropy: genetically adapting the human species to the planets they want to colonize, as developed by James Blich in *The Seedling Stars* (1957). Frederik Pohl takes another axis and surgically adapts a man to Mars, turning him into a cyborg in *Man Plus* (1976). Looking back at the potential issues with human health on Mars, we may eventually turn to real-world versions of such genetic or cybernetic modifications even if Mars terraforming proves feasible in principle.

10.4 "Into the Future We Go, To-Morrow Is the Eventful Thing for Us"

The year 2023 saw the release of a French animated noir/murder mystery *Mars Express* (Périn, 2023), dark adventure videogame *Deliver Us Mars* (2023), Deborah Willis' novel *Girlfriend on Mars* (Willis, 2023), offering witty criticism of society revolving around social media and reality TV shows, and continuing to destroy Earth's ecosystems while attempting to solve the problem by sending colonists to Mars. It also produced the *Light Bringer*, a new addition to Pierce Brown's young adult series *Red Rising* set on Mars (Brown, 2014), Nathan Ballingrud's "Old Mars" space western *The Strange* (Ballingrud, 2023), multiple popular science books citing SF (most notably *A City on Mars* by Weinersmith & Weinersmith, 2023), and more Mars science fiction in various forms of media and languages. This shows that Mars SF continues to encompass all areas of the SF genre, our hopes, interests, and fears. Mars SF stories ceaselessly inspire us and ask questions relevant to our shared future on Earth, the Red Planet, and elsewhere. What do we do if planetary protection measures fail us and we contaminate Mars with Earth-based microbes—or, possibly, vice versa? How do we ensure that if we settle on Mars, we create a fair and equal society instead of transferring and possibly aggravating our social issues from Earth? How is that society going to be governed?

Questions like these will never run out, and hopefully, Mars science fiction can provide us with mirrors and sandboxes to help us answer them in the real world.

10.5 Take-Home Message

Science fiction has explored numerous issues of Mars exploration, potential settlements, and even terraforming. It has been instrumental, for good and bad, in shaping public (mis)conceptions about the difficulty of settling on Mars, likelihood of finding indigenous Martian life, and various other topics.

Moreover, it has a great and only partly tapped outreach and educational potential due to its widespread popularity (e.g., *The War of The Worlds* by H. G. Wells has become a cultural staple and has been adapted many times as films, series, games, even a musical; *The Martian* by Andy Weir has sold over 3 million copies, led bestseller lists for several months and has been turned into a successful movie by Ridley Scott). More attempts at using Mars science fiction in education and outreach have recently been created, and more will be needed as we venture toward the red planet in future missions, or as we try to shape the legal landscape of exploring (and potentially, in a more distant future, settling) it.

In surveying the public opinions and thoughts about Mars exploration and settlement and in serving as outreach and science communication material, science fiction is likely to play a role in the preparation of future Mars missions, especially if crewed.

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Chapter 11
Conclusion: Horizons of Red and Green



Michel Viso, Muriel Gargaud, Kirsi Lehto, and Cyprien Verseux

The main goal of this book is to provide the reader with a realistic view of Mars exploration and settlement. Under the auspices of the Editorial Board, 61 European experts drawn from a large variety of fields gathered to make a thorough analysis of a range of scenarios.

Mars, the fourth planet from the Sun, has been described by planetary scientists and astrobiologists. It is small, dry, and cold. The northern and southern hemispheres exhibit a sharp contrast, known as the Martian dichotomy. The southern hemisphere is heavily cratered by impacts. Large, ancient volcanoes are found at mid-latitudes. The surface is covered by a thin layer of unconsolidated rock—the regolith—which contains hazardous components, such as chlorinated species, and little organic material. Water ice has been identified in the polar caps and within impact craters. Hydrogen atoms (attributed to the presence of water) have been detected over a large part of the surface at mid and high latitudes. Radar soundings suggest that there could be massive ice sheets buried in the northern plain region. There is neither a global magnetic field, nor a thick atmosphere to protect against

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radiation. The atmosphere is mostly composed of carbon dioxide and its surface pressure is equal to one hundredth of Earth's pressure at sea level. As the rotation axis is tilted by about 23° from the ecliptic plane, Mars has four seasons with large variations in photoperiod, temperature, and surface pressure. These changes initiate winds that blow up the smallest grains of regolith, leading to dust storms which can last for months and cover the planet. No prebiotic chemistry or indigenous life has so far been detected, but some may in the future.

Since the early sixties, Mars has been an important target for space agencies. The rockets used until now have been designed to use the Hohmann transfer—named after Walter Hohmann, a German engineer, who in his 1925 book established the theoretical basis for efficiently moving a spacecraft between two orbits around a given celestial body. The first missions to Mars were Soviet or American. They ended in mishaps. The first successful flyby of Mariner 4, in 1964, confirmed the main features of the planet. Since then, at least seven additional flyby missions, from both the US and Russian space agencies, have been successful and made further observations. Nearly 20 orbiting satellites, launched by the US, Russia, Europe, China, India, and the United Arab Emirates, have been flying in the Martian system. About ten landers have placed robots with various instrument suites on the surface. The hindside of these efforts has been the high number of failed missions, with most problems occurring at either launch or landing. Landing is especially arduous. Over the decades, innovative and highly advanced technologies have been developed to reach the surface safely and accurately. Numerous options have been used for the last leg of the descent to the ground, after a heat shield and a parachute have brought the payload to an acceptable velocity and altitude; they include retro rockets, bouncing bags, and sky cranes. Each technique has its own limitations, related to the ratio between the mass landed and the mass of the landing system. Broad knowledge has been gained by the wide range of instruments carried by satellites, landers, and rovers—cameras, spectrometers, seismometers, analytical laboratories, weather stations, ground-penetrating radars, and others—whose performances keep improving from one mission to the next. Each study, be it carried out from orbit or on the surface, has brought surprises and novelties. Today, and although some steps remain to be taken with robotic missions, the US and China aim to send a crew to Mars in the coming decades and return it safely.

Whoever lands first will set the tune for subsequent activities; the underlying motivations are therefore no trivial matter. An intention to be first is clearly expressed within US policy documents and motivates the third step of the Artemis programme. Lunar activities are being viewed as training, and as a way to regain experience and test new technologies. The Chinese policy is much less publicised but follows the same track. The ethical, political, and societal issues of Mars exploration and settlement may appear as distant problems, both spatially and temporally. However, what humanity does in the following decades will affect generations upon generations of people—and of other living beings.

Mars has played a significant role in the twentieth-century popular culture and science fiction. The debate on whether it hosted civilisations continued until 1964, when the first photographs of the surface were taken by the US spacecraft Mariner

4. Currently, the most outspoken reasons for going to Mars are scientific or economic. Yet it is obvious that, for some parties, there is a strong political interest in reaching the red planet first—and there will be a strong incentive for latecomers not to leave the winner of the race alone there. Eventually, settling Mars may become a new political struggle in a newly opened space, where all participants and stakeholders build new political ideologies, as well as governing institutions, that are tailor-made for a new era of human history.

Since 1967, space activities have been governed by an international treaty adopted by almost all countries in the world. This Treaty on the Legal Principles Governing the Activities of States in the Exploration and Use of Outer Space (better known as the Outer Space Treaty, or OST) enshrines the principle of freedom of exploration and use of outer space and celestial bodies, albeit with conditions. It is based on a consensus between states, and it is in no one's best interest to work outside of this framework. With new ambitions, the US promotes an intergovernmental agreement that supports the Artemis programme to explore the Moon (the Artemis Accords) and encompasses the next step: exploring Mars. China and Russia initiated an agreement to jointly explore the Moon. As long as exploration is science-driven, such agreements are relatively straightforward. They are less so when other interests (economical, political, etc.) are expressed. To this day, disagreements persist on the appropriation and exploitation of resources of celestial bodies—the Moon, Mars, and beyond. Several private stakeholders are now participating in, or initiating, space exploration programmes; some even prepare, or at least claim to prepare, the establishment of industry, transient or permanent settlements, or even permanent societies on Mars. When visiting or settling a virgin planet, however, stakeholders and operators will have to deal with the OST and with planetary protection guidelines, as well as to respect the rights of future generations. The legacy of knowledge is a crucial element. Exploration itself could forever destroy elements of answers to this essential question: was there, or is there, indigenous form of life? A challenge is to identify future rights to fundamental needs that can be presumed to last as long as humanity itself. A legal framework must also account for the numerous stakeholders involved in, or collaborating with, national institutions. A trend, particularly in the USA, is to initiate public–private partnerships along with international, institutional cooperation. This approach could ease the intense competition among administrative or regulatory bodies and various stakeholders by bringing them together as constituencies. Six such constituencies could be identified: the spacefaring nations, the other states, intergovernmental organisations, non-governmental organisations, private companies and finally, a group of individuals or charities who would contribute funds in the sole interest of seeing missions succeed.

The future is already being defined by developmental programmes within different organisations, which create plausible scenarios towards a human footprint on Mars. NASA and the US Academy of Science have produced numerous reports and surveys which are used as references in this book. That is part of the reason why the long-standing dilemma—human versus robots, on Mars or elsewhere—is not being debated here. It is instead admitted that the political decision to send astronauts to Mars, or around it, has already been taken by a single entity, a coalition, or a wide

international agreement. The political will to reach this next frontier first will be the primary motivation. Scientific research will be presented as a secondary driver. Indeed, Mars fascinates planetary scientists: the lack of plate tectonics preserves its pristine, very ancient terrains, which enables a detailed deciphering of its geological history, and of its water and atmosphere, as well as refining the history of the early Solar System. It fascinates astrobiologists, too, who want to thoroughly search the terrain for traces of a past, or even present, microbial form of life.

In early crewed missions, astronauts would likely stay on Mars for around 500 or 30 days, depending on whether a conjunction or opposition trajectory is chosen. Thanks to sophisticated, miniaturised instruments, they will start the analysis of samples on site and select the most promising targets for further investigation on Earth. The latter would be brought back, with appropriate protective measures, for a thorough analysis in selected laboratories.

In practice, how could crews reach and stay on Mars? In its 2023 Moon-to-Mars Architecture Definition Document, NASA describes its commitment to pursuing human landings and scientific missions on the Moon, then on Mars. However, detailing these missions' architecture would require extensive development and involve the definition of concepts, operations, functions, and technologies with interdependent development schedules. A full architecture design has previously been attempted several times over, with limited success. Many of the main challenges come from the four factors outlined below.

The first challenging factor is the very harsh environments to which astronauts will be exposed in interplanetary space and on the Martian surface. It creates the need for effective radiation shielding, and for a containment which can hold breathable air. The basic supplies (oxygen, water, food, basic tools tools, ...) required during travel or stay must either be carried from the Earth alongside the crew or be placed on Mars, or in Martian orbit, before the crew arrives.

The second challenging factor, intertwined with the first, is the vulnerability of the human body and mind to the mission's conditions. These pose a significant risk to the crew members' health, physical integrity and capability to maintain a rational behaviour.

The third challenging factor lies in space mechanics. Regardless of the chosen architecture, spaceship and crew will for the most part be out of reach of a rescue mission. Depending on propulsion technology and flight trajectory, each leg of the journey will take 5–9 months; and the crew must stay on Mars for the 30 or 500 days that separate the landing from an appropriate launch window. The full mission will thus last around one and a half or three years, during which the crew will be entirely dependent on the supplies and technologies that have been transported from the Earth and the minor amounts of resources that can be sourced on site. The challenge is exacerbated by the fact that, in or around Mars, the radio-connection to Earth has a minimal delay that varies (with the distance between both planets) between 3 and 21 min; real-time communication is impossible.

A fourth challenging factor stems from the three previous ones: considerable cargo must be transported to Mars. It has been estimated that the first crewed mission requires at least two preceding cargo missions, each landing 25 metric tons.

Such factors make the mission design complex, and a single mission is expected to require several launch windows (at least three from the Earth and one from Mars), causing operations to span about 10 years. Numerous knowledge and technology gaps must be filled to ensure the safety of the crew.

NASA is now considering the use of nuclear propulsion technologies to follow opposition trajectories, which would be faster than the most economical conjunction trajectory (the Hohmann transit orbit). If implemented, this would also allow the crew to embark for a return trip in principle any time, for instance after 30 days in the Martian system. Opposition trajectories however impose a swing-by around Venus and take the crew closer to the Sun, thereby increasing the intensity of radiation and heat exposure of the spacecraft, and of radiation exposure of the crew.

Among the numerous questions raised by the perspective of the first crewed missions to Mars are some on the physiological effects of a long duration in microgravity or partial gravity, and under large radiation dose rates. All physiological systems are affected by these conditions. The effects of a solar eruption could be highly deleterious, and in some cases lethal. The evolution of the human microflora and of the built environment's microbiome cannot be predicted. Preventive measures against several risk factors can be taken, but their effectiveness can only be partial. A crucial point is the need for physical recovery upon reaching Mars's gravity, and that to be rapidly operational in the absence of extensive medical staff or facilities.

Costs as well may be an obstacle to early missions, depending on political will. A thorough evaluation currently cannot be made. NASA advertises a value of circa US$ 100 billion, spent over a period of about 10 years. There is no public evaluation for the costs of the CNSA programmes. For comparison, NASA is advertising a cost of about US$ 17 billion for a putative Martian flyby in 2033. The accuracy of this number can be questioned, considering that the cost of the US part of a mission to retrieve 500 g of samples collected by Perseverance was estimated to be US$ 11 billion. Assuming any of these assessments are reasonably accurate, a crewed mission is affordable only to a large, powerful country or combination thereof.

The first crew will likely be composed of up to six professional astronauts covering a variety of professional backgrounds. They will be thoroughly selected and scrutinised. For political, social, and ethical reasons, if the mission is US-led, it is expected to include several ethnic origins and genders. The mission will be demanding and risky, but the crew will be aware of the dangers involved in the harsh Martian environment, the adverse health effects of long space flights, and the constraints on their personal freedom. Beyond their own country, they will have the role of representing humanity.

In addition to their political impact and contribution to science, the first missions will pave the way for the possible next step: establishing a permanent science base which could be visited repeatedly. Crews may then rotate, most likely every 500 days. The level of comfort and safety can be expected to increase gradually: missions will become less reminiscent of the expeditions of Scott or Amundsen to the South Pole in the early twentieth century, and more of winterovers in modern Antarctic stations. For a permanent presence to be sustainable, recycling and in situ resource utilisation must reach a very high degree. The scientific exploration of the

geological, and possibly biological, history of Mars will remain the focus. However, key activities are likely to also include prospecting for local resources. The cumulated presence of a large number of people, perhaps selected less stringently, will pose new medical and social challenges. Due to the size of the facilities, and to a compliance that may decrease as Mars missions are less and less perceived as extraordinary, planetary protection may be increasingly challenged. Ethical and legal questions will evolve as activities diversify.

The development of habitable infrastructures, in situ resource utilisation capabilities, and other key assets may—although at present, this is highly hypothetical—allow permanent research stations to evolve into settlements whose dependency on Earth for material resources gradually decreases. Such a situation would raise new practical, legal, and ethical questions. Over the long term, the settlers' living conditions (which include confinement, high levels of ionising radiation, partial gravity, pervasive dust, etc.) would create new medical challenges. Reproductive biology would also be affected, which may impair the long-term viability of the community. And whether children raised on Mars (or even settlers wishing to return after many years) could safely be exposed to Earth's environment is questionable.

One may be tempted to conjecture that, rather than crews living confined and subjected to the Martian environment, the planet may be made more hospitable, more Earth-like—that it may be terraformed. Such an idea has been popularised in pop culture and, recently, by Elon Musk. Thorough scientific work performed in the 1990s suggested that it may be possible and described ways of doing so. Yet the knowledge accumulated over the following three decades makes terraforming appear unfeasible, at least with the technologies that can be foreseen today. Besides, assuming that we could, whether we should terraform Mars is highly questionable. It violates many principles of modern environmental ethics—especially if any indigenous Martian life is found—and raises a wealth of legal and societal issues. Some pertain, for instance, to the relationships between a community on Mars and terrestrial societies.

The last chapter of the book is dedicated to science fiction. It was included as fantasist claims made by the otherwise highly rational scientific community, or the heat behind the debates on Mars exploration and settlement, can hardly be understood without considering its influence on our perspectives. One should not, either, underestimate the role it has played—and will keep playing—on the public perception of matters related to the red planet.

We presume that, as this book draws to its end, the reader will concur: Mars is a harsh place. Although claims are still made that it could be turned into a world which is habitable to humans, this is—at least for the foreseeable future—at odds with our current knowledge of life and of the red planet. Beyond the technical, economical, and legal considerations pertaining to terraforming Mars, the physical reality prevails. It is also questionable that humanity could be sustained without the biosphere that surrounds it on Earth and that an ersatz, with selected plant and microbial species, would be viable over the long term—although ardent promoters of Mars colonisation profess that the emergence of 3D printing, artificial intelligence, and other technologies could compensate for these missing elements.

Building on misled beliefs, it is sometimes claimed that Mars could be used as a planet B if the Earth was on the verge of becoming uninhabitable. Considerations on feasibility set aside, the question of who, among the billions of people that compose humanity, would be chosen and saved, is usually eluded. When used to minimise the need to care for our planet, for instance in the face of climate change, pretending that Mars offers a fallback solution is either extremely naive, or direly unethical.

Exploring Mars is certainly a valuable endeavour. It may unfold similarly to the exploration of Antarctica, with heroic expeditions and, perhaps, permanent research stations. This should not be taken for granted: the challenges are large and overcoming them will require vast amounts of resources, not least among which is human ingenuity. We may nonetheless succeed in reaching that goal. Yet, for centuries to come, the biosphere to which humans belong will be tied to the fate of one planet: the Earth.

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