COLONY 01

Challenges of Establishing Permanent Human Presence on Other Planets

Edited by

András Edl

LUDOVIKA
UNIVERSITY PRESS

Colony 01

Challenges of Establishing Permanent Human Presence on Other Planets

Colony 01
Challenges of Establishing Permanent Human Presence on Other Planets

Editor
András Edl

LUDOVIKA
UNIVERSITY PRESS
Budapest, 2024

This publication was supported by the National Media and Infocommunications Authority (Nemzeti Média- és Hírközlési Hatóság).

Authors

László Balázs
Gábor Bihari
Zsófia Biró
Federico Bonarota
Antonio Carlo
Zsolt Csepregi
András Edl
Bea Ehmann
Márton Farkas
Zsolt Hetesi
Ákos Kereszturi
Árpád Kis
Róbert Marc
Boudour Mefteh
Lucia Adele Savatteri
Tamás Sipos
Norton O. Szabó
Sándor (Alex) Szabó
Dávid Szebeni
András Szkalisity
Nándor Zoltán Tráser

Reviewers
Balázs Bartóki-Gönczy
Előd Both
László Kiss
Gábor Sulyok

Cover image: © ESA - AOES Medialab

Published by the Ludovika University of Public Service
Ludovika University Press
Responsible for publishing: Gergely Deli, Rector

Address: HU-1083 Budapest, Ludovika tér 2.
Contact: kiadvanyok@uni-nke.hu

Managing Editor: Krisztina Kamarás-Vida
Copy Editor: Zsuzsánna Gergely
Layout Editor: József Tihanyi

Printed and bound in Hungary
ISBN 978-963-653-139-3 (print)
ISBN 978-963-653-140-9 (ePDF)
ISBN 978-963-653-141-6 (ePub)
DOI: https://doi.org/10.36250/01209_00

Contents

Foreword

The chapters of this book all revolve around the challenges of establishing humanity's permanent presence on other planets, notably on the Moon. The opinions about the whole topic are divided, some say this is a futile attempt and the resources should be focused on more urgent matters, and spent here on Earth. For those against the investment in space exploration and space activities, education, health care, food production and green energy all seems a better investment. And they are right, these topics are all very important and the challenges awaiting us in the coming years are indeed formidable. They also highlight the many obstacles: distance, radiation, psychological effects, lack of materials, decreased gravity, low return on investment, etc. Many of those are still unsolved problems at our current technological level.

These obstacles do not mean, however, that it is pointless to deal with them. On the contrary, if we believe that space exploration and human missions are beneficial for humanity, obstacles must be overcome. Supporters of further expansion of space activities emphasise the benefits derived from space activity which has an immense GDP multiplier effect[1] and has an overall positive effect on life on Earth, and there is reason to believe that human missions on other planets will have the same effect in the long run. Beyond the sake of development, space powers seem to invest in Moon programs also due to geopolitical tensions, leading to a new space race.

Whether the Reader supports or not investing in projects enabling humanity to create permanent stations on other planets, we all must agree that the competition has already begun and scientific research stations might be a reality on the Moon in the next decade. Our prior aim was to offer a broad spectrum of topics related to the next chapter of human space flight.

The title of the book is purposefully provocative. We are aware of the debate and controversy surrounding such terms as "space colony" and "colonisation".

1 European Space Policy Institute (2023): *More than a Space Programme. The Value of Space Exploration to Empower the Future of Europe.* 1.

It is with purpose that we use the word colony as an anti-goal since we hope that history does not repeat itself and space powers will have the wisdom to avoid hostility, self-centred exploitation of resources and will conduct their activity in the spirit of Article I of the Outer Space Treaty which states: "The exploration and use of outer space, including the moon and other celestial bodies, shall be carried out for the benefit and in the interests of all countries, irrespective of their degree of economic or scientific development, and shall be the province of all mankind."

As I mentioned, permanent human presence on the Moon and later on Mars is not science fiction any more but a subject of spacefaring nations' strategy. Even if many obstacles must be overcome yet and we do not have answers to many questions, it is interesting to conceptualise different future possibilities and raise awareness of certain issues. The condition for such thought experiments is that it has to be rooted in real science. Part of the chapters therefore describe the current situation and offer solutions, questions and possible pathways of thinking about these problems.

Mars and Moon are both mentioned in the chapters, in some instances focus shifts between the two, or is mostly centred on one particular celestial body. The order of the chapters does not reflect a hierarchy of importance. All the topics and challenges discussed are crucial and need to be solved sooner or later to establish and maintain a permanent colony of humanity on another planet. Consequently, the chapters can be read in varying order, the current sequence is only a suggestion.

Space weather is important at every stage of the journey. It will influence the equipment and the living beings on board the spacecraft or living on the colonies. Both will spend considerable time outside Earth's protective magnetic field and therefore adequate protection is a must.

The medical and psychological chapters cover the difficulties of survival in unhospitable and dangerous environments while maintaining optimal performance and avoiding severe, long-term, permanent damage to their body and psyche. To guarantee the safety and the performance of the crew, more medical and psychological research is indispensable. The results will shape both the equipment development they will need and the selection process and training of the crew.

Humans arriving on another planet will need shelter, energy, different kinds of resources, equipment, vehicles and a reliable communication network. Without these, humans could only visit for a short time and would need to leave just like the crew of the Apollo mission. Some of these can be delivered, provided and built in advance via previous missions or robots. Weight, reliability and autonomous operation capability could be a crucial factor. Engineers, software developers, architects and other STEM experts must take all factors imaginable into consideration and build resilient systems with backup options. The task is enormous and requires a lot of funding, long-term design thinking, testing and building the equipment.

It is also a fascinating question how these settlements might influence geopolitics, with special emphasis on security and defence policy. How could the cislunar area contribute to the space industry? How can the current international legal framework assure legal certainty, security and peace, as well as the balance between competing economic interests?

As the distances between Earth and the chosen planet increase, so do the problems. As a final note in our book, we have two chapters focusing on Mars with its specific conditions and unique challenges. Travelling to Mars and making sure the crews can operate for a longer time before they can return will require even more effort than going to the Moon. The guidelines and lessons learned in previous more general chapters will also be valid for Mars with tailor-made modifications for that specific planet.

All in all, our book tries to explore the topic in an interdisciplinary way, fully aware that for the time being there are more questions than answers. I sincerely hope that the reader will also find it interesting and thought-provoking and that we will have the chance to see their confirmation or refutation in the coming decades.

Balázs Bartóki-Gönczy
Head of Institute
Eötvös József Research Centre – Institute of Space Law and Policy
Budapest, 2024 October

Árpád Kis[1]

Possible Effects of Space Weather on Mars Colonies

INTRODUCTION: ON THE THRESHOLD OF A NEW EXPLORATION PERIOD FOR MANKIND

We are at the beginning of a new era of human discovery, an era that we could only encounter on the pages of science fiction literature a few decades ago: we are preparing to colonise other planets. To achieve that, we must prepare for a long interplanetary journey and an environment that is completely different from what we already know and what we are already used to on planet Earth. The new environment is expected to be hostile and unforgiving, therefore we must be prepared extremely well. In the age of previous great discoveries, when they set off for the unknown on sailing ships, at least one could know that wherever they arrived, there would be breathable air, drinkable water, and a temperature that would help them to stay alive. In the age of space exploration and colonisation, this is not the case: the air, water and temperature that are needed for maintaining life have to be also provided, which is making everyday life far more complex. So far, we have only talked about the environment that can be expected on the surface of a foreign planet. In addition to that the colonies will also have to face the dangers of various space weather effects. Under terrestrial conditions, we know that space weather can be considered a constant threat to modern technology and critical infrastructure including communication (surface-to-surface or communication using satellites), safe operation of the electrical network (power lines), positioning, and the secure

1 HUN-REN Institute of Earth Physics and Space Science; ORCID: https://orcid.org/0000-0003-1841-7202; e-mail: Kis.Arpad@epss.hun-ren.hu

DOI: https://doi.org/10.36250/01209_01

operation of digital devices and networks. Furthermore, there is the radiation hazard that we have to take into consideration. As we can see, space weather is a non-negligible risk factor in terrestrial conditions as well. This becomes interesting when we consider that the Earth has a very effective and extensive protective shield, as it has a strong and extensive magnetic field of its own. The focus of our study is the planet Mars. Mars does not have its own magnetic field, at least not as strong and extensive as Earth's. As a result, space weather phenomena will appear with completely different effects than what we are used to under terrestrial conditions.

We will analyse the possible space weather effects on Mars colonies and we thoroughly examine the possibilities and methods of defence against them by taking into consideration the special Martian conditions and environment. It is important to mention that we lack the necessary measurement data related to space weather effects on the surface of Mars and in the near vicinity of the red planet, therefore in our study we are forced to rely on the available data we have, on theoretical assumptions and on the knowledge acquired in the near-Earth environment.

SPACE WEATHER EFFECTS

Generally speaking, the source of all space weather events is the Sun, more precisely the physical processes that take place on the surface of the Sun. The strongest space weather events are caused by eruptions from a sunspot region. It is well known that solar activity has an approximately 11-year time period cycle during which the Sun activity can change substantially. The period of high solar activity is usually called Solar Max, during which time the number of sunspots is represented in the highest number. The time of lower solar activity is referred to as the Solar Minimum, during which period the number of sunspots is low or close to zero. This also means that strong space weather events can have a substantially higher probability during high solar activity.

We basically have to reckon with four types of space weather phenomena: bursts, radio bursts, SEPs (solar energetic protons) and CMEs (coronal mass ejection). In many cases, these events occur together, but there are also cases where they can be observed separately. X-ray bursts are emitted by solar flares, and they can be characterised by intensive, high-energy X-ray packages travelling with the speed of light. Radio bursts also travel with the speed of light, and they are a high intensity, bright bursts of electromagnetic (EM) radiation packages, that can be detected in radio wave frequencies. SEP events are high-energy particle (proton, electron and heavy ion) clouds that travel with high speed through the interplanetary space: the particle energies range from a few tens of keV to GeV, and the fastest particles can reach about 80% of the speed of light. CMEs are plasma eruptions or ejections emitted by the Sun into the interplanetary space with significant plasma mass and the accompanying magnetic field. A CME can reach a speed of 3,000 km/sec in certain cases, so the time required from the moment of the eruption to the arrival on Mars can vary between 21 hours and 5 days. It is obvious that in case of X-ray bursts and radio bursts, we cannot detect the phenomenon before arriving at the planet, since they propagate at the speed of light. In case of SEP events, it is possible to detect the event a few hours before arrival to the planet. On the other hand, a CME can be detected even days before arrival on the planet and thus can be predicted. Therefore, the situation on Mars is very similar in terms of forecasting to Earth, but there is a catch. In case of Earth, we have spacecraft that are located in the vicinity of the L1 point (ACE, SOHO, etc.), so in principle, we can constantly take measurements and detect if there is any change in the interplanetary space. With this, SEP and CME events can be well predicted, and even the expected time of arrival can be determined with great accuracy. In contrast, in case of Mars, we do not have such spacecraft at least not yet. To be able to provide any kind of space weather forecast for the Martian colonies, it will be necessary to build a spacecraft–space-based observation system, as in case of Earth. In the absence of this, it is not possible to give a reliably accurate forecast. This means that – at least in the early days – preparing for and defending against space weather events will be carried out without a forecast service, which greatly narrows the options and possible solutions. It is worth mentioning that serious efforts are currently underway to predict flares and solar flares from the observation of sunspots and the dynamics of their development. If this venture succeeds, it would greatly facilitate space weather forecasts. However, even in this case, there is still uncertainty about the direction in which a possible flare or CME will spread, that is, whether it will hit Mars at all.

To understand what space weather effects we have to expect on the surface of Mars, it is worth learning about the magnetosphere and atmosphere of Mars (including the Martian ionosphere). The Earth's magnetosphere and ionosphere serve as reference points because through this we better understand the differences and why a space weather event can have completely different consequences in the Martian environment.

THE MAGNETOSPHERE AND IONOSPHERE OF MARS

Planet Mars does not have its own extensive magnetic field like Earth does. This is because Mars does not have an internal dynamo mechanism that can create and maintain a strong, extended magnetic field like Earth's. In case of Earth, the intrinsic magnetic field (magnetosphere) extends far towards the Sun: at the subsolar point (the point along the line connecting the Sun with Earth) the position of the magnetopause (in other words: the boundary of the magnetosphere) is located at a distance between 6 and 15 Earth radii, depending on the parameters of the solar wind.

The extended magnetosphere means that Earth's magnetic field can resist the pressure of the solar wind, that is, there is a dynamic balance between the planet's magnetic field and the pressure of the solar wind. For the solar wind, the lines of force of the magnetosphere form an impenetrable barrier, so the solar wind – to put it figuratively – collides with the magnetosphere, slows down, and then changes direction and flows around the magnetosphere. The solar wind is slowed down by the so-called shock wave, which forms even before the magnetopause, as a result of which the solar wind that reaches the magnetopause already loses a lot of its kinetic energy.

For Earth, the extended magnetosphere means that the position of the magnetopause is located much further out than the Earth's atmosphere, so the solar wind cannot come into contact with the atmosphere, and there is practically no interaction between the atmosphere and the solar wind. For Mars, on the other hand, there is no internal dynamo mechanism that could create an extensive magnetic field around the planet; nevertheless, Mars does have its own magnetic field. The Mars Global Surveyor (MGS) satellite (NASA [s. a.]a) carried out measurements between 1997 and 2006 at 100 and 400 km above the surface, based on which it can be concluded that there are relatively strong magnetic fields of a few hundred nT in the Martian crust. These areas of residual magnetism suggest that Mars may once have had an extensive magnetosphere and an internal dynamo mechanism.

Crustal magnetism is typically low in the Tharsis Ridge, impact basins and northern plains. In contrast, the value of the magnetic field is much stronger in the southern areas, where these magnetic fields frozen in the rock practically create small, local magnetospheres, the value of which, according to MGS measurements, can locally reach 1,600 nT on the surface. This is very small compared to the terrestrial magnetic field, which varies between 25,000 and 65,000 nT on the surface. On the other hand, this value is already enough to withstand the pressure of the solar wind at 400 km altitude (Ma et al. 2008), and it can presumably be strong enough to ward off the major effects of a space weather event. These small, local magnetospheres act as a kind of shield because they prevent charged particles from reaching the surface of the planet in these areas (Connerney et al. 2004). Therefore, these areas will be very important in selecting colony locations.

The Martian ionosphere is the part of the planet's upper atmosphere in which ions are created under the influence of the Sun's ultraviolet radiation, and therefore it is in an ionised state. Earth's ionosphere is located deep inside the magnetosphere and is not in contact with the solar wind. For Mars it is different, the solar wind is in direct contact with the ionosphere. This is a fundamental difference between the two planets that determines the environment around Mars and how it changes. In addition to the extreme ultraviolet and X-ray radiation of the Sun, the Martian ionosphere is also affected by the local magnetic environment and the shower of charged particles. Of these, the main reason for the development and changes in the ionosphere is clearly the interaction of the material of the solar wind with the already mentioned local magnetic fields (WITHERS et al. 2012). The interaction of the Martian ionosphere with the material of the solar wind results in the creation of an upper boundary that separates particles (electrons) originating from the Sun from charged particles (electrons) originating from the Martian atmosphere. Although this limit can vary significantly, it is usually found at an altitude of 400 km (WITHERS et al. 2012).

The ionosphere of Mars has a layered structure, typically with two important layers. The first layer is located approximately 120 km above the surface, this is the so-called M1 layer. The M1 layer is basically excited and created by the Sun's low-energy X-ray radiation.

The M2 layer is created by the Sun's extreme ultraviolet radiation, where the highest electron density is typically found at an altitude of 140 km. Above this layer, the electron density decreases exponentially with height (WITHERS et al. 2012).

The Martian ionosphere therefore is capable of absorbing a significant part of the Sun's low-energy X-ray and extreme UV radiation, thus it can have a protective effect against these radiations during quiet times. On the other hand, during a space weather event most probably the Martian ionosphere will not be able to provide a substantial shielding effect, especially against high-energy X-ray radiation and high-energy particles, like the ones expected during SEP events and CMEs.

Another characteristic of the Martian ionosphere is that the height of the upper part of the ionosphere can vary significantly, as evidenced by the Mars Express (MEX) measurements. According to the MEX data, in 1% of the detections, this height was located at 650 km, while in 25% of the detections, this limit (ionopause) was below 250 km height. Based on the analyses, it seems that the unusually high ionopause occurs above areas where there is a locally stronger (crust-derived) magnetic field. These local spaces can keep the solar wind away from the planet by "acting" as a local magnetosphere (Withers et al. 2012). Lower-than-average ionopause heights occur during intense solar activity, which indicates that lower-than-average or much lower ionopause heights should also be expected during space weather events, which can significantly increase the risks caused by radiation on the surface. Another characteristic is that the composition of the ionosphere can vary according to geographical location. The reason for this is that molecular oxygen is more common in the lower parts of the Martian atmosphere (i.e. closer to the planet's surface), while atomic oxygen is dominant at higher altitudes.

The ionosphere does not only depend on the local conditions, as we presented above but also depends to a large extent on the time of day. In the absence of the Sun's radiation, the structure of the ionosphere changes completely on the night side, and the electron density is greatly reduced (Withers et al. 2012).

Based on all of this, it can be said that we are dealing with a very variable Martian ionosphere, dependent on many factors, even during quiet periods from the point of view of space weather. During a space weather event, the structure of the ionosphere is expected to become even more complicated and diverse, and this will be important for the colonies from the point of view of communication, which we will return to later.

THE MAGNETIC ENVIRONMENT STRUCTURE ON MARS

After learning about the magnetic properties of the planet Mars and the structure and processes of the ionosphere, the global structure and its consequences become understandable, but for this, we still need to examine the interaction with the solar wind, which completes the picture.

In the flow of the solar wind, Mars appears as an obstacle, therefore a shock wave forms in front of Mars, where the flow of plasma of the solar wind slows down to subsonic speed. As a result of the Sun's ultraviolet radiation, the upper atmosphere of Mars is ionised, thereby turning it into an electrically charged medium. The magnetic field of the solar wind does not penetrate this medium, so the solar wind flows around the planet. As a result, it interacts with the planet's ionosphere and creates a so-called induced magnetosphere (Szegő 2016). For this reason, the magnetic environment of the planet Mars is special in that it consists of a superposition of the induced magnetosphere and the local crustal magnetic fields.

Based on MGS measurements, the bow shock is located at a distance of approximately 2.33 Mars radii from the planet, which in case of Earth – as mentioned earlier – is much further away. At the shock wave, the magnetic field strength increases suddenly, and due to the acceleration processes taking place here, high-energy electrons also appear (Acuña et al. 1998). Moving towards the planet, the next interface is the so-called Magnetic Pileup Boundary (MPB), which separates the Magnetic Pileup Region (MPR) from the magnetic sheath (Martian magnetosheath or simply sheath). The MPR is the region dominated by the ions of the planet's atmosphere and characterised by a stronger magnetic field (Nagy et al. 2004).

The innermost boundary is the Photo Electron Boundary (PEB), which separates the ionosphere from the outer plasma environment (Wang et al. 2022). As already mentioned, the height of the PEB depends to a great extent on the crustal magnetism of the areas below it: where crustal magnetism is present, this limit is pushed up, as can be seen in *Figure 1*. This is typically observed in the southern hemisphere (Bertucci et al. 2005).

The atmosphere of Mars is constantly eroding due to the interaction with the solar wind and has already lost a significant part of its atmosphere in the past. According to analysis, the erosion of the atmosphere began after the planet's internal magnetic field ceased.

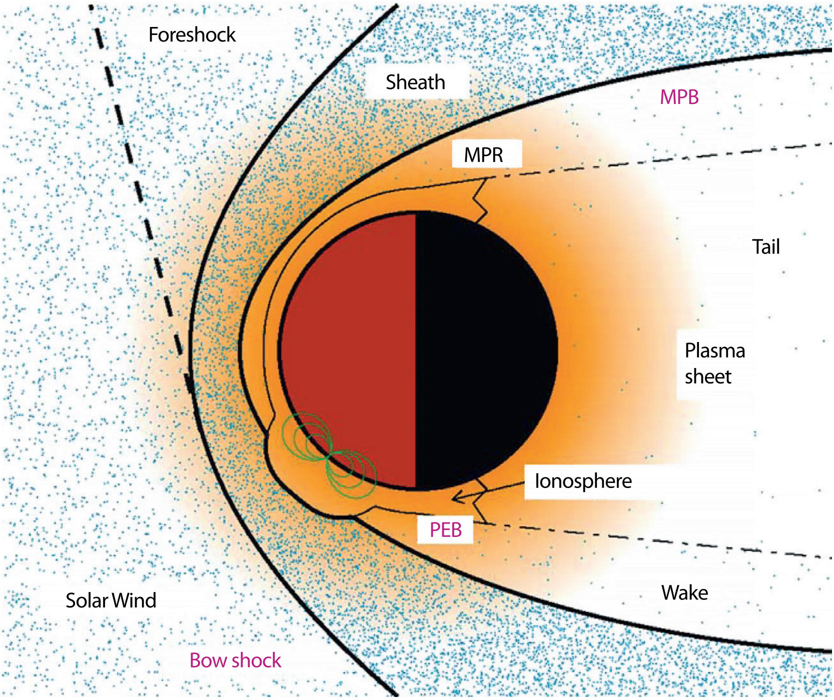

Figure 1
Structure of the magnetic environment on Mars
Source: Brain 2006: 79.

RADIATION

If we want to create settlements on Mars, settlements where people stay and work for a longer or shorter period of time, we must examine the issue of radiation as a condition. As we have already mentioned, Mars does not have a protective magnetosphere like the Earth, so ionising, high-energy radiation can reach the surface practically unhindered. Furthermore, the solar wind is constantly eroding the rare atmosphere that still remains on Mars, so the atmosphere is not an appreciable protection against radiation either. To be precise, the Martian atmosphere can provide some protection against cosmic radiation and moderate protection against radiation from the Sun.

Therefore, it can be said that a much higher radiation exposure than the terrestrial environment must be expected on Mars, and to this we must also add the occasional space weather effects, which can carry even lethal amounts of radiation, and that is in a very short time. The risk posed by space weather events is of course even more pronounced during the solar maximum.

To be more specific, let us discuss specific events and specific numbers. Most particles from most SEP events are likely to be intercepted by the Martian atmosphere. At the same time, these particles interact with the particles of the atmosphere, and neutrons can be created from this interaction, and these neutrons can reach the surface. In other words, it can be said that although the direct risk posed by SEP particles can be greatly reduced by the presence of the atmosphere, it does not completely eliminate the health risk.

The protective effect of the Martian atmosphere also depends to a large extent on where on the planet we are, i.e. near the equator or rather near the poles. In other words, because of the angle of inclination, radiation coming from near the horizon has to travel a much longer distance through the atmosphere than radiation coming from near the zenith. For the settlement to be established on the surface of Mars, this aspect should also be taken into account as much as possible. On the other hand, it has to be taken also into consideration that the temperature conditions are not very favourable for colonies in the vicinity of the poles.

If we want to talk about specific numbers, we should know that there are various, sometimes different, estimates in the literature about the expected radiation on the surface of Mars. The average radiation dose on Earth's surface, which comes from cosmic rays, is about 0.26 mSv/year. This value naturally increases with altitude and corresponds roughly to 10% of the total annual radiation exposure. The dose caused by cosmic radiation on the surface of Mars is about 230mSv/year, taking into account the data measured by the Curiosity Mars rover. As estimated by other models, the annual radiation dose on the surface of Mars varies between 156.4 mSv/year and 273.8 mSv/year; the former value is expected at the time of solar maximum, and the latter at the time of solar minimum.

The Mars Odyssey probe (NASA [s. a.]b) was equipped with an instrument specifically designed to measure the radiation environment around Mars. The name of the instrument is MARIE (Martian Radiation Experiment), and the radiation value measured by it corresponds approximately to what is expected on the surface due to the rare atmosphere of Mars. During 18 months, the instrument measured an average value of 22 millirads per day, which corresponds to 8 rads or about 80 mSv/year (1 mSv = 100 millirads). As can be seen, the expected radiation value (from cosmic rays) on the surface of Mars on average is about 300–1,000 times higher compared to radiation values on the Earth's surface.

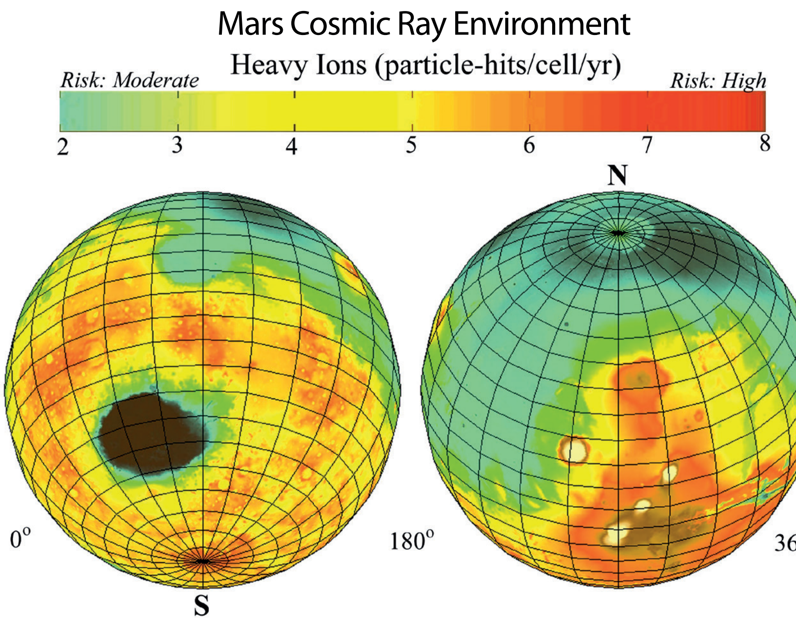

Figure 2
Estimate of the high energy cosmic radiation reaching the surface of Mars
Source: NASA/Jet Propulsion Laboratory/JSC 2002

THE STRUCTURE AND CONDITIONS OF THE MARTIAN COLONY

When examining the possible effects of space weather on a Martian colony, it is worth mapping out the vital elements of such a colony, so what are the things that are absolutely necessary for such an establishment. The list is obviously incomplete and rough, its main purpose is to list the elements that can be directly affected by space weather events. These are the following:

- the complex systems controlled by computers that ensure life support
- growing plants that provide food
- communication between stations and units on Mars
- communication with satellites (including positioning)
- satellites orbiting Mars and performing various tasks
- the larger structural units and facilities of the colony (electrical network, possibly railway and water supply network, etc.)
- the structures providing radiation protection

When compiling the list, it is necessary to start from the assumption that the operation and security of a colony cannot be imagined without space technology applications; therefore, the presence and use of satellites are absolutely necessary. The space station (which ensures the transportation of people and useful materials), industrial facilities and mining sites were not specifically mentioned, because the latter can be integrated into the above list.

Effects on plants and crop production

The primary condition for the existence of colonies is the provision of food. This is obviously not possible with transport supplies from Earth, which is why it is necessary to start growing crops on Mars as early as possible. In this section, we examine the potential consequences of radiation and space weather events for plant development. We have never tried to grow plants outside of Earth, so this is an interesting task and challenge in itself. Note: there were valuable plant growing experiments onboard the ISS, but since the space station orbits between 370 and 460 kilometres above the Earth's surface, these experiments were conducted still in the protective Earth's environment, deep inside the Earth's magnetosphere.

Fortunately, there has already been an experiment (Tack et al. 2021) that specifically examined the development of cultivated plants, exposing them to approximately the amount of radiation expected on the surface of Mars, according to calculations and measurements. The radiation was simulated or more precisely replaced by the gamma radiation of cobalt-60. In the test, the germination and development of rye and garden cress were investigated after being exposed to radiation. The experiment ended with some interesting results.

The results showed that radiation had no detectable effect on germination, however, biomass development was significantly reduced in the first four weeks. The decrease was 48% for rye and 32% for cress. The article notes that, in principle, the not exactly identical environment, possible changes in temperature and humidity can explain some of the difference, however, the difference measured in the experiment is such that it can clearly be attributed to the effect of radiation. In addition, discolouration, necrosis and browning of the leaves were also observed. It is also described that the short-term, but higher-intensity radiation (with which they tried to simulate solar SEP events) that reached the plants in their various development phases did not significantly affect the amount of the crop.

Knowing this, it is clear that plants should be protected from radiation, e.g. considering that the cultivation could take place deep underground, but in this case, we obviously lose what would be the most important from the point of view of plant cultivation: natural light.

Overall, based on the results of the experiment, it can be said that in order to ensure the appropriate amount of the planned crop, the production area must be increased at least twice as compared to the conditions on earth.

SEU–SEE

Under Martian conditions, we must definitely discuss the effects of various ionising radiations on electrical devices, which may occur more frequently during space weather events. Here we are not thinking of events that, for example, cause permanent damage to electronics as a result of strong radiation, because space vehicles normally are built in such a way that they are resistant to (expected) radiation. This is called the "rad-hard" requirement, and as a result, devices built in this way usually operate safely in environments with significant radiation.

However, there is also an event when a single ionising particle, be it an ion, an electron or even a photon, which has sufficient energy, hits a sensitive point (node) in microelectronics and causes a state change in it. The change of state is the result of the ionising particle creating a free charge that changes the value of a bit in a memory cell or the processor, for example. This obviously causes an error in the output signal, the consequence of which is an operational error (program error), which can also cause a complete interruption in the operation of the system.

This is called single event upset (SEU) or single event error (SEE). It is important to emphasise that this does not cause permanent damage to the system, but rather an operational error or shutdown which typically occurs after the incomprehensible program instruction. This error usually disappears after restarting the program or the process. It is also worth noting that this error typically occurs during operation, and not when it is turned off. The first article (Binder et al. 1975) describing the SEU event was published in 1975.

It is clear that during space weather events, especially SEP events, SEU failures can be expected more frequently, not only for satellites orbiting Mars but also on the surface of Mars. The reason is obvious: due to the lack of an extensive magnetosphere and the rare atmosphere, ionising radiation reaches the surface much more easily, posing a serious threat to electronic devices. Taking into account the fact that the living conditions for the colony on the surface of Mars are provided by well-functioning devices controlled by complicated electronics, even a temporary malfunction cannot be allowed because it can have fatal consequences.

For this reason, it is clear that when designing and building systems using microelectronics, maximum consideration must be given to failures caused by SEU and adequate redundancy must be ensured. Without it, the protection and proper functioning of the colonies cannot be ensured.

Data protection must also be mentioned here: malfunctions caused by space weather events can seriously threaten the integrity of the data stored in the databases. For this reason, duplicated redundant data protection will probably not be enough, but it may also be necessary to make the units storing important data geographically redundant. According to this, all data will have to be stored on servers that must have at least one (or even more) copies at a location as far away from the primary data server as possible, possibly deep below the surface, which is maximally protected from all kinds of space weather events.

In the case of satellites orbiting Mars, we can expect even more SEU events, because the satellites will be located outside the atmosphere, so even the minimum protection that the rare atmosphere might mean for the satellites will not be provided.

Magnetic storm on Mars and its expected consequences

A CME under terrestrial conditions (if it hits the Earth) causes a geomagnetic storm. The Earth's magnetosphere is compressed, which causes a significant and rapid change in the magnitude of the local magnetic field that can also be measured on the Earth's surface. We know that a rapidly changing magnetic field induces an electric field, which generates currents in the ionosphere and the Earth's crust. These are the so-called geomagnetically induced currents or GIC. Mars does not have an extensive magnetic field, but it does have some remanent and induced magnetic fields, as has been discussed previously.

If a CME hits Mars, we can expect similar consequences, that is, a rapid change in the magnetic field that can also be felt on the surface. It is important to note that the consequences of a CME on Mars have not yet been measured; therefore, we do not have reliable measurement data for such an event. Here we can only refer to analogy and physical laws, but this is enough to be able to predict the expected consequences. The rapidly changing magnetic field creates an induced electric field on the surface of Mars, this is certain.

Compared to the effects that can be observed on Earth, this will not cause a global effect, but rather we can expect local, quite specific effects, which are more characteristic of the given areas and can be very different in different areas of Mars. For this reason, it is difficult to predict the changes in the magnetic field perceptible in specific areas. If, however, these are significant changes, the appearance of an excited electric field and, as a consequence, crustal currents in the soil of Mars can be expected. We can call these Martian Magnetically Induced Currents, or MMIC.

These induced currents seek a path and flow where the resistance is least, so they tend to attach to man-made metal structures that span over great distances. In terrestrial conditions, such are, for example, railways, petroleum pipelines and high-voltage lines. In case of a Martian settlement, similar structures can be expected: electric lines, pipe systems, etc., which are absolutely necessary for the operation of the settlement.

MMIC can attach to these structures and devices and due to that can cause failures. As has been said, sensitive electronics can be potentially endangered by these stray currents, which can be in some cases very high-intensity currents. How to defend against MMIC? Fortunately, a magnetic storm is a space weather event that can be predicted before it happens with sufficient certainty. A CME (depending on the propagation speed of the plasma cloud) needs 1–4 days to reach Mars.

The CME can be detected immediately after its ejection if a satellite is available at the appropriate observation point. And here is a problem: in case of Earth, several satellites are available to observe CMEs (SOHO, ACE, etc.), but they can only be used to predict geomagnetic storms that are expected on

Earth. We do not (at least for now) have such an option for Mars. The existing satellites are of limited use to detect the plasma cloud spreading towards Mars, if the position of the Earth and Mars and their relative positions make this possible. However, if Earth and Mars are at two very different points in their orbits, then obviously no prediction or observation is possible.

Communication on Mars

For radio communication on Earth, the presence of the terrestrial ionosphere is of primary importance. Since Mars does not have an ionosphere comparable to Earth's, it can be clearly stated that radio communication will be realised with a completely different technology than on Earth. On Earth (especially in case of radio broadcasting on the HF band), communication over long distances (to targets beyond the horizon) is possible in such a way that the radio wave can travel between the ionosphere and the Earth's crust like a waveguide.

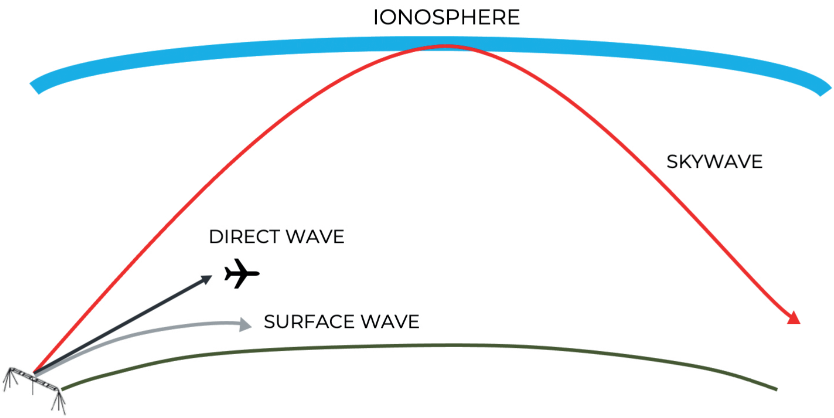

Figure 3
The path of the HF radio wave in the terrestrial environment
Note: Most probably it will not be possible to use the skywave in radio communication on Mars due to the dynamic nature of the Martian ionosphere.
Source: Daly 2021

HF is popular even today, when communication via satellites is already widespread because it is a very reliable method in normal conditions.

On HF frequencies we communicate with aircraft, the frequency is used by government agencies and by the military, just to name a few. In terrestrial conditions, problems in HF band radio communication usually arise when the structure of the ionosphere changes due to a space weather event. In this case, partial or complete data loss may occur.

On Mars, radio communication will probably be achieved by using a direct wave (when the receiver "sees" the transmitter), or through communication satellites orbiting in stationary position. The reason for this is obviously the lack of a "stable" ionosphere similar to Earth's, which enables reliable radio communication. In principle, it might be possible to communicate on Mars by using the presence of the Martian ionosphere, but due to its dynamically changing nature, it is unlikely that this can be realised.

According to our current knowledge, the use of direct waves and communication via satellites seems to be possible on Mars. On the other hand, both can have serious problems, especially during space weather events. During radio burst events serious interruptions can occur even when the direct wave is used.

We have to prepare for such events. These events cannot be predicted or forecasted, because a radio burst arrives at the speed of light. Note: this may also partially or completely limit the operation of radars. Radio bursts do not cause permanent damage to the instruments, but they can cause temporary disturbance.

Communication via satellites is also exposed to the effects of space weather, as we have seen by satellites around Earth. Communication with satellites on Mars also takes place through the Martian ionosphere, which means that the radio wave must pass through the ionosphere. During a space weather event, the structure and density of the Martian ionosphere can change significantly, which changes the path and direction of the radio wave passing through it.

This is when the phenomenon called scintillation (Kenpankho–Suwanjan 2004) occurs, when, to put it simply, the radio signal bounces back and forth in the ionosphere, travels through several paths, and the signal arriving at the receiver (if a signal arrives at all) is formed by the interference of the original signal travelling through several paths, which was broken up. Obviously, this can result in partial or even complete data loss. The condition persists until the ionosphere returns from its disturbed state to its "normal" state.

Here, however, it is worth noting that in case of the Martian ionosphere, we are facing a highly dynamic environment, and as a result, we can expect data loss even in a period free of space weather events.

When using GPS, we can also expect scintillation during space weather events resulting in satellite-based positioning becoming unreliable. The reason for this is that the signal from the satellite arrives from a different direction due to the scintillation, so the degree of positioning will be incorrect, and if strong scintillation occurs, it might become completely unreliable.

Where should we settle on the surface of Mars?

The complete question would rather sound like this: Where can we create settlements on the surface of Mars, where the colony is as protected as possible from the effects of space weather? Obviously, it is very difficult to give a clear answer to this question, so we will take a look at the possible options.

1. The first and logical option would be for the colony to be established deep below the surface of Mars, where the thickness of the crust provides reliable and sufficient protection against all kinds of radiation and space weather effects. The creation of a functional city underground or under the soil/crust of Mars would involve incalculably high costs and technical solutions. It is necessary to ensure breathable air, suitable temperature, drinking water, food production (using artificial light!) and, of course, an acceptable living space for people (and, where appropriate, animals). Not to mention the expected psychological effects of living in such a closed and humanly oppressive environment, deep inside an actual cave. If we want to be insightful, we could imagine such a colony as the city of Zion in the Matrix movie.

2. If we start from the assumption that the effects of space weather occur mainly on the side facing the Sun, then it is possible to imagine a colony that retreats to safety during the Martian day and is only active during the night. Here it is no longer necessary to plan a city deep under the crust, the buildings can be located on the surface, assuming sufficient protection against all kinds of influences. On the other hand, the effects on technology must also be taken into account, against which protection can be provided by ensuring that devices, machines, computers, etc. on the day side switch to a "protected" or "sleep" state, ensuring that failures are minimised while the colony residents are in a safe and protected space. On the night side, one can move more freely, the technology becomes active, and it is possible to perform all the activities that are the purpose of the colony.
3. If the goal is to create a colony that is not significantly restricted in its operation, and all kinds of activities can be carried out relatively freely even on the day side with an acceptable risk, the position of the colony on the surface of the planet must be chosen extremely carefully.

The requirement is obviously the maximisation of the protection capacity of the natural environment. This means that the chosen place must be one that provides the best possible natural protection against radiation and other space weather effects. It has two important elements: the atmosphere and the magnetic field; both act as a protective shield. The atmosphere must be as thick as possible, therefore, it is necessary to look for a place that is as low as possible compared to Martian conditions.

Basins and low-lying regions can be considered. The other condition requires the strongest possible magnetic field to be present in the given area, therefore, it is worth looking for places where the crustal magnetic field is as strong as possible. If we manage to find a low-lying region where the crustal magnetic field is strong enough, then we have practically found the ideal location for the colony.

SUMMARY

It is very important to emphasise that all the topics and discussions presented in this analysis can be considered only a preliminary study due to the simple fact that at this point we do not have enough reliable data and experience from the red planet. On the other hand, the conclusions are the result of careful and deliberate use of the available scientific knowledge.

We currently do not know exactly where, when, under what conditions and future knowledge the first Martian colony will be created. We can only hope that this study can provide useful assistance in one of the greatest enterprises of mankind: the colonisation of other planets and the expansion of human civilisation beyond the borders of the cradle of life, the Earth.

REFERENCES

Acuña, M. H. – Connerney, J. E. P. – Wasilewski, P. – Lin, R. P. – Anderson, K. A. – Carlson, C. W. – McFadden, J. – Curtis, D. W. – Mitchell, D. – Reme, H. – Mazelle, C. – Sauvaud, J. A. – d'Uston, C. – Cros, A. – Medale, J. L. – Bauer, S. J. – Cloutier, P. – Mayhew, M. – Winterhalter, D. – Ness, N. F. (1998): Magnetic Field of Plasma Observations at Mars: Initial Results of the Mars Global Surveyor Mission. *Science,* 279(5357), 1676–1680. Online: https://doi.org/10.1126/science.279.5357.1676

Bertucci, C. – Mazelle, C. – Acuña, M. H. (2005): Interaction of the Solar Wind with Mars from Mars Global Surveyor MAG/ER Observations. *Journal of Atmospheric and Solar-Terrestrial Physics,* 67(17–18), 1797–1808. Online: https://doi.org/10.1016/j.jastp.2005.04.007

Binder, D. – Smith, E. C. – Holman, A. B. (1975): Satellite Anomalies from Galactic Cosmic Rays. *IEEE Transactions on Nuclear Science,* 22(6), 2675–2680. Online: https://doi.org/10.1109/TNS.1975.4328188

Brain, D. A. (2006): Mars Global Surveyor Measurements of the Martian Solar Wind Interaction. *Space Science Reviews,* 126(1–4), 77–112. Online: https://doi.org/10.1007/s11214-006-9122-x

Connerney, J. E. P. – Acuña, M. H. – Ness, N. F. – Spohn, T. – Schubert, G. (2004): Mars Crustal Magnetism. *Space Science Reviews,* (111), 1–32. Online: https://doi.org/10.1023/B:SPAC.0000032719.40094.1d

Daly, D. (2021): HF Communications are making a comeback, and here's why you need to get in on it! *Base Camp Connect,* 14 Dec 2021. Online: www.basecampconnect.com/hf-communications-making-a-comeback/

Kenpankho, P. – Suwanjan, P. (2004): *GPS Based Ionospheric Scintillation for Space Weather.* Online: https://a-a-r-s.org/proceeding/ACRS2004/Papers/NVS04-2.htm

Ma, Y.-J. – Altwegg, K. – Breus, T. – Combi, M. R. – Cravens, T. E. – Kallio, E. – Ledvina, S. A. – Luhmann, J. G. – Miller, S. – Nagy, A. F. – Ridley, A. J. – Strobel, D. F. (2008): Plasma Flow and Related Phenomena in Planetary Aeronomy. *Space Science Reviews,* 139(1), 311–353. Online: https://doi.org/10.1007/s11214-008-9389-1

Nagy, A. F. – Winterhalter, D. – Sauer, K. – Cravens, T. E. – Brecht, S. – Mazelle, C. – Crider, D. – Kallio, E. – Zakharov, A. – Dubinin, E. – Verigin, M. – Kotova, G. – Axford, W. I. – Bertucci, C. – Trotignon, J. G. (2004): The Plasma Environment of Mars. *Space Science Reviews,* 111(1–2), 33–114. Online: http://doi.org/10.1023/B:SPAC.0000032718.47512.92

NASA [s. a.]a: *Mars Global Surveyor.* Online: https://mars.nasa.gov/mars-exploration/missions/mars-global-surveyor/

NASA [s. a.]b: *Mars Odyssey.* Online: https://mars.nasa.gov/odyssey/

NASA/Jet Propulsion Laboratory/JSC (2002): PIA03479: Estimated Radiation on Mars, Hits per Cell Nucleus. Online: https://photojournal.jpl.nasa.gov/catalog/PIA03479

Szegő, K. (2016): *A nem mágneses bolygók magnetoszférája.* Online: www.rmki.kfki.hu/~opitz/NF2016/08_SzK_A_bolygok_magnetoszferaja.pdf

Tack, N. – Wamelink, G. W. W. – Denkova, A. G. – Schouwenburg, M. – Hilhorst, H. – Wolterbeek, H. T. – Goedhart, P. W. (2021): Influence of Martian Radiation-like Conditions on the Growth of Secale cereale and Lepidium sativum. *Frontiers in Astronomy and Space Sciences,* 8. Online: https://doi.org/10.3389/fspas.2021.665649

Wang, Y. – Cao, Y. – Cui, J. – Wei, Y. – Rong, Z. (2022): An Automatic Identification Method for the Photoelectron Boundary at Mars. *The Astronomical Journal,* 163(4). Online: https://doi.org/10.3847/1538-3881/ac5825

Withers, P. – Fallows, K. – Girazian, Z. – Matta, M. – Hausler, B. – Hinson, D. – Tyler, L. – Morgan, D. – Patzold, M. – Peter, K. – Tellmann, S. – Peralta, J. – Witasse, O. (2012): A Clear View of the Multifaceted Dayside Ionosphere of Mars. *Geophysical Research Letters,* 39(18). Online: https://doi.org/10.1029/2012GL053193

Sándor (Alex) Szabó[1]

Medical Aspects of Long-Term Settlements on Other Planets

"Earth is the cradle of humanity,
but one cannot remain in the cradle forever."

Konstantin Tsiolkovsky

THE CHALLENGE FOR SPACE MEDICINE

The dream of manned space travel has proved to be very attractive for centuries for scientists and the general population as well. "Man must rise above Earth to the top of the atmosphere and beyond, for only then will he fully understand the world in which he lives" – stated Socrates (469–399 B.C.). The first person to write about living and travelling in space was Johannes Kepler in the early 1600s. In 1865 the French writer Jules Verne wrote in his novel *From the Earth to the Moon* about the attempt to build an enormous "space gun" and launch three people in a projectile with the goal of Moon landing. In the 1860s, Edward Hale wrote about the "Brick Moon" which had many of the characteristics of a space station; it was a man-made structure that orbited Earth and provided housing and life support for its crew while serving as a navigation aid for people on Earth. The Russian theoretician Konstantin Tsiolkovsky (1857–1935) inspired by the fiction of Jules Verne theorised many aspects of space travel and rocket propulsion: he envisioned a certain design for a space station that would serve

1 Associate Professor at the University of Szeged, Head of Department of Aviation and Space Medicine, Chief Flight Surgeon of the Hungarian Defence Forces, DAvMed UK King's College London – Royal Air Force (1999), ESA Space Physician Training Course (2021); ORCID: https://orcid.org/0000-0002-1362-4723; e-mail: sasi19620@gmail.com

DOI: https://doi.org/10.36250/01209_02

as a miniature Earth, with the growth of vegetation in the interior and that could use sunlight as an energy source. In 1928 Herman Noordung gave the first details of the engineering, design and construction of a space station (*wohnrad* or *living wheel*). He identified the possible harmful effects of weightlessness and recognised the significant role of rotation (evolving centrifugal force) required to create artificial gravity for the crewmembers. Ley wrote about life in a space station in 1952 (well before it actually happened), also imagining "a wheel-shaped space station revolving around the Earth much as the moon does". The necessity of a new discipline concentrating on human factors of spaceflight emerged after World War II as technical development (ballistic missiles and rocket technique) stepped over the von Kármán line considered the aerodynamic cutoff limit (Ley–Bonestell 1950; Antonsen 2019; Nicogossian et al. 2016: 5).

For life science and space medicine specialists, the first spaceflight (limited one-turn-around 108 minute long "excursion" by Yuri Gagarin into LEO – Low Earth Orbit) on 12 April 1961 became the first solid evidence that spaceflight is survivable and humans can maintain their working ability with basic physiological functions. But even now and for the foreseeable future space travels continuously challenge our competency to maintain and extend even more our living capability and habitation onboard space stations, spaceships and on the surface of other moons and planets. Considering the habitability potential of celestial objects we should take into account chemical, physical, geological and geographic attributes that can shape the environmental settings on the surface: a combination of approximately 20 basic factors can predict the habitability of that planet or moon. We should prioritise the presence of water, overall atmospheric pressure (excluding poisoning gases), proper temperature range (avoiding extreme diurnal fluctuation), the availability of nutrients (C, H, N, O, P, S sources and essential metals, essential micronutrients) due to volcanic activity or production, an energy source, and protection from solar ultraviolet and galactic cosmic radiation, reduced gravity. All these parameters can interfere with deployed human life support systems and can deteriorate human adaptability to harsh environmental settings to withstand them in a sustained form (McKay–Stoker 1989: 189–214).

50 years after Apollo 17 set foot on the Moon for the last time, space exploration could get a new impetus: as a first step to returning to the Moon, the Artemis program is focusing on the development of a "Lunar Gateway" orbiting unit and a stationary lunar surface base ("Lunar Outpost" as a Base Camp Concept). But it is only a small step heading to and preparing for the much longer and more dangerous travel to Mars. Today's advanced technology has enabled astronauts to live on ISS (International Space Station) since 2001 continuously (usually in six-month rounds), performing a wide range of biomedical experiments and research projects to better understand the effects of space environmental stressors on the human body. Outer space is really a hostile and harsh environment for any form of life, acute (explosive) exposure to it without any technical protection (encapsulation in a spaceship or hermetised spacesuit) can cause immediate incapacitation and even death within a few seconds. For prolonged spaceflights into deep space (despite hermetised and climatised modules and compartments onboard spaceships or space stations) other highly relevant stressors like extreme radiation levels and microgravity-induced pathophysiological processes can lead to diminished working ability and loss of functional activity. The imminent consequences on the human body can include circulatory changes (deconditioning cardiovascular reflexes, space anaemia – reduced red blood cell volume), space motions sickness, gradually worsening muscle atrophy (loss of lean body mass and strength), bone demineralisation (like age-dependent osteoporosis), eye problems with headache in SANS (space associated neuro-ocular syndrome) and we should consider the adverse long-term effects of confinement and isolation from psychological aspects as well (Ong et al. 2023: 895–900). Isolated settings combined with extremely threatening environmental challenges can easily lead to profound psychological changes (depression, mood instability) in a remote ground-based situation (e.g. Antarctic research station as a space analogue) and emotional downgrading (negative patterns) can interfere with proper verbal and written communication among team members. By content analysis of diaries and reports, we can characterise social dynamics as an essential parameter for teamwork efficiency (Ehmann et al. 2018: 112–115).

Partially restored gravitational force on the surface of targeted moons and planets (the average gravitational acceleration on Mars is 3.72 ms−2, about 38% of that of Earth) can provoke again malfunctioning in readaptation, orthostatic intolerance (fainting tendency) and leaving the shield of spaceships can expose the astronauts to an even higher dose of cosmic radiation, especially during SPEs (Solar Particle Events). So maintaining the working ability and overall health of astronauts is a huge challenge for space medicine from the very beginning, demanding a complex medical support system, including telemedicine and surgical, resuscitative capabilities, with proper preventive countermeasures in certain pathophysiological processes like musculoskeletal atrophy, carcinogenesis, space radiation-induced atherogenesis. These entities might be showstoppers and can raise ethical concerns about the real cost and benefit of astronauts' health and well-being status (a "one-way ticket" to Mars is not a real option).

It is often criticised that human missions are too expensive compared to unmanned automatic platforms designed for Earth observation or Solar System exploration. But we shall be out there personally in order to utilise our competencies in an inherently inexact science: we should take into consideration individual physiological variability and execute repeated measurements to improve the survivability of humans. As Wilbur Wright, pioneer of the heavier-than-air flight stated: "If you are looking for perfect safety you will do well to sit on a fence and watch the birds; but if you really wish to learn you must mount a machine and become acquainted with its tricks by actual trial."

The same is applied to spaceflight: if you do plan to live in space and explore other moons and planets you are forced to prepare for unfamiliar and harsh environmental settings and forced to cope with them in a prospective way. With proper steps like medical surveillance (biomedical monitoring) methods and even therapeutical countermeasures, we can improve the quality of life in space. Furthermore, it may be possible that by using the same proper and effective countermeasures applied in space we can improve the health of people on Earth suffering from similar age-dependent clinical problems (like osteoporosis and muscle atrophy). In other words: patients with illness live in a normal Earth environment but evolve abnormal physiology. On the contrary, astronauts are scrutinously selected applicants with normal physiology who live in an abnormal (evolutionary not experienced and not adapted) environment: their adaptive processes can be evaluated and proactively utilised in general sick population on Earth as well (WILLIAMS et al. 2009: 1317–1323).

THE HISTORY OF SPACE MEDICINE

Space medicine as a new science was born after WWII, closely related to rocket research (planning and building), focusing on the physiological consequences of altered gravitational forces (accelerative overloads and microgravity as well) in animal experiments. In 1948, U.S. flight surgeon Harry G. Armstrong together with biologist Hubertus Strughold and astrophysicist Heinz Haber initiated the formation of a new aerospace discipline within the frame of preventive medicine and in 1951, a new Space Medicine Association formed within the Aerospace Medical Association in close cooperation with experts in astronautics, human factors, habitability engineering and biomedical research (NICOGOSSIAN et al. 2016: 5).

Dr Hubertus Strughold, a German medical doctor (former researcher in flight physiology in the Luftwaffe during WWII) became "the Father of Space Medicine" studying the physical and psychological effects of manned spaceflight. After WWII he became the director of the Physiological Institute at Heidelberg University. In 1947 he was invited to the United States as part of Operation Paperclip and working for the U.S. Air Force and NASA he was involved in animal (monkey) experiments and human medical investigations as well. NASA even used Primates and chimpanzee Ham flew onboard Mercury-Redstone in 1961 for a suborbital flight (CAMPBELL et al. 2007).

Russian Vladimir Jazdovsky was the first space medicine specialist: working for the Aeromedical Research Institute of the Soviet Air Force he was invited by Sergei Korolev, chief constructor of space rockets to participate in preliminary animal tests in space programs (Russian scientists preferred dogs since Pavlov's famous experiments). The very first living creature Laika was launched into orbit onboard Sputnik 2 in 1957. It was planned to live for 6 days before running out of oxygen, but due to thermal instability, heat stress finally killed the animal within 6 hours (George 2018).

Commencing the era of manned spaceflight, the role of Flight Surgeons (aviation medicine later dedicated space medicine specialists) became even more complex and significant: they provide improved selection methods and medical surveillance for astronauts. Considering the increased mission length, space flight surgeons set up new equipment for biomedical monitoring of physiological parameters and improved tools for aerobic exercise to prevent cardiovascular deconditioning, bone and muscle atrophy. One of the most renowned NASA physicians was Charles "Chuck" Berry, who worked from the very beginning in the U.S. space program "Man in Space Soonest". Later, he took full responsibility for Medical Operations during the Apollo program in NASA's Manned Spacecraft Center – Johnson Space Center (Butler: 1999). He performed extreme stress tests at the selection phase of NASA classes and sent 42 astronauts into space in over 30 missions – including Apollo 11. During the historic mission of Apollo 11, he was the responsible Medical Officer while Neil Armstrong walked on the Moon. He also worked as an aviation medical examiner for the Federal Aviation Administration and was an aerospace medicine consultant for many years. He was considered a pioneer in aerospace medicine throughout his 68 year long career, and his son Michael Berry as a Federal Air Surgeon at the Federal Aviation Authority continues his mission dedicated to flight safety and new innovations in space travel (Ragin Williams 2020).

Russian Boris Borisovich Yegorov was the very first physician participating in the first multimanned spaceflight onboard Voskhod ("Sunrise") 1, on 12–13 October 1964, with cosmonauts Vladimir M. Komarov (later died in Soyuz 1 crash) and Konstantin P. Feoktistov (engineer). The results of medical research projects executed by the Voskhod 1 flight contributed to a better understanding of human adaptation processes and to the effective and successful preparation for long spaceflights performed in the 1990s for the MIR Russian space station. Doctor–cosmonaut Valery Vladimirovich Polyakov still holds the record for the longest single spaceflight in history. He joined the Institute of Biomedical Problems in Moscow and flew his first mission into space in 1988–1989 as the doctor–cosmonaut onboard Soyuz TM-6. During his 241-day flight aboard the MIR space station, he conducted numerous medical experiments. He flew again on Soyuz TM-18 to the MIR space station in 1994 setting the (still persisting) record of 438 days for the longest continuous stay in space, extensively studying the alteration of human sleep and circadian rhythm during spaceflight (Siddiqi 2023; Gundel et al. 1997).

The Hungarian Space Program aiming at sending the first astronaut into orbit in 1980 within the Intercosmos program (scientific organisation of the Warsaw Pact countries for space exploration) was a real success: Captain Bertalan Farkas, a fully trained military fighter pilot was selected in the Aeromedical Research Institute of the Hungarian Defence Forces, Kecskemét city in 1977–1978. From the 95 combat-ready fighter pilots the 7 best applicants were selected by Hungarian aeromedical experts. The team was led by Colonel Dr John Hideg, deputy chair Lieutenant Colonel Dr Péter Remes. From them the Russian expert team prioritised further; the astronaut training program was performed in the Gagarin Space Centre, and selected Bertalan Farkas and Béla Magyari. The latter became reserves for the flight onboard Soyuz 36. The mission was launched to the Salyut 6 space station on 26 May 1980 and he returned on Soyuz 35 on 3 June. Being the 7th nation and sending the 95th astronaut into orbit (51st from the Russian launching pad in the Baikonur Cosmodrome), Hungary has earned a prominent place in space exploration. With a wide range of biomedical experiments, including the "Pille" dosimeter and "Balaton" psychocalculator, Hungarian scientists have significantly contributed to the development of space sciences (Remes 2020: 281–340). In 2024 we are preparing for the training and launch of the second Hungarian astronaut in the HUNOR (Hungarian to Orbit) program, in close cooperation with ESA, NASA and Axiom Space Inc., a U.S. private company.

At the very beginning (practically until the Space Shuttles' era), the designated roles of astronauts onboard of spaceships and space stations were overlapping, providing multiple roles (and demanding huge responsibilities) for real military pilots as commanders, spaceship/shuttle pilots and mission specialists. Later on, the continuously increasing demand for more specialised experts has led to the subgroup of "mission specialised medical experts" with dedicated and tailored practical skills to perform research projects safely, but being aware of the dangers of spaceflight. Brave Flight Surgeons (colleagues from U.S. Navy Laurel Clark and David Brown) aboard the Columbia Space Shuttle on the STS-107 mission perished during the failed re-entry phase (disintegration) on 1 February 2003.

After the end of the Cold War other international space agencies like ESA (the European Space Agency) have started their developing involvement in cooperation, for example, at the European Astronaut Centre (EAC Cologne). ESA's Space Medicine Team comprises medical doctors, biomedical engineers, exercise physiologists, psychologists, IT specialists, education coordinators, administrators and project managers. ESA is also selecting from member countries its own astronaut classes, providing their full training and intercultural team building and contributing to the staffing of the ISS crew.

Emphasis is on the special knowledge and skills of each space crewmember: focusing on continuous medical support of the ISS, medical experts possessing special medical knowledge and competencies, performing active survival and ground-based aeromedical trainings. They can actively participate in future space missions as well, and can provide permanent medical support even onboard space stations and spacecraft travelling to the Moon or other satellites (possibly Titan orbiting around Saturn) and planets (Mars). It is the responsibility of the Medical Officer(s) to provide medical surveillance and possible intervention in case of medical emergencies and maintain spaceflight safety throughout the mission. The stake is high: medical human factors influencing overall crew performance are crucial for safe deployment and return.

Physiological hazards associated with space travel

Space as a harsh and hostile environment can pose unique sudden or sustained hazards to humans: considering the long process of biological evolution we are quite strictly adapted to the physical parameters of the atmosphere (overall pressure and partial pressure of oxygen) and gravitational force, building up and stabilising the internal environment for human tissues ("milieu intérieur" as defined by French physiologist Claude Bernard). We are not adapted to weightlessness, high intensity of cosmic radiation (provoking high rate of genetic mutations) and their threatening consequences on human organs – loss of muscle mass (atrophy), loss of calcium from bones, radiation-induced processes (like cataracts and long-term carcinogenesis). Depending on the time of space travel the psychological adverse effects of confinement might evolve as well, leading to instability in the small team of astronauts. The main objectives of space life sciences is to extend knowledge in human physiology, to maintain astronauts' health in order to withstand hostile physical and chemical parameters and to establish new medical technologies for adaptation. In the post-flight period, the support and improvement of medical recovery in a complex rehabilitation program is also essential (Clément 2011: 1–12, 36).

ACUTE EXPOSURE TO THE VACUUM OF SPACE

A person in space without any protective garment (spacesuit) or shielded and hermetised compartment (spaceship or space station living module) can be exposed to fatal physical stressors of vacuum: loss of ambient pressure and temperature drop can rapidly demolish internal environmental stability at tissue level. Depicting the "spacewalk outside in space" without life equipment assembly (spacesuit and helmet) like Bowman floated in Stanley Kubrick's movie "2001: A Space Odyssey" is surely fiction (with artistic liberty) and would be lethal for any human being.

Upon sudden decompression in a vacuum, rapid onset of hypoxia and gas (mainly nitrogen) bubble forming processes can commence immediately. Due to the lung distensive barotrauma (explosive expansion of trapped air in the respiratory tract) lung tissue rupture is imminent. Above the Armstrong line (19,200 metre altitude) as overall ambient pressure drops below 47 mmHg (less than the partial pressure of H_2O in body fluid compartments at 37 °C body temperature) the body fluids can boil: water vapour can also form bubbles in tissue compartments, giving way to ebullism (altitude subcutaneous emphysema, i.e. bubbles under the skin surface, with swelling and bruising) (Cooper–Hanson 2022). At worst, it can cause gaseous embolism, and gas bubbles in the bloodstream with blockage (like thrombi). Real hypobaric decompression sickness (starting above 18,000 feet altitude and unavoidable at decompression to vacuum) can provoke nitrogen bubble formation in all tissues (especially those that are considered "slow" from a circulatory aspect, like fat and bone marrow), explosively expanding by the entry of all other diffusion capable molecules following their diffusion gradients (Foster–Butler 2009: 678–690).

The most threatening and limiting factor is the full lack of oxygen, i.e. hypoxia. In vacuum, the normally large diffusion gradient from alveoli to pulmonary capillaries is reversed, and oxygen is sucked *out* of the bloodstream when the overdistended lungs are exposed to vacuum. Deoxygenated blood circulation (even without a real stop of perfusion caused by bubble blockage) can effectively stop normal brain functions in the imminent process of clinical death, commencing an unconscious state within 6 seconds (Kanas–Manzey 2008: 15–30).

Temperature drop alone is fatal in a slightly slower manner because heat transfer cannot occur as rapidly by thermal radiation separately: conduction and convection cannot physically work without matter, so heat transfer is limited in space. Due to the temperature of the "cosmic microwave background" (leftover from the Big Bang), the real temperature can drop to 2.7 Kelvin (–455 °F, –270.3 °C), and pending on the direct radiant heat from the Sun, the process of fatal freezing (if it could occur separately) would take a few minutes more (Lea 2022).

Long-term effects of space travel

After reaching weightlessness within half an hour after launch (stabilising the LEO – Low Earth Orbit – just around 400 km altitude high) both immediate and gradual, but long-lasting physiological changes can commence attributed to microgravity. The apparent lack of gravity (weightlessness) can provoke pathological consequences interfering with the normal responses and reflexes of the different systems of the human body. The loss of responsiveness especially in the cardiovascular, nervous and musculoskeletal systems can lead to deconditioning (loss of physical condition and mental alertness), but affected gastrointestinal, immune systems can also reduce working capability (loss of appetite, dehydration, anaemia).

The normal hydrostatic gradient at 1 G from head to toe linearly increases in standing position, but in microgravity, a dramatic redistribution of fluids from the legs to the upper body (torso and head) can commence within only a few moments of weightlessness, which is completed within days. Due to the cephalad shift, fluid volume in the legs decreases by 10%, accompanied by a 17% reduction in plasma volume due to the initially increased filtration through the kidneys. This fluid redistribution phenomenon is called "puffy head and birdy legs" and refers to significant facial swelling and significantly (by 10–30%) decreased leg circumference. Astronauts subjectively often complain of buzzing headache, nasal congestion and anosmia (loss of smell), diminished taste (and appetite) and eye abnormalities (blurred vision, diminished visual acuity) after extended stays in space, which are likely symptoms of SANS (space associated neuro-ocular syndrome) with increased intracranial pressure (Setlow 2003: 1013–1016).

The gradual decrease in erythropoietin secretion can commence, leading to a 10% decrease in total blood volume and decreased red blood cell quantity ("space anaemia"). Lower cardiac output and decreased stroke volume can commence due to lower demands on the cardiovascular system to counteract gravity. Upon return to Earth's gravity, due to a significant orthostatic intolerance, 25% of astronauts suffer a collaptiform episode (being unable to stand for 10 minutes without experiencing heart palpitations or fainting) (Williams et al. 2009: 1317–1323).

The functional inactivity of "antigravitational muscles" results in muscle atrophy, up to 50% muscle mass loss and a decrease in muscle strength. The muscular atrophy seen in astronauts is very similar to deconditioned bedrest patients, and upon return to Earth, some astronauts experience difficulty simply maintaining an upright posture with muscle soreness and tightness. Major postflight impairments require a proper rehabilitation programme after return to 1 G gravity on Earth: full recovery of muscle mass and strength can exceed 2 months (Payne et al. 2007: 583–591; Springel 2013).

Loss of physical stimuli from gravity in space on load-bearing bones in the lower torso and extremities can lead to demineralisation of the skeleton and decreased bone density, osteoporosis or osteopenia. Bone demineralisation is really an insidious and dangerously invisible threat: gradual loss of bone density (1–2% per month) accompanied by a 60%–70% increase in calcium loss by urine and stool, increasing the risk for bone fracture and kidney stones as well. Reduced parathyroid hormone and vitamin D production can also increase imbalance in bone structure maintenance processes (osteoclast decomposing versus osteoblast restorative building activity). After re-entry, the almost complete restoration of bone density can be 2–3 times longer than the space mission itself with an elevated risk for fractures (Williams et al. 2009: 1317–1323; Springel 2013).

The sensorial network (visual, vestibular and sensorimotor proprioceptive systems) can provide spatial orientation on Earth that contributes to a normal sense of balance and can maintain upright postural tone and harmonised motor coordination. Even during a flight on the Kepler path onboard aircraft spatial disorientation (loss of situational awareness) can commence just in seconds in simulated short-term weightlessness. The majority of astronauts (in the Apollo program about one-third of the space crew, from the Russian side e.g. Valentina Tereshkova during a solo flight onboard Vostok 6) suffered from nausea and physical discomfort. A full spectrum of space motion sickness or incapacitating disorientation can commence for the first few days in space, and these symptoms usually stop or weaken by the fourth or fifth day. During the flight of Apollo 8 in 1968 (the first human space mission to leave Earth and orbit the Moon) commander Frank Borman had nausea and vomiting as a first manifestation of space adaptation syndrome (Fong 2019). After returning to Earth, the same process as "debarkation" can confuse the sensory organs for a while, causing a "wobbling" phenomenon as a transient imbalance period (quite similar to the recovery phase after long-term bedrest) (Springel 2013; Mulavara et al. 2018).

Normal sleep cycles might be affected as well: orbiting within 90 minutes around Earth (resulting in 16 sunrise and sunset daily) the dream phases of astronauts are distorted, and circadian dysrhythmia can commence due to the altered light-dark cycle (Miller [s. a.]). High-energy cosmic radiation can cause bright flashes in the visual fields, disturbing deep sleep periods of space crew (Narici et al. 2004: 1352–1357).

Another main source of long-term harmful effects is cosmic radiation. The Earth's atmosphere can dampen space radiation: ultraviolet (UV) radiation from the Sun is largely absorbed by the Earth's atmosphere (ozone layer between 12–42 km with maximum concentration just around 30 km altitude level). The ionosphere can reduce the primary cosmic radiation into less harmful secondary ionising radiation with considerably less energy and diminishing the ionising effect, falling to 1/70 portion compared to the dose measured at 21 km altitude level (Gradwell 2006: 7).

Leaving the atmosphere (even the van Allen magnetic protective belt) a human would suffer sunburn from UV radiation within seconds and can receive a high dose of primary cosmic radiation. Cosmic electromagnetic radiation (depending on the wavelength) can be reduced with a specially designed fabric layer in a spacesuit (EMU – Extravehicular Mobility Unit worn for 6–8 hours outside of the space station) but high-energy nuclei particles in solar and galactic radiation can penetrate shielding and astronauts' bodies (Setlow 2003: 1013–1016; Springel 2013; Barratt et al. 2019: 520).

Radiation (by means of stochastic/probability based and deterministic/dose dependent effects) can cause radiation sickness, genetic abnormalities (mutations in DNA), can damage brain cells (leading to neurodegenerative diseases), increase the risk of early onset cataracts and can provoke carcinogenesis, can boost atherosclerosis ("ageing of arteries"). Radiation induced immune system suppression and microbiome distortion in the bowels can provoke infections, radiation sickness can occur with a higher cumulative incidence above a certain threshold intensity. Chromosome break yields were doubled in the Apollo space crew compared to

Gemini astronauts, giving way to harmful mutations. For Apollo 14, the highest skin dose was 14 mSv, and for MIR crewmembers 30 mSv/event during a magnetic storm in 1989. Based on a full review of cancer incidence and mortality in the U.S. space crew population, the increased case number for melanoma and reduction in colon cancer rate was explained by UV radiation related to lifestyle (not to space specific exposure) and enhanced screening methods (Williams et al. 2009: 1317–1323; Barratt et al. 2019; Reynolds et al. 2021).

Even long-term, low-energy levels of radiation can provoke DNA damage possibly leading to carcinogenesis or fetal malformations without real threshold. Based on the Radiation Assessment Detector measurements of NASA's Curiosity rover during its transit to Mars, the astronauts would be exposed to a minimum of 660 ± 120 millisieverts during a full mission. NASA's career exposure limit set for astronauts is around 1,000 millisieverts (as analogues to nuclear industrial plant workers, maximising the dose in 100 mSv for any 5 consecutive working years, aiming to keep ALARA as low as reasonably achievable). Powerful ionising radiation particles can target living tissues within the body throughout the mission, so presently the unpredictable radiation burden might be even showstopper from an ethical aspect (Townsend 2005: 44–50; Kerr 2013: 1031; Chylack et al. 2009: 10–20; Zeitlin et al. 2013: 1080–1084; Springel 2013; Onorato et al. 2020; Nicogossian et al. 2016: 25, 206–207).

Challenges for future deep space missions and colonisation

> "Who are we? We find that we live on an insignificant planet of a humdrum star lost in a galaxy tucked away in some forgotten corner of a universe in which there are far more galaxies than people."
>
> Carl Sagan

In 1950 Ley envisioned that "life will be cramped and complicated for space dwellers [...] it will be a self-contained community in which all man's needs, from air-conditioning to artificial gravity, have been supplied" (Ley–Bonestell 1950).

Even now with long-term rounds of space crew on ISS, space adaptation involves some very complex changes in the human body, both short-term and sustained ones. These changes can cause health problems both in space and on return to Earth or in settlements on the surface of other planets/moons (Easter 2019).

Due to the new challenges of the return to the Moon with Artemis and the prospect of interplanetary missions with colonisation purposes require flexibility. Ground-based solutions should be adapted and altered to endure the space environment. Presently the most frequently observed clinical signs and symptoms related to space adaptation syndrome are back pain, headache, constipation, insomnia, nasal congestion, motion sickness and visual impairment (Antonsen et al. 2017).

Sustainable Lunar–Martian orbital flight ("staging capability" on orbiting the Lunar–Martian Gateway) and surface exploration (with Base Camp Conception, Surface Habitat and Habitable Mobility Platform) require adaptation to weightlessness and then (after a long deconditioning process) readaptation to a certain level of gravity of the Moon or Mars.

Polyakov, the Russian cosmonaut spent 438 days in space (but more astronauts spent more days in space on consecutive missions altogether: Russian Gennady Padalka more than 1,000 days, Peggy Whitson from NASA more than 665 days). For a longer deep space mission even the possible deterioration of cognitive performance should be calculated due to the high intensity of cosmic radiation. Microgravity itself through different changes in cerebral perfusion due to the cephalad shift can contribute to the deterioration of certain cognitive functions based on comparison with ground-based head-down tilt bedrest (Cherry et al. 2012; Barkaszi et al. 2022).

The other key point is the selection process of new astronaut candidates with proper somatic and mental features to endure the possible harsh environmental conditions during routine workdays and in emergency situations as well. From the very beginning, there was a great emphasis on "selecting in" proper physical abilities (muscle strength and stamina, aerobic exercise capacity) and psychological mental capabilities (cognitive functions like attention, multitasking problem solving and decision-making capacity). At the same time, it was important to "select out" unfavourable parameters (low physical and mental working capacity, dangerous psychological traits and attitudes like psychopathology), and improve the cohesion of the space crew as a team: proper communication techniques, complacency, cooperation (smoothing possible intercultural differences) can lead to enhanced overall performance during a mission by means of CRM (Crew Resource Management). Even more difficult is to augment the prognostic value of selection standards: the longer the space mission, the more unforeseeable changes can occur in somatic and mental health state as a complicated interference between individual genetic background and actual environmental challenges, leading to real clinical symptoms and entities. The same is applied to "space tourists" with less detailed mission oriented tasks, but with possibly enhanced risk for incapacitation and diminished working ability (Seedhouse 2008).

The most frequently occurring medical conditions can be categorised as common (already experienced) problems: Space Motion Sickness, headache, nasal–sinus congestion (both related to cephalad fluid shift), constipation (related to dehydration), back pain (related to the increased water content of disc and elongation of the spinal column), upper respiratory tract infection (related to dysbiosis and thermal discomfort), minor abrasion and musculoskeletal traumas (related to inadvertent movements during EVA – extravehicular activities), corneal irritation and insomnia (related to circadian dysrhythmia). Less common but already observed and anticipated conditions are renal stone formation, acute urinary retention, cardiac dysrhythmia, including benign extrasystoles, bigeminy, and a more serious complex form of Supraventricular Tachycardia (SVT) and non-sustained ventricular tachycardia (asymptomatic salve), inflammations like gastroenteritis, prostatitis, serous otitis media (tympanic membrane and middle ear inflammation), contact dermatitis (skin allergic inflammation). Especially after EVA decompression accidents DCS decompression sickness (joint pain), near drowning (after spacesuit failure) can commence, and aspiration of a foreign body might be a threat as well. One case of venous thrombosis was detected by ultrasound imaging incidentally in the left internal jugular vein (and no symptoms accompanied). Presently, there are no real medical training methods and toolkits addressing the treatment of cardiogenic shock, malignancies, acute glaucoma, compartment syndrome, serious head injury, hypovolaemic shock, lumbar spine fracture or major joint (shoulder–elbow) dislocation (HODKINSON et al. 2017: i143–i153; PIETRZYK et al. 2007: A9–13; AUÑÓN-CHANCELLOR et al. 2020: 89–90).

In the early phase of space exploration, the extended morphological and functional medical examinations provided the proper assessment of physical and mental health state and the prognostic evaluation of working ability. Diagnostic procedures included vitamax aerobic exercise capacity (physical performance on treadmill or bicycle up to age-adjusted maximum pulse rate) and special ground-based simulated exposition to aeromedical stressors like hypoxia (in a barochamber), simulated weightlessness (on tilting table head-down position up to 15–30°) or acceleration and overloads (in a centrifuge). Pressure breathing training is also critical in preparation for extreme hypobaric-hypoxic settings. These physiological exhaustive examinations could provide information about the endurance, stamina, responsiveness and functional reserve of the cardiovascular and musculoskeletal system, while psychometric and cognitive tests could give cues about the mental performance of astronauts. Regarding the huge development in clinical diagnostic tests including new visualisation technologies (Magnetic Resonance, Computer Tomography and Ultrasound imageries), now we are able to describe the anatomy and functions of even smaller organ tissue details, observing their possible adverse alteration during repetitive simulated or real space travel.

Practical training sessions should include flight on the Kepler trajectory simulating weightlessness for 30–40 seconds (!), immersion training in pool (imitating EVA protocols in spacesuit), hypoxic training in barochamber, thermo-barochamber (heat exposition), isolation exercises to tolerate confinement, centrifuge runs, vibration platform training, vestibular training, parachute (and land-sea survival) training, general physical training, sports, education of first aid (first-line management of injuries–diseases), team building processes.

In the future we should forecast the possible deterioration during space travel by assessing genetic susceptibility for clinical problems (like space-induced accelerated atherosclerosis, perhaps carcinogenesis and cataract tendency), acknowledging that certain other problems (caries, impacted wisdom tooth, appendicitis, traumas) can commence just "out of the blue". Certain medical capabilities (including medication, operational toolkits) should be available onboard spaceships heading to deep space or other planets (e.g. a rare case of jugular vein thrombosis occurred and ISS medical decision required concerted efforts to overcome the numerous logistic and operational challenges). Heading to Mars, active astronaut surveillance by Medical Officers and experimental models in Earth-based space analogue settings will be essential to prevent or properly manage such unusual clinical entities (Auñón-Chancellor et al. 2020: 89–90). (And due to the limitation in technologies and knowledge onboard perhaps we should be aware of the possibility of a fatal outcome, loss of astronaut comrades.)

The final goal of space medicine is to keep astronauts healthy in space: maintaining their working ability during LEO or deep space missions, minimising the harmful effects of microgravity on different organ systems and reducing the risk of radiation-induced atherosclerotic and carcinogenetic processes. Proper medical toolkits for operational procedures, extended use of telemetry and AI might be helpful in responding adequately to threatening medical conditions.

The future of space exploration will be linked to the development and application of artificial intelligence (AI) technologies. The ever-increasing distances in space missions (and the time demand for radio communication) can cause significant logistical-technical problems and challenges in command and control systems. In medical issues Earth-based monitoring will no longer be real-time, requiring telemedicine capabilities, and perhaps a medical expert "Avatar" artificial intelligence will be present to react immediately to urgencies (not waiting for response from Earth-based experts during deep space missions). Robotic (robot-assisted) surgery might help to perform minimally invasive surgery with proper flexibility. Long-duration missions necessitate further technological breakthroughs in teleoperations and autonomous technology (Mayo Clinic [s. a.]).

On the road to Mars, we anticipate even more complicated and dangerous scenarios, with new physiological challenges for the human body and mind, requiring common efforts and forcing peaceful cooperation in space. There will be a huge emphasis on the competencies of spacewalking space crew as EVAs are being conducted in Earth orbit, on the Moon's surface and in deep space and dedicated to vital assembly and critical maintenance missions on the soil of Mars. Possible traumatic injuries due to outer construction works and compromised cardiovascular and postural stability and working inability caused by deconditioning and SANS (or VIIP syndrome, referring to visual impairment and intracranial pressure increase driven by cephalad fluid shift) could threaten the success of deep space missions (Nicogossian et al. 2016: 233).

Effective countermeasures are currently under investigation to explore how we could mitigate accompanying risks: medical device intervention (load-bearing regular exercise and low-level vibration provoked strain), nutritional supplementation (micronutrients and vitamins), artificial gravity (centrifugal rotating arms?), radiation shielding and possible antioxidant countermeasure and enhanced pre-flight risk assessment are the most important opportunities to combat the deconditioning process (Springel 2013; Schwirtz 2009).

1. Lower body negative pressure (LBNP) is a well-established, non-invasive device (Russian name is Chibis) that can maintain the negative pressure (20 mmHg as optimal level) by hermetised covering (encapsulation) of the lower torso and extremities and redistributing blood away from the cephalad region (upper torso and head), decreasing ICP (intracranial pressure) as the main factor in SANS induced headache. Mobile, flexible LBNP gravity suits might be an efficient and effective countermeasure for astronauts during future missions generating "ground reaction forces": blood is forced down to the wearer's legs, increasing the heart rate and cardiac output (Ashari–Hargens 2020).

2. Venoconstrictive thigh cuffs can force back blood and can elevate venous return and restore effective blood volume: it might be useful during the early phase in the gravity field, or generated artificial gravity can be maintained via centrifugation with proper arm length. Centaur is a corset-like garment worn

like a pair of shorts. It is worn during descent to keep blood from pooling in the legs on the return to gravity and prevent fainting (Robin et al. 2020).

3. Penguin-3 suits or bungee cords are jumpsuits embedded with sewn-in elastic straps which provide resistance loads for the wearer in response to the arm and body movement (making periodic pedalling leg movements for 5–10 minutes, 6–8 times per day). Providing exercise for the musculoskeletal system can reduce the inactivity-induced deleterious effects of microgravity. With a combination of aerobic and resistive (resistance) exercise lean muscle mass can be preserved. Further investigation of drug therapy (as skeletal muscle growth factors, human growth hormone, thyroid hormone, insulin-like growth factor) is necessary to introduce as preventive measures for proper maintenance of muscle mass and strength (Nicogossian et al. 2016: 353).

4. Pressurised goggles can locally modulate cerebro-ocular hemodynamics as a countermeasure for SANS. It might be useful in the prevention of retinal disc oedema by diminishing the pressure difference between normally higher intraocular pressure (IOP) and lower optic nerve sheath (myelin) pressure (Ong et al. 2023).

5. Certain genetic backgrounds (critical alleles) in combination with reduced vitamin B2, B6 and B9 status can increase the risk of vision deterioration. Vitamin B supplementation as proper antioxidants (riboflavin, pyridoxine, methylcobalamin and folate) can reduce cytotoxic oedema – local oxidative stress at the optic nerve head from microgravity-induced venous stasis (Smith–Zwart 2018: 481–488).

6. Beyond proper technical radiation shielding some initiatives for pharmacological protection are under investigation: drugs can play the role of radioprotectors (which decrease or prevent tissue damage before exposure), radiomodulators (which increase baseline resistance to radiation exposure) and radiomitigators (which limit or prevent tissue damage after exposure). Real medications like statins widely used on Earth (against high blood lipids), nonsteroidal anti-inflammatory drugs and antihypertensive drugs (ACEIs and ARBs, calcium channel blockers, β adrenergic receptor blockers) are also under investigation to prevent accelerated atherosclerosis (possibly induced by cosmic

radiation). Special combination of antioxidants and other micronutrients (N-acetyl cysteine, pentoxifylline, ascorbic acid (vitamin C), α-lipoic acid (a type of vitamin B), coenzyme Q10, vitamin E succinate, sodium ascorbate and L-selenomethionine (SeM), perhaps Bowman-Birk Inhibitor Complex (BBIC, a protease inhibitor derived from soybeans) can diminish the radiation induced cardiovascular alterations as well (Meerman et al. 2021; McLaughlin et al. 2017: 665–676).

7. Aerobic exercise of 2.5 hrs/day is time consuming, but low intensity vibration strain and pharmacological countermeasures might have added value against osteoporosis: reduced bone formation, increased bone resorption, inhibition of mineralisation might be influenced by properly administered new bisphosphonates (blocking the breakdown of bones) and PTH (parathyroid hormone slowing down the excretion of calcium). Presently long-term measurements show that only 50% of the bone structure (density) would recover by 9 months post-flight. Possible use of "nutraceuticals" (micronutrients, antioxidants, vitamins as dietary supplements) or gene-derived therapies might be promising options in the future. Unfortunately, the exercise itself can further elevate core body temperature set for a higher level of weightlessness, as a further component of physical discomfort (Clément 2011: 219; Nicogossian et al. 2016: 353–356; Stahn et al. 2017).

CONCLUSIONS

Medical research aiming at sustainable human life in space should address not only spaceflight itself (with permanent microgravity resulting in overall atrophy, deconditioning, higher flux of cosmic radiation resulting in possibly accelerated atherosclerosis and carcinogenesis), but the "colonisation" phase as well, as utilising new settlements on the surface of the Moon, and on the surface of other planets and their moons. From an occupational aspect, possible professions like mining, construction or industrial processes require at least partial readaptation to gravitational force (although it might be reduced compared to Earth, disturbed by orthostatic intolerance and post-flight hypotension), breathable ambient air in self-supporting containment equipped with environmental control system, fully pressurised mobile compartments in order to provide "short sleeve" working environment. But it also means that stepping out from the protected zone we face the harsh environment settings again with extreme thermal conditions, winds, poisoning or polluting components (like regolith dust, as loose, unconsolidated superficial deposits in the soil of Mars and Moon, and perchlorates in Martian soil). Spacesuit-like personal protection assembly with higher mobility is a must to provide even limited working capability for a while. Adapting the Fine-Kinney occupational risk matrix as mathematical risk analysis to the long-term surface missions, not only the microgravity and radiation but "traditional" Earth-based occupational risk factors, like noise, vibration, dust exposure to the airways during mining procedures and industrial accidents can occur as well (Yilmaz–Ozcan 2019).

The next generation of pioneers should rely on their creativity very much to utilise all elements of their limited cargo with a small chance of an emergency return to Earth. A NASA report emphasises that "advanced frontier technologies (robotics, machine intelligence, nanotechnology, synthetic biology, 3D printing/additive manufacturing, and autonomy) combined with the vast natural resources should enable to greatly increase reliability and safety pre- and post-human arrival ISRU (In Situ Resource Utilization) and reduce cost for human colonization of Mars" (Moses–Bushnell 2016).

In 1928 Tsiolkovsky in his work *The Will of the Universe. The Unknown Intelligence* was convinced that humans would eventually colonise the Galaxy. His prophetic thought preceded the Space Age by decades, and some of his ideas have come true. Now the voyage of exploration continues with new demands. New ways of thinking and technical approaches – "curiosity and readiness for adventure" – are required from that idea, through design and test procedures to the validation and execution phases to overcome hurdles (Fong 2019: 205–207).

"Space: the final frontier. These are the voyages of the starship *Enterprise*. Its continuing mission: to explore strange new worlds; to seek out new life and new civilizations; to boldly go where no man has gone before!" (Star Trek) Science fiction is turning into reality: pioneers of mankind are really pushing the limits to the endless final frontier. As it was cited by NASA administrator Bill Nelson in his eulogy of Frank Borman astronaut, commander of the first flight to the Moon on Apollo 8 who passed away recently at the age of 95: "Exploration is really the essence of the human spirit" (Nelson 2023).

REFERENCES

Antonsen, E. (2019): *Human System Risk in Spaceflight.* Online: https://ntrs.nasa.gov/api/citations/20190032988/downloads/20190032988.pdf

Antonsen, E. – Bayuse, T. – Blue, R. – Daniels, V. – Hailey, M. – Hussey, S. – Kerstman, E. – Krihak, M. – Latorella, K. – Mindock, J. –Myers, J. – Mulcahy, R. – Reed, R. – Reyes, D. – Urbina, M. –Walton, M. (2017): *The Risk of Adverse Health Outcomes and Decrements in Performance Due to In-Flight Medical Conditions.* Houston: National Aeronautics and Space Administration.

Ashari, N. – Hargens, A. R. (2020): The Mobile Lower Body Negative Pressure Gravity Suit for Long-Duration Spaceflight. *Frontiers in Physiology,* 11. Online: https://doi.org/10.3389/fphys.2020.00977

Auñón-Chancellor, S. M. – Pattarini, J. M. – Moll, S. – Sargsyan, A. (2020): Venous Thrombosis during Spaceflight. *The New England Journal of Medicine,* 382(1), 89–90. Online: https://doi.org/10.1056/NEJMc1905875

Barkaszi, I. – Ehmann, B. – Tölgyesi, B. – Balázs, L. – Altbäcker, A. (2022): Are Head-Down Tilt Bedrest Studies Capturing the True Nature of Spaceflight-Induced Cognitive Changes? A Review. *Frontiers in Physiology,* 13. Online: https://doi.org/10.3389/fphys.2022.1008508

Barratt, M. R. – Baker, E. S. – Pool, S. L. eds. (2021): *Principles of Clinical Medicine for Space Flight.* New York: Springer. Online: https://doi.org/10.1007/978-1-4939-9889-0

Butler, C. (1999): *Edited Oral History Transcript: Charles A. Berry.* Online: https://historycollection.jsc.nasa.gov

Campbell, M. R. – Mohler, S. R. – Harsch, V. A. – Baisden, D. (2007): Hubertus Strughold, the Father of Space Medicine. *Aviation, Space, and Environmental Medicine,* 78(7), 716–719.

Cherry, J. D. – Liu, B. – Frost, J. L. – Lemere, C. A. – Williams, J. P. – Olschowka, J. A. – O'Banion, K. M. (2012): Galactic Cosmic Radiation Leads to Cognitive Impairment and Increased Aβ Plaque Accumulation in a Mouse Model of Alzheimer's Disease. *PLoS One,* 7(12). Online: https://doi.org/10.1371/journal.pone.0053275

Chylack, L. T. – Peterson, L. E. – Feiveson, A. H. – Wear, M. L. – Manuel, F. K. – Tung, W. H. – Hardy, D. S. – Marak, L. J. – Cucinotta, F. A. (2009): NASA Study of Cataract in Astronauts (NASCA). Report 1: Cross-Sectional Study of the Relationship of Exposure to Space Radiation and Risk of Lens Opacity. *Radiation Research,* 172(1), 10–20. Online: www.jstor.org/stable/40305968

Clément, G. (2011): *Fundamentals of Space Medicine.* New York: Springer. Online: https://doi.org/10.1007/978-1-4419-9905-4

Cooper, J. – Hanson, K. (2022): *Decompression Sickness.* Online: www.ncbi.nlm.nih.gov/books/NBK537264/

Easter, B. (2019): *Medical Risks and Capabilities for Human Exploration Spaceflight.* Online: https://ntrs.nasa.gov/api/citations/20190025249/downloads/20190025249.pdf

Ehmann, B. – Altbäcker, A. – Balázs, L. (2018): Emotionality in Isolated, Confined and Extreme (ICE) Environments: Content Analysis of Diaries of Antarctic Winteroverers. *Journal of Environmental Psychology,* 60(3), 112–115. Online: https://doi.org/10.1016/j.jenvp.2018.09.003

Fong, K. (2019): Moon Landing: Space Medicine and the Legacy of Project Apollo. *The Lancet,* 394(10194), 205–207. Online: https://doi.org/10.1016/S0140-6736(19)31568-5

Foster, P. – Butler, B. (2009): Decompression to Altitude: Assumptions, Experimental Evidence, and Future Directions. *Journal of Applied Physiology,* 106(2), 678–690. Online: https://doi.org/10.1152/japplphysiol.91099.2008

George, A. (2018): The Sad, Sad Story of Laika, the Space Dog, and Her One-Way Trip into Orbit. *Smithsonian Magazine,* 11 April 2018. Online: www.smithsonianmag.com/smithsonian-institution/sad-story-laika-space-dog-and-her-one-way-trip-orbit-1-180968728/

Gradwell, D. P. (2006): The Earth's Atmosphere. In Rainford, David J. – Gradwell, David P. (eds.): *Ernsting's Aviation Medicine.* London: Hodder Arnold. 3–12. Online: https://doi.org/10.1201/b13238

Gundel, A. – Polyakov, V. – Zulley, J. (1997): The Alteration of Human Sleep and Circadian Rhythms during Spaceflight. *Journal of Sleep Research,* 6(1), 1–8. Online: https://doi.org/10.1046/j.1365-2869.1997.00028.x

Hodkinson, P. D. – Anderton, R. A. – Posselt, B. – Fong, K. (2017): An Overview of Space Medicine. *British Journal of Anaesthesia,* 119(Supplement 1), i143–i153. Online: https://doi.org/10.1093/bja/aex336

Kanas, N. – Manzey, D. (2008): Basic Issues of Human Adaptation to Space Flight. In *Space Psychology and Psychiatry.* Dordrecht: Springer. 15–48. Online: https://doi.org/10.1007/978-1-4020-6770-9_2

Kerr, R. A. (2013): Planetary Exploration. Radiation Will Make Astronauts' Trip to Mars even Riskier. *Science,* 340(6136), 1031. Online: https://doi.org/10.1126/science.340.6136.1031

Lea, R. (2022): How Cold Is Space? Physics behind the Temperature of the Universe. *Space.com,* 7 July 2022. Online: www.space.com/how-cold-is-space

Ley, W. – Bonestell, C. (1950): *The Conquest of Space. New York:* Viking Press.

Mader, T. H. – Gibson, R. – Pass, A. F. – Kramer, L. A. – Lee, A. G. – Fogarty, J. – Tarver, W. J. – Dervay, J. P. – Hamilton, D. R. – Sargsyan, A. – Phillips, J. L. – Tran, D. – Lipsky, W. – Choi, J. – Stern, C. – Kuyumjian, R. – Polk, J. D. (2011): Optic Disc Edema, Globe Flattening, Choroidal Folds, and Hyperopic Shifts Observed in Astronauts after Long-Duration Space Flight. *Ophthalmology,* 118(10), 2058–2069. Online: https://doi.org/10.1016/j.ophtha.2011.06.021

Mayo Clinic [s. a.]: *Robotic surgery.* Online: www.mayoclinic.org/tests-procedures/robotic-surgery/about/pac-20394974

McKay, C. P. – Stoker, C. R. (1989): The Early Environment and Its Evolution on Mars: Implications for Life. *Reviews of Geophysics,* 27(2), 189–214. Online: https://zenodo.org/records/1231452

McLaughlin, M. F. – Donoviel, D. B. – Jones, J. A. (2017): Novel Indications for Commonly Used Medications as Radiation Protectants in Spaceflight. *Aerospace Medicine and Human Performance,* 88(7), 665–676. Online: https://doi.org/10.3357/AMHP.4735.2017

Meerman, M. – Bracco Gartner, T. C. L. – Buikema, J. W. – Wu, S. M. – Siddiqi, S. – Bouten, C. V. C. – Grande-Allen, K. J. – Suyker, W. J. L. – Hjortnaes, J. (2021): Myocardial Disease and Long-Distance Space Travel: Solving the Radiation Problem. *Frontiers of Cardiovascular Medicine,* 8. Online: https://doi.org/10.3389/fcvm.2021.631985

Miller, K. [s. a.]: *Wide Awake in Outer Space.* Online: www.firstscience.com/SITE/ARTICLES/sleep.asp

Moses, R. W. – Bushnell, D. M. (2016): *Frontier In-Situ Resource Utilization for Enabling Sustained Human Presence on Mars.* Online: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20160005963.pdf

Mulavara, A. P. – Peters, B. T. – Miller, C. A. – Kofman, I. S. – Reschke, M. F. – Taylor, L. C. – Lawrence, E. L. – Wood, S. J. – Laurie, S. S. – Lee, S. M. C. – Buxton, R. E. – May-Phillips, T. R. – Stenger, M. B. – Ploutz-Snyder, L. L. – Ryder, J. W. – Feiveson, A. H. – Bloomberg, J. J. (2018): Physiological and Functional Alterations after Spaceflight and Bed Rest. *Medicine and Science in Sports and Exercise,* 50(9), 1961–1980. Online: https://doi.org/10.1249/MSS.0000000000001615

Narici, L. – Bidoli, V. – Casolino, M. – de Pascale, M. P. et al. (2004): The ALTEA/ALTEINO Projects: Studying Functional Effects of Microgravity and Cosmic Radiation. *Advances in Space Research,* 33(8), 1352–1357. Online: https://doi.org/10.1016/j.asr.2003.09.052

Nelson, W. (2023): *NASA Administrator Honors Life of Apollo Astronaut Frank Borman*. Online: www.nasa.gov/news-release/nasa-administrator-honors-life-of-apollo-astronaut-frank-borman/

Nicogossian, A. E. – Williams, R. S. – Huntoon, C. L. – Doarn, Charles R. – Polk, J. D. – Schneider, V. S. eds. (2016): *Space Physiology and Medicine. From Evidence to Practice.* New York: Springer. Online: https://doi.org/10.1007/978-1-4939-6652-3

Ong, J. – Tarver, W. – Brunstetter, T. – Mader, T. H. – Gibson, C. R. – Mason, S. S. – Lee, A. (2023): Spaceflight Associated Neuro-Ocular Syndrome: Proposed Pathogenesis, Terrestrial Analogues, and Emerging Countermeasures. *British Journal of Ophthalmology,* 107(7), 895–900. Online: https://doi.org/10.1136/bjo-2022-322892

Onorato, G. – Di Schiavi, E. – Di Cunto, F. (2020): Understanding the Effects of Deep Space Radiation on Nervous System: The Role of Genetically Tractable Experimental Models. Review article. *Frontiers in Physics,* 8. Online: https://doi.org/10.3389/fphy.2020.00362

Payne, M. – Williams, D. – Trudel, G. (2007): Space Flight Rehabilitation. *American Journal of Physical Medicine and Rehabilitation,* 86(7), 583–591. Online: https://doi.org/10.1097/PHM.0b013e31802b8d09

Pietrzyk, R. – Jones, J. – Sams, C. F. – Whitson, P. (2007): Renal Stone Formation among Astronauts. *Aviation, Space, and Environmental Medicine,* 78(Supplement 4), A9–13. Online: https://pubmed.ncbi.nlm.nih.gov/17511294/

Ragin Williams, C. (2020): Pioneering Flight Surgeon Dr. Charles Berry Dies at 96. *Roundup Reads,* 6 March 2020. Online: https://roundupreads.jsc.nasa.gov/roundup/1379

Remes, P. (2020): *Az első magyar űrrepülés története* [The History of the First Hungarian Spaceflight]. Published by the author.

Reynolds, R. – Little, M. P. – Day, S. – Charvat, J. – Blattnig, S. – Huff, J. – Patel, Z. S. (2021): Cancer Incidence and Mortality in the USA Astronaut Corps, 1959–2017. *Occupational and Environmental Medicine,* 78(12), 869–875. Online: https://doi.org/10.1136/oemed-2020-107143

Robin, A. – Auvinet, A. – Degryse, B. – Murphy, R. – Bareille, M.-P. – Beck, A. – Gharib, C. – Gauquelin-Koch, G. – Daviet, A. – Larcher, F. – Custaud, M.-A. – Navasiolava, N. (2020): DI-5- CUFFS: Venoconstrictive Thigh Cuffs Limit Body Fluid Changes but Not Orthostatic Intolerance Induced by a 5-Day Dry Immersion. *Frontiers in Physiology,* 11. Online: https://doi.org/10.3389/fphys.2020.00383

Sagan, C. [s. a.]. Online: www.brainyquote.com/quotes/carl_sagan_122799

Schwirtz, M. (2009): Staying Put on Earth, Taking a Step to Mars. *The New York Times,* 30 March 2009. Online: www.nytimes.com/2009/03/31/science/space/31mars.html

Seedhouse, E. (2008): Medical and Training Requirements for Suborbital Flight. In *Tourists in Space.* New York: Springer Praxis Books. 47–79. Online: https://doi.org/10.1007/978-0-387-74644-9_4

Setlow, R. (2003): The Hazards of Space Travel. *EMBO Reports,* 4(11): 1013–1016. Online: https://doi.org/10.1038/sj.embor.7400016

Siddiqi, A. A. (2023): Valery Vladimirovich Polyakov. *Encyclopedia Britannica,* 15 September 2023. Online: www.britannica.com/biography/Valery-Vladimirovich-Polyakov

Smith, S. M. – Zwart, S. R. (2018): Spaceflight-Related Ocular Changes. The Potential Role of Genetics, and the Potential of B Vitamins as a Countermeasure. *Current Opinion in Clinical Nutrition and Metabolic Care,* 21(6), 481–488. Online: https://doi.org/10.1097/MCO.0000000000000510

Springel, M. (2013): *The Human Body in Space: Distinguishing Fact from Fiction*. Online: https://sitn.hms.harvard.edu/flash/2013/space-human-body/

Stahn, A. – Werner, A. – Opatz, O. – Maggioni, M. – Steinach, M. – Weller von Ahlefeld, V. – Moore, A. – Crucian, B. – Smith, S. – Zwart, S. R. – Schlabs, T. – Mendt, S. – Trippel, T. – Koralewski, E. – Koch, J. – Choukèr, A. – Reitz, G. – Shang, P. – Röcker, L. – Kirsch, K. – Gunga, H.-C. (2017): Increased Core Body Temperature in Astronauts during Long-Duration Space Missions. *Scientific Reports,* 7. Online: https://doi.org/10.1038/s41598-017-15560-w

Townsend, L. W. (2005): Implications of the Space Radiation Environment for Human Exploration in Deep Space. *Radiation Protection Dosimetry,* 115(1–4), 44–50. Online: https://doi.org/10.1093/rpd/nci141

Williams, D. – Kuipers, A. – Mukai, C. – Thirsk, R. (2009): Acclimation during Space Flight: Effects on Human Physiology. *Canadian Medical Association Journal,* 180(13), 1317–1323. Online: https://doi.org/10.1503/cmaj.090628

Yilmaz, F. – Ozcan, M. S. (2019): A Risk Analysis and Ranking Application for Lifting Vehicles Used in Construction Sites with Integrated AHP and Fine-Kinney Approach. *Advances in Science and Technology Research Journal,* 13(3), 152–161. Online: https://doi.org/10.12913/22998624/111779

Zeitlin, C. – Hassler, D. – Cucinotta, F. A. – Ehresmann, B. – Wimmer-Schweingruber, R. F. – Brinza, D. E. – Kang, S. – Weigle, G. – Böttcher, S. – Böhm, E. – Burmeister, S. – Guo, J. – Köhler, J. – Martin, C. – Posner, A. – Rafkin, S. – Reitz, G. (2013): Measurements of Energetic Particle Radiation in Transit to Mars on the Mars Science Laboratory. *Science,* 340(6136), 1080–1084. Online: https://doi.org/10.1126/science.1235989

Bea Ehmann[1] – László Balázs[2]

Isolated Groups on Earth and in the Sky: Outlines of Space Psychology

SPATIAL AND TEMPORAL ANCHORAGES OF SPACE PSYCHOLOGY

Mankind is only beginning the long process of conquering Deep Space. The full career arc of space conquest is still only in our imagination.

In this endless scope, four phases are usually distinguished. The first is the era of near-Earth or neighbourhood missions: the world of orbiting spacecraft and conquering the Moon. The second phase is the landing and settlement on Mars – the return journey is known to take about 500 days. The third stage would be to conquer the Solar System. The fourth stage, the age of interstellar travel, is known only from science fiction literature and films where we have seen and heard a lot about frozen, fertilised ovum colonies, astronauts travelling in suspended animation, or gigantic generational spaceships (Kanas 2011: 576–581).

Whatever era of space travel we are talking about, all of them feature small groups of people who live enclosed in capsules in an environment unsuitable for human survival. Crews who live in such capsules for a relatively long time are called Isolated, Confined and Extreme groups – in short, ICE groups. The main focus of space psychology is on how ICE groups in outer space feel, think

[1] HUN-REN Research Centre for Natural Sciences, Institute of Cognitive Neuroscience and Psychology; ORCID: https://orcid.org/0000-0002-2634-3410; e-mail: ehmann.bea@ttk.hu

[2] HUN-REN Research Centre for Natural Sciences, Institute of Cognitive Neuroscience and Psychology; ORCID: https://orcid.org/0000-0002-6701-973X; e-mail: balazs.laszlo@ttk.hu

DOI: https://doi.org/10.36250/01209_03

and do; how they can maintain their physical and mental integrity; how they get along with each other; how they relate to the mission centre on Earth, and how they can perform and succeed in their mission. Terrestrial capsule environments – and ICE groups within them – have existed throughout history and continue to exist today and in the future (Suedfeld–Steel 2000: 228).

For many decades, we have had comprehensive knowledge of the psychodynamics of ICE groups winterovering in Antarctica and the Arctic. These accounts contain almost all the elements that are still studied by space psychologists today. Therefore, space psychology has incorporated polar psychology into the model, and that is why we can say that its roots go back at least a century or more. At present, studies are conducted in two main areas: in space, analogue sites and simulations, commonly referred to as ground-based analogues.

Ground-based habitats and simulations

In the past decades, many simulation habitats have been built and operated to study the human factors expected on the Moon and on Mars (for a review see Heinicke–Arnhof 2021). We briefly mention two analogue sites and two simulations that included Hungarian research interests in the investigation of the psychodynamics of the crews.

Concordia Research Station

Opened in 2005, Concordia is a French–Italian permanent research facility, built at 3,233 m above sea level, located more than 1,000 km inland in Antarctica (IPEV 1992/2024). It hosts about 70 people in the Summer, and 12 to 15 winteroverers. Its primary goal is to conduct research in a variety of fields, such as astronomy, glaciology and atmospheric science. The station is a good terrestrial space analogue because it is one of the most isolated places in the world in an extremely hostile – cold, dry and dark for long months – environment.

Halley VI Research Station

Established in 1956 to study the Earth's atmosphere, the Halley Research Station is operated by the British Antarctic Survey (BAS). Operational since 2012, and comprised of eight interlinked pods, the present Halley VI is suitable to accommodate about 70 people (BAS 1962–2024).

It is the world's first relocatable research facility. Built on skis, the pods can be towed across the ice by specialist heavy vehicles. Being able to move the research station is vital: in 2017, the station was relocated because of a nearby large ice crack on the Brunt Ice Shelf.

Mars Desert Research Station (MDRS)

MDRS was created by the Mars Society, a U.S. organisation founded in 1998. The Society's mission is to raise worldwide scientific and public awareness of Mars research and to promote scientific research and space industry activities that support Mars exploration and settlement (Mars Society MDRS 2001–2024). The Station started its activities in 2001. The facility is constantly expanding and is located in a Martian landscape in Utah. It offers a habitat for seven people and has several complementary structures. The simulation is based on the idea that the crews, who have been going there for more than 20 years, mostly for two weeks, live as "Martian colonists". By now, more than 280 international crews have been turned up at this desert station. The Hungarian aspect of the story is that between 13 and 26 April 2008, the seventy-first crew was Hungarian. The Hungaromars 2008 project, funded by the Hungarian Space Office, involved a team of six scientists and media professionals, and was followed with great interest by the public (Hungarian Space Office 2008).

Ground-based Experimental Complex (NEK) in Moscow

A whole different world of terrestrial space analogue simulation is revealed in the Ground-based Experimental Complex (Nazemnyy Eksperimental'nyy

Kompleks – NEK) at the Institute for Bio-Medical Problems (IBMP), Moscow, which also involves extensive international cooperation.

Experiments in the IBMP facility were started in the late 1960s (IBMP 1960–2024). The series of Mars 500 simulations began in 2007. Following a 14-day, then a 105-day isolation, the 520-day main project lasted from April 2010 to October 2011. It simulated a complete flight of an international crew to Mars and back, including communication delays with the Earth, limited consumable resources, etc. (IBMP 2007–2011). The same facility also hosts the Sirius space simulation, including a series of several model experiments lasting 17, 120, 240 and 365 days (IBMP 2017–2024).

PSYCHOLOGICAL ISSUES IN ICE GROUPS

Although in our days, the overwhelming majority of psychological information still comes from ground-based analogues, the investigation methods are changing and expanding very rapidly.

Sources of knowledge

In the early stage of polar expeditions, the life of ICE groups was not remotely visible. From the moment the ship vanished on the horizon, there was no way of knowing the fate of the crew until the explorers returned, and their reports became known to the public. These reports took the form of interviews, newspaper articles, diaries, memoirs and books written by the participants, mostly by leaders and doctors of the groups. These types of documents are called anecdotal reports. Even the earliest anecdotal sources contain abundant information about group events and problems and their solution in ICE settings.

In the heroic age of polar exploration, the members of the Belgica expedition to Antarctica in 1897–1899 suffered deep depression, which the expedition's doctor Frederick A. Cook tried to treat by sitting the crew in front of a large blazing fire – the modern-day equivalent of winter depression or seasonal affective disorder therapy (Palinkas–Suedfeld 2008: 153–154).

In his book, *Alone,* Admiral Byrd reports how being cramped into a small space can cause even the most carefully selected, disciplined people to freak out over the smallest things – like someone moving their belongings into their area or taking too long to chew a bite. "During my first winter at Little America, I walked for hours with a man who was on the verge of murder or suicide over imaginary persecutions by another man who had been his devoted friend. For there is no escape anywhere. You are hemmed in on every side by your own inadequacies and the crowding pressures of your associates. The ones who survive with a measure of happiness are those who can live profoundly off their intellectual resources, as hibernating animals live off their fat" (Byrd 1938: 19).

Anecdotal sources are considered to be of historical importance and are seen as good places to start in developing ideas and hypotheses for more formal studies (Kanas–Manzey 2008: 3). The rapid rise of text analytics technologies today has radically improved the processing of both old and new anecdotal sources by computer-aided qualitative research and content analysis.

Another source of knowledge about ICE groups is the psychological questionnaires and tests. Many versions of these are known and used today. The more familiar and widespread a test is, the better the opportunity for comparing different settings.

Psychophysiological symptoms and syndromes

Psychological problems may overlap with medical ones. This includes some well-known somatic symptoms, such as fatigue, weight gain, gastrointestinal problems, rheumatic aches and pains, and headaches. Another set of problems is related to disturbed sleep, e.g. circadian rhythm sleep disorder, including difficulty falling and staying asleep, and loss of slow-wave or REM sleep. These are sometimes referred to as the Big Eye Syndrome.

A cluster of issues is related to impaired cognition and performance, e.g. reduced accuracy and increased response time for cognitive tasks of memory, vigilance, attention, reasoning and intellectual inertia. (For more details of psychological effects, see PALINKAS–SUEDFELD 2008: 155–158).

Emotional and interpersonal issues

In the investigation of ICE groups, emotionality has always been treated as a multifaceted psychological construct, which includes mood and morale, anxiety, depression, aggression, hostility, life satisfaction, positive psychological outcomes, and so on. Settings, crew sizes and methodologies of emotionality assessment have also been varying broadly.

Negative affect problems, such as depression, subsyndromal seasonal affective disorder, anger, irritability and anxiety are mostly within the normal range but may sometimes overlap with psychiatry. Chronic fatigue, nervous tension and the resulting conflicts may lead to lasting interpersonal hostility and clique formation within the group. In extreme cases, excommunication, or exclusion of an individual from the group may result in a spontaneous fugue state sometimes referred to as Antarctic stare or Long Eye Syndrome.

In addition, emotional problems, tensions and conflicts may lead to the deterioration of work performance, including task negligence and forgetfulness.

A unique problem: The Third-Quarter Phenomenon

In the realm of eternal frost, nothing is evergreen, except the debate on the third quarter of emotional dysphoria.

It has been mentioned long ago that sleep difficulties, bad mood and irritability are considerably higher during the mid-winter period in polar settings. In examining this question, researchers initially proposed a three-phase time model (for an overview see PALINKAS 2003: 356). In an early empirical study on fourteen men in Antarctica, Palmai divided a one-year period into four segments, and, by different methods, he found that "the third quarter saw some further decline in morale, reflected also in irritability of the more responsible members" (PALMAI 1963: 265).

Nearly 30 years later, Bechtel and Behring summarised the – mostly anecdotal – evidence for the fact that mood and morale "reach nadir somewhere between the one-half and two-thirds mark of the mission" and coined the term "Third-Quarter Phenomenon" (Bechtel–Berning 1991: 261). Empirical support of the model was e.g. Stuster et al. 2000; Sandal 2000; Décamps–Rosnet 2005; Ehmann et al. 2018. However, Steel and Suedfeld found no evidence of this emotionality drop pattern (Steel–Suedfeld 1991; Steel 2001).

Kanas and his colleagues most recently reviewed research on the third-quarter phenomenon in ground-based space simulations and in-orbit missions in space. They concluded that one reason for the conflicting results is that factors other than time may influence the well-being of crews in the third quarter. They also found that previous research has paid little attention to the effects of on-mission events. For the Mars mission, it is thought that, as the mission will consist of three main phases – outbound, Mars landing–exploration and return to Earth – each of these will have its unique temporal characteristics and stressors, and the effects of these will be explored in future research (Kanas et al. 2021).

SELECTION OF CREWS

The psychological issues of ICE groups can be studied from several points of view, such as whether psychological problems and their countermeasures concern the individual, the human relations within the group, the group as a whole, or the crew's relation to the Mission Control – but at the start of it all, the most important factor is crew selection.

Space psychology literature agrees that the selection process consists of two main parts: the Selecting Out (Screening) and the Selecting In (Choosing) phases (Suedfeld–Steel 2000: 239–240).

Societal background and support to astronauts

For “Phase Zero” of the selection process to begin, there must be a pool from which applicants are drawn. Early polar explorers did not start their crew recruitment by Selecting Out but right by Selecting In – candidates were chosen from the contacts and personal recommendations of expedition organisers and leaders; they usually sought experienced professionals in specific fields – seamen, doctors, scientists, etc.

An exception to this was Admiral Byrd. An honorary Chief Scout himself, he had the idea of taking a boy scout with him on his new Antarctic expedition. In 1928, he called on the National Council of the Boy Scouts of America to nominate one of its 826,000 members for the trip. He sent a radio message to the American scouting community with the strict conditions of the application. Following the call, 28,400 scout troops were mobilised and, according to the book, “thousands upon thousands” of eager boy scouts submitted their applications. After a “thorough sifting” of thousands of applications, there remained 88 candidates, then 17, then 6, and finally 1 – Paul Siple, who later wrote a book about his adventure. The foreword by James E. West, the then U.S. Chief Scout not only gives a detailed history of the selection process (which is an early forerunner of today’s astronaut selections) but also reflects the enormous social popularity that the call brought to the cause of polar exploration (Siple 1931: 5–18).

Today, both large and emerging space nations are paying increasing attention to educating the public, including young people, about space activities.

The fascination with astronautics often starts from a childhood dream. According to a Harris Poll survey conducted in the U.S., U.K. and China as NASA celebrated 50 years of Moon landing, “86% of children aged 8 to 12 said they are interested in space exploration, and 90% of them wanted to learn more. Interestingly, 83% of parents (averaged across the three countries) who participated in the survey believe their children are interested in space. Yet, only 53% of kids say their interest in space is fueled by their parents, they are citing teachers (79%) and the internet (71%) as primary learning sources” (The Harris Poll 2019).

In Hungary, the media, the government (Department for Space Activities of the Hungarian Ministry of Foreign Affairs and Trade 2024), and the various space portals (e.g. Space News 2024) provide up-to-date and historical information for those interested in space activities. The Hungarian Astronautical Society (MANT) organises student competitions, high school team competitions, student clubs, space camps and educational publications, and also publishes presentations on YouTube (MANT 1956–2024). All this allows not only space organisations to search for astronaut candidates, but also for the candidates to find their way to both Hungarian and international organisations.

Selecting out and selecting in

The selecting out and selecting in phases are designed to gradually select the final crew from a large pool. The first stage is essentially a psychiatric screening.

The process is usually one-way, but not always. The scope of possible candidates becomes ever broader with advancing time. In 1928, in Admiral Byrd's polar expedition, anybody who was not American, not a scout and not a boy had no chance even to apply. In 1963, two years after Gagarin, the first female cosmonaut, Valentina Tereshkova, appeared in the history of space travel. In 1998, the age limit for spaceflight was also significantly extended when the first American astronaut, John Glenn, returned to space at the age of 77.

In our days, all space agencies combine select-out and select-in methods: candidates who are healthy in every respect are subject to personality questionnaires, performance tests, life interviews and group exercises.

According to Santy and Jones, the psychological screening phase is no longer aimed at identifying negative traits but is used as a basis for identifying the characteristics desirable for various activities: the aim is to select the most suitable persons for the job in question. Astronauts working on space stations perform a wide variety of jobs, and it is therefore very difficult to define in general terms what the desirable personality traits of astronauts are. The authors stress that these aspects should in no way be used as a starting point but require continuous assessment, i.e. it should be established whether they are indeed valid predictors of the desired behaviour and performance (Santy–Jones 1994: 901).

Over time, it has also become clear that short- and long-term missions do not have quite the same order of importance of psychological strengths. In their data collection on Russian, European and American astronauts, Galarza and Holland compared ten sets of characteristics. The two most important are 1. Mental and Emotional Stability; and 2. Good Performance under Stressful Conditions. Of these two sets of traits, the former is more important for long-term missions, the latter for short-term missions. 3. Group living skills (including multicultural adaptation) are the third most important aspect for long-duration space missions but are relegated to seventh place in the short term. 4. Teamwork skills (including conflict resolution and cooperation; the ability to put the team's interests ahead of personal goals; and the ability to follow and carry out instructions) is ranked fourth in both types of mission. 5. The ability to cope with isolation from family and friends is of roughly equal importance, ranking sixth in the short term and fifth in the long term. 6. Achievement motivation (commitment and perseverance at work, determination) is ranked eighth in the short term and sixth in the long term. 7. Decision-making ability (including situational awareness and alertness) is the third most important aspect for short-term missions, but only seventh for long-term ones. 8. Conscientiousness (responsibility and attention to detail) is ranked fifth in the short term and eighth in the long term. 9. Communication; and 10. Leadership skills are ranked ninth to tenth in both mission types (Galarza–Holland 1999: 4).

Currently, all space agencies involved with ISS operations recruit their astronauts using psychiatric and psychological selection strategies that combine select-out and select-in approaches that usually occur at the time that individuals are screened in their application to become astronaut candidates (Kanas–Manzey 2008: 169).

Hungary is planning to send a second Hungarian astronaut to orbit. The history of the selection and training of the first Hungarian astronaut and his space journey is inextricably linked with the history of Hungarian aerospace medicine (Remes et al. 2013; Remes 2020). The phases of the selection and preparation of the Hungarian astronaut can be followed continuously in the media and on various internet platforms.

The next question is how the selected excellent people will get along with each other during long-duration spaceflights.

THE RIGHT STUFF

The ideally assorted crew would be the "right stuff". The term was first coined in NASA jargon. Its origin is a play on words like staff and stuff ('personnel' versus 'what-d-ya-call-it') and comes from Tom Wolfe's novel of the same title (Wolfe 1979).

The psychological aspects of long-duration spaceflight have raised the issue of crew matching as a priority. Suedfeld identified four historical phases in the development of this area.

The first phase was the "right stuff mentality". This essentially meant that crews that were properly matched were seen as invulnerable.

During the second phase of this approach, already in the 1970s, researchers realised that the invulnerability of optimally assembled crews was a myth, and a shift in focus towards resilience (i.e. full recovery from negative effects) was initiated.

In the third phase, in addition to the pathogenetic approach, salutogenetic or positive psychological thinking gained ground, where the positive after-effects of missions were also involved.

In the fourth phase, the author outlines "an integrated, complex Gestalt" in which, in addition to the selection and compatibility issues, attention must also be paid to the life course of the men and women who complete their careers in space (Suedfeld 2005).

The Right Stuff for long-duration exploratory missions

Space psychology is getting ever closer to creating the picture of an ideal crew for long-duration exploratory missions, i.e. for the settlements on the Moon and Mars.

In their overview, Landon and her colleagues discuss two such NASA models in detail. One is the Spence-Helmreich model, the other is the more traditional Five-Factor Model (FFM) (Landon et al. 2017). Both models have been investigated for decades in a wide variety of empirical research.

The Spence-Helmreich model of personality

The Spence-Helmreich model of personality consists of two elements: Instrumentality and Expressivity. Both attributes have positive and negative aspects and are assessed by the Personality Characteristics Inventory (PCI) (Chidester et al. 1991). Instrumentality is an indication of achievement and goal orientation and reflects three main needs: Mastery, Work and Competitiveness. Expressivity is an indicator of interpersonal attitudes and behaviours, with four categories of attributes: Expressivity, Verbal Aggression, Negative Communion and Impatience–Irritability. As the names suggest, there are positive and negative aspects to both personality traits. On this basis, three clusters are currently distinguished. The Right Stuff or Positive Instrumental–Expressive Group, the Wrong Stuff or Negative Instrumental Group, and the No Stuff or Low Motivation Group (Landon et al. 2017: 39). This model is a complement of the Five-Factor Model.

The Right Stuff Profile according to the Five-Factor Model

The Five-Factor Model (FFM) has a long conceptual history and has been used in a comprehensive variety of fields in personal, clinical and organisational psychology. Its present assessment tool, the Neuroticism Extraversion Openness Personality Inventory, or NEO-PI, and its more recent variants are connected to the lifework of Costa and McCrae (for history and description see e.g. McCrae–John 1992; Costa–McCrae 2000). The Model consists of five personality trait factors: Neuroticism, Extraversion, Openness, Agreeableness and Conscientiousness. These factors are continuous dimensions.

As mentioned above, the Galarza–Holland model for crew selection was also partly built on the five-factor approach (Galarza–Holland 1999). The Five-Factor Model describes the personality traits of an imaginary optimal crew as well.

So, what are the optimal personality traits of an imaginary crew in a Lunar or Martian colony?

Multiple studies have confirmed that the most important personality trait is Emotional Stability (Ursin et al. 1992; Palinkas et al. 2000). It is the other end of the Neuroticism spectrum. Along the subscales of this factor, the ideal Right Stuff member is not anxious, not hostile, not depressed, not self-conscious, not impulsive and not vulnerable.

As to the Extroversion–Introversion spectrum, authors agree that a range of low to moderately high is acceptable, i.e. the optimal crewmember is a sociable introverted person.

As to Openness to Experience (with subscales including Aesthetics, Feelings, Actions, Ideas, Values and Fantasy), a moderate range is acceptable – adaptability and cross-cultural competence are important.

The Agreeableness factor indicates the quality of interpersonal orientation with facets of Trust, Straightforwardness, Altruism, Compliance, Modesty and tender-mindedness. The moderately high to high level of this trait is optimal.

Subscales of Conscientiousness are competence, order, dutifulness, achievement striving, self-discipline and deliberation. In general, this trait is very important in long-term exploratory missions, because it is a strong predictor of team performance. However, e.g. Palinkas and colleagues argue that high scorers in this trait may easily become frustrated by deficiencies, inadequacies, delays, or similar difficulties, and this may be a source of stress in the group, whereas less conscientious individuals may better manage these problems and express a more flexible and adaptable attitude toward them (Palinkas et al. 2000: 623).

In sum, the Five-Factor Personality Trait Model appears to be a fairly strong predictor of individual and team performance, but further research is needed in the field to solve the remaining debates (Landon et al. 2017).

Beyond the issue of individual personality traits, Right Stuff has several aspects that affect the group as a whole. The most important of these are crew autonomy and cultural differences.

Crew autonomy

Concerning individual autonomy, Suedfeld and Steel (2000) call attention to a personality paradox "that cries out for research" (Suedfeld–Steel 2000: 242). The paradox is between adventure and boredom. On the one hand, people who join ICE groups, whether it is for Antarctic winterovering or space travel, are looking for excitement, adventure and challenge, and very quickly find themselves in a monotonous and boring environment from which they are unlikely to escape for a long time. On the other hand, such adventurous people have a high need for autonomy and sometimes find it difficult to tolerate being controlled by others or by the organisation.

Concerning group autonomy, expeditionary ICE groups are usually set up, funded and launched by an organisation that defines the purpose of the mission. Accordingly, the concept of crew autonomy makes sense in the context of the relationship between the crew and Mission Control and accompanies the whole history of ICE groups. In case of ships, direct contact with the sending organisation was lost as soon as the ship ran out to the open sea. In polar expeditions, the winteroverers had practically no connection with their homeland – but today, in the age of the Internet, the situation is different. There is relatively little experience with this issue in space, but the aim is to achieve an optimal level of crew autonomy. Space psychologists agree that crew autonomy is medium in Antarctic winterovering, low-to-high in orbital ISS missions; it will be high in Lunar missions and extremely high in Mars missions (Kanas–Manzey 2008: 217). The issue has been investigated, for example, in the Mars 500 ground-based space simulation in Moscow (Gushin et al. 2012; Gushin et al. 2016; Supolkina et al. 2021).

Space psychologists started to investigate a phenomenon that may occur in extremely high autonomy settings. This is Groupthink, a concept taken by Irving Janis from Orwell's book, *1984* (Janis 1982). Occurring in highly cohesive groups under stressful conditions, groupthink is an illusion of invulnerability and unanimity. Further features of groupthink are ignoring warnings, unquestionable belief in the inherent morality of the group, direct pressure on any individual who expresses doubts about any of the group-shared illusions, and self-censorship of group members, i.e. avoiding deviation from group consensus. This dangerous condition may deteriorate group performance and decision-making capacity, thereby representing a serious hazard for the performance of crews acting in a high-risk environment (Kanas–Manzey 2008: 224–225).

Cultural differences

In the present and future eras of heterogeneous crews, the key question is how psychosocial adaptation by crews from different cultures can be studied. Research on cultural differences in polar and space psychology is largely based on Hofstede's wide-ranging work (Hofstede 1980; 2011).

Helmreich and Merritt found that three of Hofstede's dimensions were relevant for pilots and, consequently, for spaceflight: Individualism–Collectivism, Power Distance and Uncertainty Avoidance (Helmreich–Merritt 1998). Partly based on this model, Helmreich identified three determinants relevant to space psychology: national, organisational and professional cultures (Helmreich 2000).

Besides the three main types of cultural differences, an evolving field in the study of crew heterogeneity is the investigation of gender issues. Studies range from mixed-gender through gender-balanced to all-female studies in many settings (Bishop et al. 2010; Binsted et al. 2010; Blackadder-Weinstein et al. 2019; Supolkina et al. 2020; Tafforin 2020).

A 21-membered international team of eminent scholars of the field conceptualised a review and still valid recommendations for the future, involving the host–guest problem and the minority issue, as well (Kanas et al. 2009). A recent review refers to cultural differences in the framework of cross-cultural competency as a selection factor for long-duration exploration missions (Landon et al. 2017).

COMPARABILITY AND INTEGRABILITY OF RESEARCH

The psychodynamics of groups in isolated, confined and extreme (ICE) environments show many similarities in different settings and environments, such as Arctic and Antarctic expeditions, mountain climbing expeditions, submarines, sea-based oil drilling platforms, and underwater and land-based simulations. Sandal, however, warns of the need for caution and care in considering these similarities when extrapolating psychological findings across settings (Sandal 2000).

Suedfeld thought carefully about the concept of analogy and argued that Antarctica is not a simulacrum (an insubstantial form or semblance) of outer space. Thus, polar psychology is an autonomous and independently important component of psychology, especially ICE psychology. He suggests that analogies should be based not necessarily on environmental characteristics, but on similarities in experience (Suedfeld 2018).

The most notable distinction between space and all Earth-based analogues and simulations lies in the absence of weightlessness in the latter. Microgravity, through many brain physiological mechanisms, can impact cognition and consequently social interactions. An illustrative example underscoring the significance of weightlessness comes from an experiment conducted aboard the International Space Station (ISS), where Takács and colleagues observed reduced performance over a 6-month mission (Takács et al. 2021).

Interestingly, no such decline was noted when the same task was performed in an Antarctic environment (Barkaszi et al. 2016). While some physiological effects of microgravity can be simulated on Earth through head-down tilt bedrest, a recent review of the cognitive domain by Barkaszi and her colleagues revealed more disparities than similarities between findings in space and bedrest studies (Barkaszi et al. 2022).

An often underestimated distinction between space and simulations is the degree of confinement. Participants in Antarctic stations and simulations like the Mars 500 facility enjoy private bedrooms and relatively spacious living areas. Conversely, the ISS cannot afford any private space, and the confinement would be even more severe in vehicles planned for the initial Moon and Mars expeditions. Ethical considerations likely deter Earth-based studies from attempting to simulate long-term confinement to a similar extent.

In terms of extreme environments, polar stations present themselves as a highly promising analogue for space. Stations like Concordia become technically inaccessible during winter, mirroring the situation on the ISS. From a societal standpoint, this implies that crews must independently address any emergencies that may arise. Additionally, given Concordia's effective altitude of more than 3,000 m, it could serve as a testbed for examining the impact of ICE conditions combined with hypoxia. Even mild hypoxia is known to impair cognition (e.g. Reményi et al. 2018) and could be a relevant factor in future long-duration space missions where the decreased cabin pressure is being considered for technical reasons.

Reviewing more than a hundred studies in terrestrial space analogue environments, Kanas and Manzey concluded that no single site or simulation can fully reproduce the space environment (Kanas–Manzey 2008). While this assertion holds merit, it is essential to recognise that the International Space Station also cannot replicate all the conditions of interplanetary missions.

SUMMARY AND OUTLOOK

The review studies on the subject of "future perspectives of space psychology" mainly summarise the issues and their countermeasures arisen so far, and word cautiously about issues to emerge in the still unknown future (De La Torre et al. 2012; Gushin et al. 2021). Nevertheless, some developments are seen to unfold.

First, space psychology is likely to develop in close cooperation with space technology and the space industry, with a multitude of new interactions and new professions. Some of the well-known psychological problems traditionally encountered in ICE groups are likely to persist in the future. Examples include sensory and social deprivation, monotony, homesickness, loneliness and even the need for good food. For these problems, new and rapidly evolving methods will offer solutions, such as virtual reality technologies, social robotics, space food technologies, space greenhouses, and so on.

Second, the emphasis seems to shift from a focus on the recognition and description of problems to a focus on countermeasures and solutions, and this is well reflected in the changing terminology. 'Cultural differences' are recently referred to as 'Intercultural Competence', the 'Right Stuff' as 'Behavioural Health and Performance', and the 'Earth-out-of-View' as the 'Disappearing Earth Phenomenon' (or the 'Break-Off').

Finally, the experience and results gained in ground-based and orbital sites will not fade into oblivion but will be integrated into the research carried out during long-duration space missions and on lunar and Mars colonies in the future.

REFERENCES

Barkaszi, I. – Ehmann, B. – Tölgyesi, B. – Balázs, L. – Altbäcker, A. (2022): Are Head-Down Tilt Bedrest Studies Capturing the True Nature of Spaceflight-Induced Cognitive Changes? A Review. *Frontiers in Physiology,* 13. Online: https://doi.org/10.3389/fphys.2022.1008508

Barkaszi, I. – Takács, E. – Czigler, I. – Balázs, L. (2016): Extreme Environment Effects on Cognitive Functions: A Longitudinal Study in High Altitude in Antarctica. *Frontiers in Human Neuroscience,* 10. Online: https://doi.org/10.3389/fnhum.2016.00331

BAS (1962–2024): *Halley VI Station.* Online: www.bas.ac.uk/polar-operations/sites-and-facilities/facility/halley/

Bechtel, R. B. – Berning, A. (1991): The Third-Quarter Phenomenon: Do People Experience Discomfort after Stress Has Passed? In Harrison, A. A. – Clearwater, Y. A. – McKay, C. P. (eds.): *From Antarctica to Outer Space. Life in Isolation and Confinement.* New York: Springer. 261–266. Online: https://doi.org/10.1007/978-1-4612-3012-0_24

Binsted, K. – Kobrick, R. L. – Griofa, M. Ó. – Bishop, S. L. – Lapierre, J. (2010): Human Factors Research as Part of a Mars Exploration Analogue Mission on Devon Island. *Planetary and Space Science,* 58(7–8), 994–1006. Online: https://doi.org/10.1016/j.pss.2010.03.001

Bishop, S. L. – Kobrick, R. – Battler, M. – Binsted, K. (2010): FMARS 2007: Stress and Coping in an Arctic Mars Simulation. *Acta Astronautica,* 66(9–10), 1353–1367. Online: https://doi.org/10.1016/j.actaastro.2009.11.008

Blackadder-Weinstein, J. – Leon, G. R. – Norris, R. C. – Venables, N. C. – Smith, M. (2019): Individual Attributes, Values, and Goals of an All-Military Women Antarctic Expedition. *Aerospace Medicine And Human Performance,* 90(1), 18–25.

Byrd, R. E. (1938): *Alone.* New York: Putnam.

Chidester, T. R. – Helmreich, R. L. – Gregorich, S. E. – Geis, C. E. (1991): Pilot Personality and Crew Coordination: Implications for Training and Selection. *The International Journal of Aviation Psychology,* 1(1), 25–44. Online: https://doi.org/10.1207/s15327108ijap0101_3

Costa, P. T. Jr. – McCrae, R. R. (2000): NEO Personality Inventory. In Kazdin, A. E. (ed.): *Encyclopedia of Psychology.* Oxford: Oxford University Press. Volume 5. 407–409.

Décamps, G. – Rosnet, E. (2005): A Longitudinal Assessment of Psychological Adaptation during a Winter-Over in Antarctica. *Environment and Behavior,* 37(3), 418–435. Online: https://doi.org/10.1177/0013916504272561

De La Torre, G. – van Baarsen, B. – Ferlazzo, F. – Kanas, N. – Weiss, K. – Schneider, S. – Whiteley, I. (2012): Future Perspectives on Space Psychology: Recommendations on Psychosocial and Neurobehavioral Aspects of Human Spaceflight. *Acta Astronautica,* 81(2), 587–599. Online: https://doi.org/10.1016/j.actaastro.2012.08.013

Department for Space Activities of the Hungarian Ministry of Foreign Affairs and Trade (2024). Online: https://space.kormany.hu/dear-visitor

Ehmann, B. – Altbäcker, A. – Balázs, L. (2018): Emotionality in Isolated, Confined and Extreme (ICE) Environments: Content Analysis of Diaries of Antarctic Winteroverers. *Journal of Environmental Psychology,* 60(3), 112–115. Online: https://doi.org/10.1016/j.jenvp.2018.09.003

Galarza, L. – Holland, A. W. (1999): Critical Astronaut Proficiencies Required for Long-Duration Space Flight. *SAE Technical Paper,* 1999-01-2096, 1–4.

Gushin, V. – Ryumin, O. – Karpova, O. – Rozanov, I. – Shved, D. – Yusupova, A. (2021): Prospects for Psychological Support in Interplanetary Expeditions. *Frontiers in Physiology,* 12. Online: https://doi.org/10.3389/fphys.2021.750414

Gushin, V. – Shved, D. – Vinokhodova, A. – Vasylieva, G. – Nitchiporuk, I. – Ehmann, B. – Balázs, L. (2012): Some Psychophysiological and Behavioral Aspects of Adaptation to Simulated Autonomous Mission to Mars. *Acta Astronautica,* 70, 52–57. Online: https://doi.org/10.1016/j.actaastro.2011.07.020

Gushin, V. – Yusupova, A. – Shved, D. – Shueva, L. – Vinokhodova, A. – Bubeev, Y. (2016): The Evolution of Methodological Approaches to the Psychological Analysis of the Crew Communications with Mission Control Center. *Reach,* 1, 74–83. Online: https://doi.org/10.1016/j.reach.2016.05.001

Heinicke, C. – Arnhof, M. (2021): A Review of Existing Analog Habitats and Lessons for Future Lunar and Martian Habitats. *Reach,* 21–22. Online: https://doi.org/10.1016/j.reach.2021.100038

Helmreich, R. L. (2000): Culture and Error in Space: Implications from Analog Environments. *Aviation, Space, and Environmental Medicine,* 71(Supplement 9), A133–A139.

Helmreich, R. L. – Merritt, A. C. (1998): *Culture at Work in Aviation and Medicine. National, Organizational, and Professional Influences.* Brookfield, VT: Ashgate.

Hofstede, G. (1980): *Culture's Consequences. International Differences in Work-Related Values.* Beverly Hills, CA: SAGE.

Hofstede, G. (2011): *Dimensionalizing Cultures. The Hofstede Model in Context.* Online Readings in Psychology and Culture, Unit 2. Online: http://scholarworks.gvsu.edu/orpc/vol2/iss1/8

Hungarian Space Office (2008): *Hungaromars.* Online: www.elte.hu/content/magyar-mars-lakok.t.10024

IBMP (1960–2024). Online: http://mars500.imbp.ru/en/history.html

IBMP (2007–2011): *Mars 500.* Online: http://mars500.imbp.ru/en/index_e.html

IBMP (2017–2024): *Sirius.* Online: http://sirius.imbp.ru/eng.html

IPEV (1992–2024): *Concordia Station.* Online: https://institut-polaire.fr/en/antarctica/concordia-station/

Janis, I. L. (1983): Groupthink. In Blumberg, H. H. – Hare, P. A. – Kent, M. F. (eds.): *Small Groups and Social Interaction.* Volume 2. Hoboken: Wiley. 39–46.

Kanas, N. (2011): From Earth's Orbit to the Outer Planets and Beyond: Psychological Issues in Space. *Acta Astronautica,* 68(5–6), 576–581. Online: https://doi.org/10.1016/j.actaastro.2010.04.012

Kanas, N. – Gushin, V. – Yusupova, A. (2021): Whither the Third Quarter Phenomenon? *Aerospace Medicine and Human Performance,* 92(8), 689–691. Online: https://doi.org/10.3357/AMHP.5857.2021

Kanas, N. – Manzey, D. (2008): *Space Psychology and Psychiatry.* Dordrecht: Springer. Online: https://doi.org/10.1007/978-1-4020-6770-9

Kanas, N. – Sandal, G. M. – Boyd, J. E. – Gushin, V. – Manzey, D. – North, R. – Leon, G. R. – Suedfeld, P. – Bishop, S. L. – Fiedler, E. R. – Inoue, N. – Johannes, B. – Kealey, D. J. – Kraft, N. O. – Matsuzaki, I. – Musson, D. – Palinkas, L. A. – Salnitskiy, V. P. – Sipes, W. – Stuster, J. – Wang, J. (2009): Psychology and Culture during Long-Duration Space Missions. *Acta Astronautica,* 64(7–8), 659–677. Online: https://doi.org/10.1016/j.actaastro.2008.12.005

Landon, L. – Rokholt, C. – Slack, K. – Pecena, Y. (2017): Selecting Astronauts for Long-Duration Exploration Missions: Considerations for Team Performance and Functioning. *Reach,* 5(5), 33–56. Online: https://doi.org/10.1016/j.reach.2017.03.002

MANT (1956–2024): *Events.* Online: www.mant.hu/events

Mars Society (2001–2024): *MDRS.* Online: https://mdrs.marssociety.org/

McCrae, R. R. – John, O. P. (1992): An Introduction to the Five-Factor Model and Its Applications. *Journal of Personality,* 60(2), 175–215.

Palinkas, L. A. (2003): The Psychology of Isolated and Confined Environments: Understanding Human Behavior in Antarctica. *American Psychologist,* 58(5), 353–363.

Palinkas, L. A. – Gunderson, E. K. – Holland, A. W. – Miller, C. – Johnson, J. C. (2000): Predictors of Behavior and Performance in Extreme Environments: The Antarctic Space Analogue Program. *Aviation, Space, and Environmental Medicine,* 71(6), 619–625.

Palinkas, L. A. – Suedfeld, P. (2008): Psychological Effects of Polar Expeditions. *The Lancet,* 371, 153–163. Online: https://doi.org/10.1016/S0140-6736(07)61056-3

Palmai, G. (1963): Psychological Observations on an Isolated Group in Antarctica. *The British Journal of Psychiatry,* 109(460), 364–370. Online: https://doi.org/10.1192/bjp.109.460.364

Réményi, Á. – Grósz, A. – Szabó, S. A. – Tótka, Zs. – Molnár, D. – Helferrich, F. (2018): Comparative Study of the Effect of Bilastine and Cetirizine on Cognitive Functions at Ground Level and at an Altitude of 4,000 m Simulated in Hypobaric Chamber: A Randomized, Double-Blind, Placebo-Controlled, Cross-Over Study. *Expert Opinion on Drug Safety,* 17(9), 859–868. Online: https://doi.org/10.1080/14740338.2018.1502268

Remes, P. (2020): *Az első magyar űrrepülés története.* Kecskemét: Private publication by the author.

Remes, P. – Grósz, A. – Szabó, J. (2013): *A magyar repülő- és űrorvostan története.* Budapest: Zrínyi Kiadó.

Sandal, G. M. (2000): Coping in Antarctica: Is It Possible to Generalize Results across Settings? *Aviation, Space and Environmental Medicine,* 71(Supplement 9), A37–A43.

Santy, P. A. – Jones, D. R. (1994): An Overview of International Issues in Astronaut Psychological Selection. *Aviation, Space, and Environmental Medicine,* 65(10), 900–903.

Siple, P. (1931): *A Boy Scout with Byrd.* New York: G. P. Putnam's Sons.

Space News (2024). Online: https://urvilag.hu/

Steel, G. D. (2001): Polar Moods: Third-Quarter Phenomena in the Antarctic. *Environment and Behavior,* 33(1), 126–133. Online: https://doi.org/10.1177/00139160121972909

Steel, G. D. – Suedfeld, P. (1991): Temporal Patterns of Affect in an Isolated Group. *Environment and Behavior,* 23(6), 749–765. Online: https://doi.org/10.1177/0013916591236006

Stuster, J. – Bachelard, C. – Suedfeld, P. (2000): The Relative Importance of Behavioral Issues during Long-Duration ICE Missions. *Aviation, Space, and Environmental Medicine,* 71(9), A17–A25.

Suedfeld, P. (2005): Invulnerability, Coping, Salutogenesis, Integration: Four Phases of Space Psychology. *Aviation, Space, and Environmental Medicine,* 76(6), B61–B66.

Suedfeld, P. (2018): Antarctica and Space as Psychosocial Analogues. *Reach,* 9–12, 1–4. Online: https://doi.org/10.1016/j.reach.2018.11.001

Suedfeld, P. – Steel, G. D. (2000): The Environmental Psychology of Capsule Habitats. *Annual Review of Psychology,* 51(1), 227–253. Online: https://doi.org/10.1146/annurev.psych.51.1.227

Supolkina, N. – Yusupova, A. – Shved, D. – Chekalina, A. – Sarantsev, S. V. – Gushin, V. – Feichtinger, E. L. (2020): Crew–Mission Control Communicative Behaviour in Sirius-17 Experiment. *Human Physiology,* 46(7), 771–775. Online: https://doi.org/10.1134/S0362119720070166

Supolkina, N. – Yusupova, A. – Shved, D. – Gushin, V. – Savinkina, A. – Lebedeva, S. – Chekalina, A. – Kuznetsova, P. (2021): External Communication of Autonomous Crews Under Simulation of Interplanetary Missions. *Frontiers in Physiology,* 12. Online: https://doi.org/10.3389/fphys.2021.751170

Tafforin, C. (2020): Behaviors of a Mixed Gender and Culture Group during a 4-Month Confinement (SIRIUS-19). *Antrocom Online Journal of Anthropology,* 16(1), 5–19.

Takács, E. – Barkaszi, I. – Czigler, I. – Pató, L. – Altbäcker, A. – McIntyre, J. – Cheron, G. – Balázs, L. (2021): Persistent Deterioration of Visuospatial Performance in Spaceflight. *Scientific Reports,* 11(1). Online: https://doi.org/10.1038/s41598-021-88938-6

The Harris Poll (2019): *Lego Group Kicks Off Global Program to Inspire the Next Generation of Space Explorers as NASA Celebrates 50 Years of Moon Landing.* Online: https://theharrispoll.com/briefs/lego-group

Ursin, H. – Comet, B. – Soulez-Lariviere, C. (1992): An Attempt to Determine the Ideal Psychological Profiles for Crews of Long-Term Space Missions. *Advances in Space Research,* 12(1), 301–314. Online: https://doi.org/10.1016/0273-1177(92)90298-c

Wolfe, T. (1979): *The Right Stuff.* New York: Farrar, Straus and Giroux.

Dávid Szebeni[1] – Nándor Zoltán Tráser[2] –
Márton Farkas[3] – András Szkalisity[4]

Approaches and Basic Principles of Settlements on Celestial Bodies

URBAN DEVELOPMENT ASSOCIATION

Urban development is one of the most challenging areas of our time and it only gets more difficult when this task arises on other celestial bodies. The perspective of an urbanist or urban developer must catch the big picture while taking into consideration engineering, physics, social, health, psychological and economic issues as well. We intend to give a glimpse into this mindset and perspective.

Therefore, this paper consists of two main parts.

In the first part, we highlight some important arguments and points from the literature of building new settlements on other celestial bodies. Due to the rapidly evolving nature of this field of expertise, we think a summary of relevant literature is of paramount importance so that the reader can gain considerable insight into the topic. Another reason is that we would like to give a sense of the complexity of developing and managing these settlements.

1 Urban Development Association, president; ORCID: https://orcid.org/0009-0003-4816-862X; e-mail: president@urbanexpert.eu
2 Department of Human Geography, University of Szeged, MSc; ORCID: https://orcid.org/0009-0003-3765-5641; e-mail: trasern@gmail.com
3 Department of Social and Economic Geography, Faculty of Science, Eötvös Loránd University, Geography MSc; ORCID: https://orcid.org/0009-0009-2314-1432; e-mail: farkasmarci01@gmail.com
4 Department of Human Geography, University of Szeged, MSc; ORCID: https://orcid.org/0009-0008-5328-4111; e-mail: szkalisity.a@gmail.com

DOI: https://doi.org/10.36250/01209_04

In the second part, we identify and suggest essential principles that can be applied to any planned settlements on other celestial bodies. These principles are based on literature, human history, lessons learned from habitats in extreme environments and our own experience in the Hungarian Urban Development Association.

In this paper, we use the term "settlement" for bases, colonies, villages, towns and cities[5] on other planets and moons.

SUMMARY OF LITERATURE

If humankind manages to create permanent settlements on other planets or asteroids, it will create new scientific questions. Throughout our history, we have experiences about colonisation processes and the challenges that accompanied them (Szocik et al. 2010). It is a possibility that new social and political order will be created during those expeditions, but it is highly recommended to learn from the previous colonisations on Earth. If we study those, we can easily identify what kind of conflicts could happen on the expeditions: criminal behaviour, social deviance can occur because of the background of the participants and the psychological stress caused by the travelling, and from the different adaptations of the individuals (Szocik et al. 2010). There are a lot of factors which can create conflicts among the expedition crew. Conflicts can easily emerge from stress in a divided group, people with different social status, rivalries between the colonies, etc. The literatures all agree that to prevent social disorder in new colonies, international laws for space expeditions should be created, and later controlled by intergovernmental institutions (Szocik et al. 2010). Throughout history, colonies on Earth had a lot of different political structures: there were examples of scientist-led technocrats, military maintained dictatorships, and direct and represented democracies as well (Wójtowicz–Szocik 2021). It

[5] The distinction methods between towns and cities are different in each country. In general, cities are one of the top 10–30 most populous settlements in a country's settlement structure.

is hard to predict which one will serve society in the best way, it is also possible that a brand new political structure will be created on the other planets (Wójtowicz–Szocik 2021).

For a human, the Moon is a quite hostile environment to live in (Stenzel et al. 2018: 8), but as the attention of both private and governmental actors enables more and more research projects to be carried out to solve these problems, we get closer and closer to colonising the Moon. But first of all, what are the main challenges of establishing human settlements on the Moon, and how much do these differ from the obstacles of living on other planets, such as Mars?

First of all, one of the biggest challenges, both on the Moon and Mars is harvesting, mining or extracting water (Matt et al. 2011). Recent research has shown that there is water ice on both planets. On the Moon, it is located on the poles (Gibney 2018: 475), and while the dendritic valley networks on the surface of Mars show that once there was fluvial activity on the planet (Howard et al. 2005: 3), right now there is only frozen water available there. Locating these spots on the planets is a complex task because of the regolith layers that might be covering them. And even if we can find these spots, transforming them into liquid form is an even bigger task, because for example on the Moon, the water spots that have been found are located in permanently shaded craters as cold as –249 °C, which are the naturally coldest spots known in the Solar System. One possible way to transform water into liquid form is using giant mirrors and the power of the Sun, as it is done for example in Norway, Rjukan (Gibney 2018: 475). The only problem with beaming reflected solar energy from mirrors at mountain peaks of eternal light to solar arrays in permanently shadowed craters is that it would require a complex infrastructure, both to aim the mirrors into the right spots and then also to capture the harvested water efficiently (Ellery 2020). Another solution, which requires less infrastructure is to equip rovers with drills and wireless ovens, that can mine both regolith and the ice buried under it, and then with the use of high-power lasers they could also warm the ice to produce liquid water (Gibney 2018: 475). Finally, a possible method is to deploy a transparent tent made of 0.1 mm thick polyethylene on the ice spots to use the greenhouse effect to warm the frozen water (Arnhof 2016: 4). Another noteworthy fact is that water hydration exists on the Moon in minerals at all latitudes, but this will be more difficult to extract than from ice (Ellery 2020). Producing water is not only an important task for human consumption but by electrolysing it into its constituent parts (oxygen and hydrogen) it could also be harvested for propellant (Gibney 2018: 475).

Secondly, a unique challenge of extraterrestrial planets is their soil, called regolith. By far the most well-known of them is the Moon, the main components of which are oxygen and silicon *(Figure 1).* However, oxygen is chemically bound in different metal oxides, so even if its extraction via electrolysis would give the highest yield, it would require temperatures above 2,100 °C. Other extraction methods would require some additives, such as hydrogen or carbon, which could only be brought from Earth initially (Stenzel et al. 2018: 11). While the composition of the regolith is similar to the basalt found on Earth, its physical attributes are very much different. Without a properly defending atmosphere, the continuous pummelling and tilling action of small meteorites, referred to as 'gardening', along with severe temperature fluctuations, have created a fine, dust like fabric with a mean particle size of 40–130 μm (Ellery 2020). On the Moon's surface, it can be several centimetres deep. It is also noteworthy, that regolith is electro-statically charged through interaction with the solar wind, and as a result of this, it is very abrasive and clingy, fouling up vehicles and spacesuits very quickly (Thangavelu 2014: 23). Moreover, the landing of a spaceship on the surface of the Moon can cause severe dust storms, which is a crucial factor to account for when planning the layout of a lunar habitat. While right now we only have a small amount of information about the regolith on Mars, it is certain that one of its components is perchlorate, which has toxic effects (Oze et al. 2021).

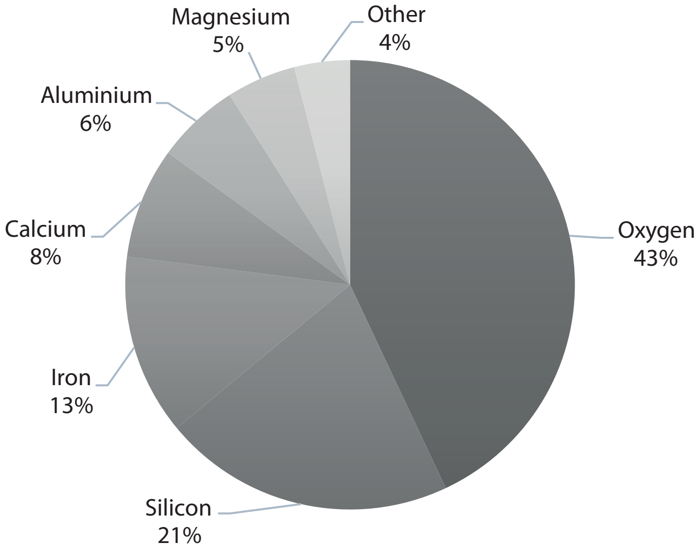

Figure 1
The composition of regolith on the Moon (varies by location)
Source: Compiled by the authors based on Gibney 2018: 477.

Thirdly, both Mars and the Moon have significantly different atmospheres than the Earth. The red planet's surface pressure at mean radius ranges from 4 mbar up to 9 mbar which is much smaller than the Earth's 1,013 mbar, and it is because the atmosphere of Mars is roughly 100–250 times thinner (Suchantke et al. 2020: 440). Moreover, the red planet, just like the Moon has no magnetic field (Gibney 2018: 477; Ehlmann et al. 2016: 1932). The latter has also no protective atmosphere (Gibney 2018: 477), and while Mars has bigger temperature swings than the Earth, the Moon can have the biggest out of the tree, with 123 °C (253 °F) noon and even –233 °C (–387 °F) predawn temperature on its equator. The Moon also does not have any seasons and only has one sixth the gravity of Earth (Thangavelu 2014: 23), while Mars has one-third of our mother planet's gravity (Suchantke et al. 2020: 440). These attributes combined, especially the lack of a significantly protective atmosphere can have serious implications, such as meteorite showers, solar particle storms (Thangavelu 2014: 23), or in the case of Mars, the Galactic Cosmic Radiation can be up to 77 cSv, while the allowed annual dose for a NASA astronaut is 50 cSv (Arnhof 2016: 5). To survive under these conditions, humans will need protecting shelters, which can be achieved by going into under surface caves or by constructing bases with the method of in-situ resource utilisation (ISRU). Not only ISRU is much more cost-effective than transporting everything from Earth, but it also has a wide range of techniques. From the simpler methods, like using inflatable components, or reinforcing the shelter with bags of regolith (Arnhof 2016: 5), to the more complex ones, like reusing the leftover parts of previous landing structures, or 3D printing with locally available resources. The recycling of abandoned structures is also a promising concept from a sustainability viewpoint. According to a recent analysis, there are already 20 tons of aluminium and 7 tons of carbon fibre-reinforced plastic on the Moon, which could be reused with additive manufacturing techniques (Stenzel et al. 2018: 9). There is also a growing interest in regolith-based 3D printing methods, which could even be used to produce bricks (Arnhof 2016: 5; Stenzel et al. 2018: 10; Gibney 2018: 476).

Possible locations for permanent settlements on other planets are the lava tubes, which represent volcanic activity from the past (Hörz 1985: 407). Those kinds of geological phenomena occur on the surfaces of both Mars and the Moon (Haruyama et al. 2012; Léveillé–Datta 2010), on the Earth, it would be unusual to consider it to settle such environments. Places which are suitable for establishing settlements are graben with pits, volcanic vents and craters created by exogen phenomena such as meteor impacts (Blamont 2014: 2140).

The following areas are more suitable for settlement on Mars (Blamont 2014: 2142):

– Radiation is much higher than in the case of our planet, the atmosphere is not as protective as here, according to previous calculations, the difference between surface and cave 'habitants' absorption of radioactive rays was three scales better for the second option (Harris 2003: 7).

– Externalities in temperature are mitigated by the cave's pits.
– Dust on Mars contains harmful composites, but deep areas are protected.
– Meteor impacts are more likely on the surface of Mars, but caves are more protected if such an event happens.
– Cave settlements help to create in-situ resource utilisation, where new resources and materials can be studied outside the settlement area.

There are also some hazards which can come up during cave habitations: We do not have any data about the geological stability–instability of those areas, this information is crucial in the case of lava tubes (Blamont 2014: 2143). If we think about transportation, elevators and ropes would play a significant role in entering the settlements, rovers will be used mostly for surface mobility (Blamont 2014: 2144). Firstly, the first space colonies should be created on the Moon, and then the experiences gained there can be adopted in later processes. Inflatable structures are the best solutions for cave dwelling; at the beginning, it is recommended to start with 10 to 20 meters deep tubes, then extend them up to 100 meters (Blamont 2014: 2143). Blamont also suggests how the settlements should be made: there would be two different tunnels at the bottom of the deep spaces, two tunnels in opposite directions, the first one for social, private and housing functions, the second one would be the place for industrial activities, recycling processes and commercial functions. The cave entrances could be used as a place for photovoltaic panels, land zones for spaceships, depos of rovers for surface mobility and communications systems to the Earth (Blamont 2014: 2144). He gives a detailed description of the colonisation process; robots and automatic systems will play an important role in his vision of discovering and creating new colonies. The energy needs of the settlements should be managed with nuclear power, which needs fewer materials but can produce enough energy (Blamont 2014: 2143).

Another challenge related to these techniques is energy production, which is likely to be covered mostly by solar power, but for backup, nuclear power, for example a Liquid Fluoride Thorium Reactor is a wise choice according to recent research (Thangavelu 2014: 22; Arnhof 2016: 3). And even with these available technologies, it is likely that the colonisation of a planet will be divided into three major phases: in the first phase, robots are going to prepare the surface for the first human habitats; in the second phase, the first bases and the basic infrastructure are going to be set up; and in the third phase, the large scale colonisation and the development of cities and societies will take place (Arnhof 2016: 7). These three steps can be observed both in the NASA's Lunar Exploration Program, called Artemis Plan (NASA's Lunar Exploration Program Overview 2020), and in the plans of the International Lunar Research Station, which is set to be built in partnership led by China and Russia (International Lunar Research Station 2021).

Feeding the first settlers, and later entire colonies is another significant challenge, especially if we not only think about the Moon but Mars too. The latter one is not only further away, but its perchlorate containing regolith is also much worse for plant growth than Earth's soil (Oze et al. 2021). However, experiments have already been constructed both on Earth (for example in China) and on the International Space Station. The results have shown that the plant with the best features is kale, which could be grown in space or on different planets with simply water and red and white LED lights (Gibney 2018: 478). Feeding people is the most important question for the colonies, to maintain a long-term settlement it is crucial to start to grow food locally, this way minimising dependence on Earth (Cannon–Britt 2019). Cannon and Britt investigated a model to show how can the population of a Mars colony reach one million people. The three main key factors are planet-based food, insect farming and cellular agriculture.

In his work, Haym Benaroya attempts to give a general summary of the scientific discussion and debates on the Moon's exploration. In the first two chapters of the book, Benaroya overviews the history of the research and scientific expeditions related to our only natural satellite. He reflects on the main challenges of the tremendous enterprise, the Moon's colonisation, such as economic, ethical and environmental questions. In the fifth chapter, among others, we can read about the urbanistic, psychological and sustainability-related questions of the lunar settlements.

While the colonisation of a new planet holds enormous opportunities, that humanity has never had before, it also comes with a huge responsibility. This includes the amount of money and time spent on preparing the missions to a new planet, which could have been spent on saving people's lives on Earth or even the ecosystem of our mother planet. Moreover, it also includes the question of how humanity tries to tackle the wide range of challenges presented by the extraterrestrial environment: do we try to modify the genetics of chosen people in a way that they will be more resilient to the possible difficulties (human [bio]enhancement) or do we try to modify the extraterrestrial environment to the point where it becomes habitable (geoengineering) (Balistreri–Umbrello 2023). As technologies related to both solutions are getting more advanced, we have to address the ethical, legal and moral questions of both methods. Scientists who support geoengineering state that any genetic reprogramming project of human beings would represent an unacceptable violation of the principles the liberal-democratic societies are based upon (Habermas 2003: 66). They also assume that the more we modify people, the more they lose their human nature and become less connected to human societies (Sandel 2007: 86). Moreover, if genetically modified people would colonise another planet, there is a chance that over time they would become so much different than the humans on Earth that we would lose the coherence of our species (Fukuyama 2002: 101). On the other hand, many scientists disagree with these opinions and support human (bio)enhancement. They state that the economic costs of modifying the genetics of astronauts are much lower than modifying the environment of an extraterrestrial planet. Moreover, just like each human, each planet is unique and special in its attributes or in the way it was formed, and by modifying or destroying any parts of it, we could delete a valuable piece of our universe. Even if at the moment a material or an object seems worthless, we cannot predict how much we will need it in the long term. All in all, it is undeniable that whichever of the two we choose, we will have to take into account the possibility of serious downsides, and as a result of this, the best method is probably to evaluate case-by-case which solution is better (Balistreri–Umbrello 2023). Nevertheless, despite Fukuyama's opinion, it is likely from a biological point of view that natural evolution will change the physical and mental attributes of the colonies' inhabitants in small steps from generation to generation. The time will come when these cumulated changes after generations of reproductive isolation are so significant that these humans can be considered members of a new species ("Homo Extraterrestrialis") (Smith–Davies 2012: 28).

Moon is closer to our planet, it is much easier and cheaper to settle there than on Mars, and it can also serve as an experimental area for later missions to other planets (Szocik et al. Wójtowicz–Braddock 2020: 7). The former leader of the European Space Agency (ESA), Johann-Dietrich Wörner came up with the 'Moon Village' concept. Briefly, he imagined that in the near future, there would be a Moon Village, which would serve as a place for experiments, and replace the role of the current International Space Station (ISS) (Köpping Athanasopoulos 2019). He avoided using the word base or colony, because he can hardly believe that there would be any intentions to settle on other planets permanently. In his opinion, the 'village' word does not represent a project, but something which is maintained by the common interest of actors, in this case by the governments, private companies, etc. International cooperation would be necessary to maintain a certain order there (Köpping Athanasopoulos 2019).

ECONOMIC ISSUES

One cannot ignore the exciting economic issues that arise as regards expansion to other planets.

In case of tremendous and extremely capital-intensive investment projects such as Moon expeditions, the return rate is a critical issue. As Benaroya writes, according to recent studies the return rate of great research and development enterprises and investments is quite high. These projects incentivise the investors' R&D activity and give them a significant technological advantage in the global economic competition. Furthermore, an extraordinary and unique undertaking such as the colonisation of the Moon can provide access to new natural resources and can open a completely new market, the economy of lunar settlements for investors (Benaroya 2018: 22).

To finance expeditions to colonise the Moon, experts say it is essential to bring together public and private capital in some kind of PPP structure. Recent examples of private capital in the space industry have highlighted the limitations of this type of financing (more limited amount of money, shorter expected payback period), making it clear that public funding will be essential in the future. The plans for cooperation for lunar deployment also envisage a combination of both types of capital and a strong predominance of public funding, while maintaining the possibility of a more mixed financing landscape for lunar investments in the future (Benaroya 2018: 22).

One of the most interesting economic and organisational suggestions of recent years as regards extraterrestrial settlements is a framework called Lunar Development Cooperative (LDC), which is worth noting in a little bit more detailed way.

In their article, the authors of the LDC concept describe their vision for a company–cooperative organisation called Lunar Development Cooperative (LDC) which would operate as a public–private partnership. The LDC's main goal is the fair and sustainable development of the Moon during its human colonisation. By functioning as a joint-stock company, LDC would be open for public and private actors of the world's economy. Any of them could buy a share in the LDC above the minimum price of 1 $. Fifty-one percent of the stocks would be opened for private actors such as companies or individuals, so the states could receive an aggregated share of 49%. None of the shareholders could have a share bigger than 10%. The developing countries could buy special options which are reserved directly for them. As a result, monopolisation and too dominant national interference could be avoided (Castle-Miller et al. 2020).

During the first phase of lunar colonisation, the LDC would operate as an actor which provides all the crucial services (heating, electricity, energy, security etc.) for the growing settlements at a nominal price. Besides the individually accessible services, the LDC would sell site utilisation licences.[6] (Later, by lowering the prices of the individually accessible services, these site utilisation licences would provide the majority of the LDC's income). The owners of these licences would be entitled to use the LDC's services for a certain fee on the designated investment sites for a certain period. At the end of this period (40 years at most) the licences would be sold again, but the former owners would hold their property connected to the licenced site in any case. Those who do not buy LDC licences could use the sites too, but the LDC's services would not be available for them. However, it would not be obligatory to be a shareholder of the LDC or buy its licences, the authors predict that the company's efficiency and wide range of supply will mean tremendous advantages for the shareholders and customers. It might persuade the other actors to join them (Castle-Miller et al. 2020).

The main decision-maker organisation of the LDC is the board of directors which would be elected by the shareholders. Besides the board of directors, the board of advisors would have a significant role in the company's functioning. To this board, every nation and indigenous group could send deputies to provide worldwide control over the LDC's activity. Anybody could claim against the LDC at any court on the Earth or on the Moon. The company's inspector general would have special access to any documents related to the LDC's work. The company's internal rules are determined by the shareholder's agreements which guarantee that the company will function according to the principles of good governance and that its work will be in humanity's best interests. The LDC would strongly support the implementation of the Outer Space Treaty of 1967 and provide equal conditions for any state to access the possibilities of the Moon's exploration (Castle-Miller et al. 2020).

By providing its services, the company could become an indispensable component of the investment and development processes on the Moon. By founding the LDC, the serious conflicts of the colonial era would not occur

[6] Of course the authors' suggestion would imply a change of the international legal environment as regards the Moon. But instead of current regulations, their focus is on practical solutions that could be followed by lawmaking processes.

again on the Moon. The LDC would endorse the development of clusters and settlements with strong, diverse and resilient economies. Moreover, as the LDC is strongly interested in the thriving and attractiveness of the Moon's investment sites, the company would force the investors and developers to work by preserving the local environmental values and using natural resources sustainably. In summary, the LDC or a cooperative similar to it could provide us with the possibility to explore and populate the Moon efficiently, sustainably and fairly (Castle-Miller et al. 2020).

THE PRINCIPLES – HOW TO DESIGN A PERMANENT SETTLEMENT ON MOONS AND OTHER PLANETS?

As we can read in the literature above, the thought of habitats, settlements, colonies and towns on other planets does not fail to fascinate researchers all around the world. Based on these works, human history, lessons learned from habitats in extreme environments and our own experience in the Hungarian Urban Development Association, we can identify and suggest essential principles that can be applied to any planned settlements on other celestial bodies. These principles could help with creating and maintaining thriving settlements.

Each principle is followed by a short explanation in the following section. Due to the complex nature of human dwellings and settlements, some of the principles might overlap to a certain extent. Of course, it is unavoidable in this field but we believe that distinguishing between the focuses of the principles will help to better understand.

SUSTAINABILITY

Becoming a multi-planet species gives humanity the possibility to avoid mistakes of the past on Earth, such as the building of unsustainable settlements and urban structures that overuse natural resources, and foster social tensions and economic declines. Therefore, we suggest the concept of sustainability as a stepping stone.

A great responsibility of humanity during the colonisation of a planet is to make it as sustainable as possible for both the Earth and the planet in question, paying attention to all three pillars of sustainability. The concept of sustainability – especially its environmental pillar – is often connected to biological ecosystems, but in the context of planet colonisation, it is also important to take into account the mindset of sustainable development. The economic pillar is important even in the short term because the colonisation of a planet is only likely to be successful if it is profitable in the first habitats. As an already existing example, the term 'space sustainability' first appeared in the second half of the 20^{th} century, when it referred to the lifetime of the different hardware and technologies sent into space, and to the financial and political difficulties of space programs, as illustrated by the cancellation of the Apollo lunar program (Newman–Williamson 2018: 31). Environmental sustainability is also important because those who arrive later should have the same variety and quantity of resources (at least roughly) as the first settlers. Additionally, this pillar is also important if we take into consideration the complexity of the consequences of discovering and meeting with extraterrestrial organisms (aliens). Researchers have already highlighted the importance of planetary protection, which includes "forward contamination" (the contamination of other solar system bodies by Earth microbes and organic materials) and "backward contamination" (the contamination of Earth systems by potential extraterrestrial life) (Conley–Rummel 2010: 792). Finally, social sustainability is not considered in current space programs, but in the long term, if we want to build independently functioning colonies, social cohesion and diversity will become a major factor (Table 1).

Table 1
The sustainability of planet colonising regarding its three pillars

Pillars of sustainability	**Economic**	**Environmental**	**Social**
What does it mean in case of colonising planets?	The colonisation produces enough financial value to cover the expenses, so it does not set back any future colonising projects.	The latecomers or second generation of settlers have the same resources available as the first settlers.	A society that is diverse enough to be able to function and reproduce itself isolated.
When is it important?	Short-, mid- and long-term	Mid- and long-term	Long-term
Main benefits it gives	It enables keeping up the support from Earth and other colonies to the new colony, it enables new colonising projects and expeditions in space.	Makes sure that there will be a liveable planet for humanity even if Earth becomes unliveable.	Avoiding ghost space colonies, enabling the support of the project(s) of the whole population of Earth, the colony(ies) can survive (and grow) without new people coming from Earth (or space).
Challenges of achieving it	Most of the current technologies are far from profitable, they are usually supported by governmental programs and accidents can cause the shutdown of whole programs.	We do not know what needs to be conserved, or even what is going to be the reaction of the planet to the first colonies, societies, pollution.	It requires cooperation from different Earth nations, not every person will be able to travel in space.
Possible solutions	Better technologies, non-governmental companies investing and making profit in the sector.	Defining the neutral environment on a planet, finding and monitoring the key aspects.	Making the groups–crews of the missions diverse in different aspects (social background, profession, gender, nation, age).

Pillars of sustainability	Economic	Environmental	Social
How can working on the solutions help life on Earth?	Developing more cost-efficient solutions encourages innovation and can lead to technologies that can solve the problems of people living on Earth.	Inventing methods and technologies that minimally damage the environment of different planets could help in saving the Earth's ecosystem.	Populating a different planet would significantly increase the survival chances of the human species and our civilisation.

Source: Compiled by the authors

Just to give an example, let us see what the principle of sustainability would mean in practice: planners of these settlements must emphasise the prospects and needs of shared public transportation modes instead of energy and place consuming individual transportation, so they have to elaborate the master plans accordingly.

THE IMPORTANCE OF LOCATION

History teaches that settlements with a monoculture economy are fragile and are prone to abandonment. That was the fate of ghost towns after the gold rush era or the reason behind the urbanistic depression in Detroit. Successful and sustainable towns and cities are built and developed on more advantages and perks. That is why the choice of the location must be carefully considered well before the landing of the first habitat module.

Requirements of the settlement location:

- Possibility of producing water. This would primarily mean ice, groundwater, water attached to regolith or water reserves in deeper layers. Water is an essential part of the life support system and a possible resource for propellant.

- Presence of mineable metals and rare metals. These elements are also dual-purpose. They can be used as in-situ resources for the structures or equipment of the colonies and they will also be export products to Earth or other colonies. The source of income generated can be used to finance the founding and maintenance of the settlement.
- Enough sunlight. Like almost everything in isolated extreme environments sunlight also serves more than one vital cause. First, a settlement should not rely only on nuclear power (see redundancy principle later[7]). Instead, it needs to be able to utilise solar power, too both for critical infrastructure and mobile equipment (e.g. rovers, machines, drones). Second, places without sunlight are extremely cold environments both on the Moon and Mars (this is true for an overwhelming part of the Solar System), therefore, creating and maintaining habitats in these dark places would mean disproportional costs. Third, we humans psychologically need to see natural light from time to time to keep our sanity in the long run.
- Places where mountains and hills meet plains and flatlands are preferred. Different geological formations usually mean more possibilities such as resources, observation and communication points and natural shelter. Shelters can provide further protection from heavy storms, dust storms, radiation or an attack. Later when the process of civilisation advances and there are more settlements and mining outposts, these locations at the foot of the hills and mountains can serve as trading hubs as well because spacecraft are more likely to be able to land on flat lands.
- Presence of natural caves or suitable locations for artificially built caves and tunnels are preferred. In the first era of extraterrestrial settlements, it is crucial to utilise these caves and tunnels to provide enough protection from radiation. Parts of the first colonies will likely be located underground, protected by a thick layer of regolith.

7 The basic principle is that the settlement must have more than one source of energy, water, food and communication method.

- Lack of dangerous seismic activity. Planners have to minimise the risks to the integrity of the structures because the possibility of rescue missions and resupply of materials and equipment is considerably limited.
- The presence of deep canyons is preferred. This is an optional requirement but it is worth paying attention to the opportunity. With proper radiation and impact shielding on the top, these canyons can be transformed into auxiliary habitats because they provide better protection from nearby meteor impacts, surface blasts and shockwaves than surface structures.

It follows from the location principle that careful examination and evaluation of the potential settlement spots are essential. This long process should start way before the first spacecraft would be able to be commissioned for the first phase of the establishment of an outpost. The process involves a great deal of exploration missions, scanning of the area with probes and beginning of constant monitoring as soon as possible. The more data we have the higher the chance that we can minimise the risks by choosing a secure location. This is crucial because a poor choice results in loss of life and a tremendous amount of resources.

REDUNDANCY AND PROTECTION

Given the impossibility of immediate rescue and resupply missions, these settlements must be resilient against a lot of effects.

The literature agrees that every colony must have shelters against extreme radiation, storms or meteor impact events; therefore, it is likely that some parts of these habitat structures will be located underground. We have to remember that equipment malfunctions, fires, etc. are also risks we cannot ignore.

The designs must take into account that parts of the colony have to be able to work even if others do not. Therefore, settlements must have more than one energy source (moreover, solar panels, reactors and other energy sources should not be in the same place) and should also have alternate cable roots to consumer buildings. The same is true for oxygen, food and water producers, storage and transporter facilities. The underground part of the colonies should have life support and other systems that can remain functional even if the surface modules–domes are lost or have to be cut from the grid.

Hygiene and isolation capabilities are also vital parts of urban planning because a pandemic could cause severe problems. The colony must be able to function and operate even with one part locked down.

Planners should not forget about connection–date resiliency either. Not only because of the obvious reason that humans can communicate with each other on that planet or with other planets, but because construction, repair and maintenance will be partly robotised, and a lot of data exchange will be needed to coordinate the robot swarm. For these reasons Internet–Lunarnet–Marsnet is necessary, possibly with satellite technology that helps geolocation as well. The net has to have reserve satellites and reserve ground facilities.

RECYCLING

History shows that great civilisations cannot thrive if they are not able to handle their waste. That is why recycling and waste management are a main pillar of successful and healthy settlements. This is especially true in case of settlements outside Earth due to the scarcity of resources. The literature also agrees that recycling water, waste, nutrients and oxygen is key for the survival of these outposts.

RESEMBLANCE

Humans are not robots. Besides the basic life functions, we have recreational, mental and spiritual needs to preserve our health. This implies that the design of successful long-term settlements must reflect our needs as human beings.

This means that the settlements have to remind people of the features they love about their home on Earth. Nowadays every experienced urban planner knows that humans need different kinds of spaces in order to feel comfortable. Therefore, the designs have to contain community places where residents can have a chat, relax or have parties and feasts. Parties and feasts are not typical words to occur in space science literature, but having these festive gatherings is one of the most ancient traditions of humankind and as such it cannot be ignored because it is rooted so deep in our culture. We also need the sight of nature and plants of some kind. Research proved that it enhances both mental and physical health. What is more, people need to see wide horizons, scenic views and the sight of the sky from time to time. We also need spaces of spiritual recreation for a completely soothing and comforting environment. It follows that soulless base designs with only purely functional modules for work, research, maintenance, sleep and nutrition are going to ultimately fail in the long run.

FINANCIAL RETURN

Any space mission, especially the establishment of permanent habitats on other planets costs a huge sum of resources. We have to accept that these costs cannot be sacrificed only from taxpayers' money and donations. Earth's history taught us that financial incentives lead to the involvement of the private sector and as a result, the whole process of expansion becomes a lot faster (enough to think about the history of trading outposts of the Dutch East India Company). We argue that these settlements have to have competitive yields and return on investment in accordance with the economic sustainability principle above. To reach this, a special economic zone system is unavoidable, partly for incentive purposes and partly because other planets are special areas in international law as well.

What could generate income in or for these settlements and communities in the first decades far away from Mother Earth that can be incentives for investors?

– government subsidy
– research time and facilities
– intellectual property rights
– mining
– video streaming and ads
– tourism

We think it is likely that in the first years, the main product of these settlements will be the results of scientific activity such as patents and intellectual property rights. That is why – like in the case of every successful civilisation – only a small portion of the population's task shall be the providing of basic needs (food, life support system). This also creates the need for the intense use of technology and AI in maintaining, repairing and monitoring structures and machinery because communication with Earth for instructions is time consuming and in the first years there will not be enough people in the colony to have professionals for every situation imaginable.

In case of the Moon, high-end tourism can also generate a significant amount of income that would contribute to economic sustainability. Tourism on Mars is only realistic if technological advancements make it possible to reduce travel time significantly.

CAREFUL SELECTION OF SETTLERS

Becoming a multi-planet species is one of the greatest endeavours of humankind. The survival of our species and civilisation depends on it and it requires the use of almost unimaginable amount of resources. Simply put, there is too much at stake and we have to conduct a careful and rigorous process of choosing crews and settlers. Populating other planets is not a place for uncontrolled migration or amnesty–prison camp like colonisation as we saw in Earth's history earlier. Successful training, useful skills, mental stability and a clean criminal record are basic requirements for would-be inhabitants. The selection process should be based on merits gained during training on Earth. Besides the common skills and knowledge, members shall have diverse individual skill sets that help with keeping thriving settlements. The groups shall be balanced in terms of social background, nationality, gender and age (to a certain extent).

NO WEAPONS

At present, according to the best knowledge of the scientific community, we do not know any species on other celestial bodies in the Solar System that endangers humans and can be fought with weapons besides humankind itself. It follows that if there were weapons in these settlements they would probably only harm humanity and these settlements, not protect them from an unknown threat. Considering the stunning costs weapons can cause in these extreme environment settlements we argue that international cooperation should ensure that these settlements remain free of weapons. The issue must be revisited if new species appear that are a direct threat to human life and are vulnerable to weapons. We emphasise this principle from a practical point of view as we are sceptic to a certain extent as regards the long-term compliance with any international space treaties on the peaceful use of space and celestial bodies. History shows that compliance with this kind of international treaty is rather a matter of technological possibilities and balance of power among the actors than the rule of law due to the lack of effective international bodies to enforce them.[8]

[8] We have to note that the weaponisation of space has already started. For example, modern military reconnaissance and guidance systems rely on devices in orbit to a great extent. Nevertheless, further military researches also seek the possibility of conducting attacks from or in space partly against these devices controlled by hostile forces.

EVOLUTION

As time passes and one generation follows the other, the effects of biological evolution will also appear in these settlements. According to our knowledge of the history of evolution, we are certain that the genome of the inhabitants will transform even without genetic engineering. At some point, this transformation will cross the point where we can call these people new species. This implies that the needs and requirements for these people's settlements can be very different from the principles we design settlements. Therefore, designs and thinking should have the possibility for flexibility and be open to changes from time to time.

CLOSING REMARKS

Becoming a multi-planet species seems unavoidable if humankind intends to survive. We are at the dawn of the era which marks the beginning of this transformation process. The enormous technological and biological challenges tend to eclipse the questions that need discussion as regards the way of human life and society in the long term outside planet Earth. That is why we think it is important to have a discussion about design principles, societal and economic viability of the settlements and environment that humans will call home in the future. Based on other authors' expertise and our experience in urban planning, we offer some basic principles that could help with designing resilient settlement structures on other celestial bodies. These principles are:

- sustainability
- location
- redundancy and protection
- recycling
- resemblance
- financial return
- careful selection of settlers
- no weapons

We believe that keeping these principles in mind will help create the experience of home for the generations to come.

REFERENCES

ARNHOF, M. (2016): *Design of a Human Settlement on Mars Using In-Situ Resources.* 46th International Conference on Environmental Systems, 10–14 July 2016, Vienna.

BALISTRERI, M. – UMBRELLO, S. (2023): Modifying the Environment or Human Nature? What Is the Right Choice for Space Travel and Mars Colonisation? *NanoEthics,* 17(1). Online: https://doi.org/10.1007/s11569-023-00440-7

BENAROYA, H. (2018): *Building Habitats on the Moon. Engineering Approaches to Lunar Settlements.* Cham: Springer. Online: https://doi.org/10.1007/978-3-319-68244-0

BLAMONT, J. (2014): A Roadmap to Cave Dwelling on the Moon and Mars. *Advances in Space Research,* 54(10), 2140–2149. Online: https://doi.org/10.1016/j.asr.2014.08.019

CANNON, K. M. – BRITT, D. T. (2019): Feeding One Million People on Mars. *New Space,* 7(4), 245–254. Online: https://doi.org/10.1089/space.2019.0018

CASTLE-MILLER, M. (2020): Supporting sustainable lunar development. *Room: Space Journal of Asgardia,* 26(4). Online: https://room.eu.com/article/supporting-sustainable-lunar-development

CASTLE-MILLER, M. – ANZALDÚA, A. – DAYDSON, H. (2020): The Lunar Development Cooperative: A New Idea for Enabling Lunar Settlement. *The Space Review,* 27 April 2020. Online: www.thespacereview.com/article/3928/1

CONLEY, C. A. – RUMMEL, J. D. (2010): Planetary Protection for Human Exploration of Mars. *Acta Astronautica,* 66 (5–6), 792–797. Online: https://doi.org/10.1016/j.actaastro.2009.08.015

EHLMANN, B. L. – ANDERSON, F. S. – ANDREWS-HANNA, J. – CATLING, D. C. – CHRISTENSEN, P. R. – COHEN, B. A. – DRESSING, C. D. – EDWARDS, C. S. – ELKINS-TANTON, L. T. – FARLEY, K. A. – FASSETT, C. I. – FISCHER, W. W. – FRAEMAN, A. A. – GOLOMBEK, M. P. – HAMILTON, V. E. – HAYES, A. G. – HERD, C. D. K. – HORGAN, B. – HU, R. – JAKOSKY, B. M. – JOHNSON, J. R. – KASTING, J. F. – KERBER, L. – KINCH, K. M. – KITE, E. S. – KNUTSON, H. A. – LUNINE, J.

I. – Mahaffy, P. R. – Mangold, N. – McCubbin, F. M. – Mustard, J. F. – Niles, P. B. – Quantin-Nataf, C. – Rice, M. S. – Stack, K. M. – Stevenson, D. J. – Stewart, S. T. – Toplis, M. J. – Usui, T. – Weiss, B. P. – Werner, S. C. – Wordsworth, R. D. – Wray, J. J. – Yingst, R. A. – Yung, Y. L. – Zahnle, K. J. (2016): The Sustainability of Habitability on Terrestrial Planets: Insights, Questions, and Needed Measurements from Mars for Understanding the Evolution of Earth-like Worlds. *Journal of Geophysical Research: Planets,* 121(10), 1927–1961. Online: https://doi.org/10.1002/2016JE005134

Ellery, A. (2020): Sustainable In-Situ Resource Utilization on the Moon. *Planetary and Space Science,* 184. Online: https://doi.org/10.1016/j.pss.2020.104870

Fukuyama, F. (2002): *Our Posthuman Future. Consequences of the Biotechnology Revolution.* New York: Farrar, Straus and Giroux.

Gibney, E. (2018): How to Build a Moon Base. *Nature,* 562(7728), 474–478. Online: https://doi.org/10.1038/d41586-018-07107-4

Habermas, J. (2003): *The Future of Human Nature.* Cambridge: Polity Press.

Harris, R. A. (2003): *HUMEX. A Study on the Survivability and Adaptation of Humans to Long-Duration Exploratory Missions.* ESA SPR 64.

Haruyama, J. – Morota, T. – Kobayashi, S. – Sawai, S. – Lucey, P. G. – Shirao, M. – Nishino, M. N. (2012): Lunar Holes and Lava Tubes as Resources for Lunar Science and Exploration. In Badescu, V. (ed.): *Moon. Prospective Energy and Material Resources.* Berlin–Heidelberg: Springer. 139–163. Online: https://doi.org/10.1007/978-3-642-27969-0_6

Howard, A. D. – Moore, J. M. – Irwin, R. P. III (2005): An Intense Terminal Epoch of Widespread Fluvial Activity on Early Mars: 1. Valley Network Incision and Associated Deposits. *Journal of Geophysical Research: Planets,* 110(E12), 1–20. Online: https://doi.org/10.1029/2005JE002459

Hörz, F. (1985): Lava Tubes: Potential Shelters for Habitats. In Mendell, W. W. (ed.): *Lunar Bases and Space Activities of the 21st Century.* Houston: Lunar and Planetary Institute. 405–412.

International Lunar Research Station (2021): *Guide for Partnership.* Online: www.cnsa.gov.cn/english/n6465652/n6465653/c6812150/content.html

Köpping Athanasopoulos, H. (2019): The Moon Village and Space 4.0: The 'Open Concept' as a New Way of Doing Space? *Space Policy,* 49. Online: https://doi.org/10.1016/j.spacepol.2019.05.001

Léveillé, R. J. – Datta, S. (2010): Lava Tubes and Basaltic Caves as Astrobiological Targets on Earth and Mars: A Review. *Planetary Space Science,* 58(4), 592–598. Online: https://doi.org/10.1016/j.pss.2009.06.004

Matt, Z. – Gertsch, L. – Abbud-Madrid, A. – Blair, B. – Zacny, K. (2011): *Real-world Mining Feasibility Studies Applied to Asteroids, the Moon and Mars.* AIAA SPACE 2011 Conference & Exposition, 27–29 September 2011, Long Beach, California. Online: https://doi.org/10.2514/6.2011-7115

NASA's Lunar Exploration Program Overview (2020): *Artemis Plan.* Online: www.nasa.gov/wp-content/uploads/2020/12/artemis_plan-20200921.pdf?emrc=f43185

Newman, C. J. – Williamson, M. (2018): Space Sustainability: Reframing the Debate. *Space Policy,* 46, 30–37. Online: https://doi.org/10.1016/j.spacepol.2018.03.001

Oze, C. – Beisel, J. – Dabsys, E. – Dall, J. – North, G. – Scott, A. – Lopez, A. M. – Holmes, R. – Fendorf, S. (2021): Perchlorate and Agriculture on Mars. *Soil Systems,* 5(3). Online: https://doi.org/10.3390/soilsystems5030037

Sandel, M. J. (2007): *The Case against Perfection. Ethics in the Age of Genetic Engineering.* Cambridge, Mass.: Harvard University Press.

Smith, C. M. – Davies, E. T. (2012): *Emigrating Beyond Earth. Human Adaptation and Space Colonization.* New York: Springer. Online: https://doi.org/10.1007/978-1-4614-1165-9

Stenzel, C. – Weiss, L. – Rohr, T. (2018): Sustainable Challenges on the Moon. *Current Opinion in Green and Sustainable Chemistry,* 9, 8–12. Online: https://doi.org/10.1016/j.cogsc.2017.10.002

Suchantke, I. – Letizia, F. – Braun, V. – Holger, K. (2020): Space Sustainability in Martian Orbits – First Insights in a Technical and Regulatory Analysis. *Journal of Space Safety Engineering,* 7(3), 439–446. Online: https://doi.org/10.1016/j.jsse.2020.07.003

Szocik, K. – Wójtowicz, T. – Braddock, M. (2020): The Martian: Possible Scenarios for a Future Human Society on Mars. *Space Policy,* 54. Online: https://doi.org/10.1016/j.spacepol.2020.101388

Thangavelu, M. (2014): Planet Moon: The Future of Astronaut Activity and Settlement. *Architectural Design,* 84(6), 20–29. Online: https://doi.org/10.1002/ad.1828

Wójtowicz, T. – Szocik, K. (2021): Democracy or What? Political System on the Planet Mars after Its Colonization. *Technological Forecasting and Social Change,* 166. Online: https://doi.org/10.1016/j.techfore.2021.120619

Gábor Bihari[1] – Tamás Sipos[2]

Building a New Colony
The Challenges of Architecture
and Inflatable Structures

INTRODUCTION

Travelling the wider outer space has always been a dream of humanity. At the very beginning of recorded history, philosophers and thinkers looked up at the night sky of their time and wrote down with great curiosity whatever tiny lights they found. They followed the movements of these shiny dots and guessed their origins. Later, others simply wanted to go to another place, which meant crossing a river or an impassable ravine. No bridge was to be found for miles, so they began to dream of a new way of transporting their goods to their destinations. Flying.

In the West, it all started with ancient Greek mythology and was followed by other thoughts and plans through the Middle Ages till the beginning of the 20th century when an engineered tool was born and brought a new era in the history of mankind. This was just the first step in a way to conquer the skies but also led to the dream of leaving the Earth's breathable layer. Nowadays, technology has already reached the level to get tourists regularly and safely outside of the Earth's atmosphere and return them. Furthermore, the next destination has already been set, sending people to the Moon and maybe later to Mars.

1 Author of the Inflatable Structures subchapter. University of Debrecen, Department of Experimental Physics; e-mail: bihari.gabor@science.unideb.hu
2 Author of the Introduction and the Basic Principles subchapter. Dipl.-Ing MSc; e-mail: tamas.sipos@zt-sipos.at

DOI: https://doi.org/10.36250/01209_05

BASIC PRINCIPLES OF CONSTRUCTION – LESSONS LEARNED ON EARTH

This chapter aims to make the challenges of architecture for establishing a permanent human presence on another planet more approachable, and more understandable. To approach this problem, architects use the laws of physics, mathematics and the technologies and experience gathered here on Earth. If the exponentially accelerating rate of development of New Space continues, the next challenge will be the housing of people in newly set communities on another planet. Maybe we will name this settlement after someone, who has not yet been born, but will be sent with an expeditionary spaceship to discover new planets and to begin to build new settlements for future generations.

However, the method to reach that location, and the location to create communities on the surface of new planets are still far away and unknown. There were a lot of scientists and thinkers, already back in the 1970s, who were playing with the idea of building permanent facilities for humans under different space circumstances (Johnson–Holbrow 1977).

As the current state and goals of space programs predict, a permanent facility can be built first on the Moon. To construct any in-situ structure far away from the main supply source – Earth – makes solving difficulties a top priority. In such a case, we are talking about some prefabricated container-like rooms that meet the requirements of the Moon, and need to be assembled on site. In the beginning, these will be delivered from Earth to the Moon onboard space cargo vehicles with limited weight and size capacity. At the moment, the SLS rocket used to launch the Artemis I mission (and planned for Artemis II and III) can get around 27 tons of payload with a trans-lunar injection manoeuvre to the Moon. An average five-seater passenger car weighs around 1.5 tons, while a pick-up truck can weigh 2.5 tons. Ten pick-up trucks and one passenger car do not contain that much material in case the aim is to establish a building. If we only talk about metals in their simplest form, one cubic meter of steel weighs 7,850 kg. Titanium is 4,500 kg/m^3, while aluminium is 2,710 kg/m^3. But this is a solid block of metal, and the payload we want to get there is not a homogenous material, but rather all kinds of equipment. This could be good news on the weight side, but not on the size of the equipment, which is also limited. The equipment also needs to safely land on the target planet, which means the payload needs to include a landing module and propellant. The only good news might be that the material transported to the Moon will not need to leave the surface of the planet and get back to Earth.

However, the launch costs for SLS are approximately USD 2 billion. This shows how expensive it is to get materials on the Moon; it also shows the engineering challenges to get light-weight but still very durable and effective equipment to our celestial companion; and underlines how decreasing the launch costs with reusable rockets is of crucial importance.

Based on our experience gathered on Earth and considering the limitations, compact, durable, low-maintenance and highly effective machines, tools, energy sources and equipment need to be taken to the construction site. A modular container system could be suitable for such purposes. As a next step the building site, based on previously gathered data, shall be chosen and set ready to accommodate these containers. After the decision is made on where the containers are to be installed, a soil analysis draws the layers of materials under the designed floor level and sets the parameters of the existing load-bearing capacity of this ground. When the structural analyses of this chosen land are ready and give a positive result to take the forces without any harmful settings of the soil, a correct method of the foundation shall be chosen. This foundation is for the very first time also prefabricated and with space cargo delivered skid-like foot, on which the facility containers *(Figure 1)* are to be mounted.

The prefabrication of such skid structures with those containers in a factory on Earth also requires a well-organised training method for the complete installation on the Moon with the adequate number of astronauts. Personnel must be trained on Earth, and as a result, they will be astronauts, but also skilled in construction and able to improvise building solutions and solve easy or slightly difficult problems during installation procedures.

Figure 1
Skid structure without cover
Source: Oilfield Service Company 2020

The site preparation on Earth is difficult and time-consuming only in extremely bad soil or surface conditions, in other cases it is a simple task to do before the first building process takes place, building the foundations. This same procedure shall be executed on the surface of the Moon with a relatively low or simple set of equipment. So, the start of the construction is the end of a well thought-out and carefully executed process, with all the necessary accessories delivered to the site.

There will be at least three different sites on the surface of the Moon. The one where all the astronauts will be stationed, possibly in a spacecraft. The second place where the construction will be mounted and finally a direct landing site where cargo will arrive and place the construction material. These places must be optimised in their layout, shortcuts and detours must be designated for a complete and uninterrupted flow of operation processes. Thus, as soon as every participant landed, all equipment unpacked, tested for functionality, the faulty ones got replaced, and the containers also arrived, the construction work can start.

To mount a skid structure, at least one vehicle with a scraping device is necessary to pull the lines next to each other to achieve a uniform surface and to reach the full load-bearing capacity of the ground layer. It is known that in many regions the upper layer of the Moon is made of regolith, which is composed of loose rock and dust that sits atop a layer of bedrock. Contrary to Earth, this does not contain soil, which is a biologically active medium. On the other hand, the Moon's regolith, due to a lack of sedimentary and erosive processes present on Earth, is made of particles which can be extremely sharp. Therefore, Moon dust can be extremely damaging to equipment and as a consequence, the protection of equipment and machinery is a unique problem. This layer needs to be removed or handled in a special way before installing any permanent building elements. Construction vehicles play a key role in the site refurbishing process. The internal uniform plane of the connected rooms in the containers can also be reached within the delivered structure with hydraulic hinges *(Figure 2)* without a uniform ground below, but that would mean extra cargo loads. The installation of a simple vehicle allows its use in the following deployments. Then the unused extra cargo load of built-in hinges can be added to deliver more essential equipment to the construction site.

Figure 2
Hydraulic hinge
Source: http://koltt.com/product/hydraulic-hinges/

This construction vehicle can also be a modular platform which enables the installation of different construction tools such as the mentioned scraper, a simple drilling device, or a crane which can help unload the arriving cargo ships.

Nevertheless, in light of the above, a simple question arises: why do we need flat planes in our transported, prefabricated container laboratories when horizontal–vertical relationships theoretically exist only in the pull of Earth's gravity, where the water level gives mankind a fix and an only reference point in any structure humans ever built. (The Leaning Tower of Pisa is an exception, but it is not used in the right way). There must be a reference point, the Zero, from where you can adjust any activity and process planned in the nearby vicinity. This Zero point determines the final position of the container units prepared for assembly. Even if their connection points and joints are designed to accumulate the hardest geometrical deviations and accuracy, having a Zero point is essential for further developments, corrections or positioning of additional parts or units. Furthermore, if there is a Zero point, an absolute reference coordinate on site of the first construction, the need to use it correctly and efficiently is inevitable and we all know its advantage in any case on Earth. This reference Zero must be created as the very first step with that particular vehicle and will be the second kind of construction element humans ever made in outer space. If we interpret the term in a broad sense, the first kind of 'construction' ever set up by humans on another planet was the rod of the American flag, stuck during the Apollo missions into the cover layer of the surface.

The first steps to mount the prefabricated units in a non-earth environment are done with all the preparation to level the site, the units are mounted together and the usage of these facilities can begin. As continued with some needed expansions of this site, other prefabricated units from Earth can be added. This can lead to a situation where the occupied area reaches its initial terrain limits. The construction vehicle with its terrain-forming shovel tool can easily form the next site by moving the regolith out of the way or handling it as the site requires. This loose regolith of the planet will be collected in a barrow or can be used as filling splits under the new units or set up as a natural barrier around the settlement to give some extra protection.

There is also a limit to predesign a settlement alone from Earth. At a particular size of the enlargement of some jointed skid container structures, an in-situ planning procedure is necessary to adopt. This extra procedure requires significant outlays and extended supply chains. Such necessity can occur, if the terrain turns unfavourable for the project, or the soil under the structure shifts properties. In-situ construction material production might also be necessary. Planning further developments right next to these first human settlements or an expansion of the existing structures (and after several reiterated essential supplements and maintenance parts of these functioning settlements), there will come a point when the decision-makers will realise that further site development with space cargo delivered from Earth is not sustainable anymore. This recognition can be measured by the costs of space cargo, the high frequencies of the supply journeys or the limited time effects for such critical parts of the structures. Therefore, numerous concepts, even for more than a decade, emphasise in-situ construction material building right from the start or the very early stages. One example is regolith foam which could also be used for radiation shielding (Hein et al. 2014).

To support the idea of such settlements with permanent human habitation, there are many well-established, existing examples in the most remote parts of the world, the Arctic and Antarctica *(Figure 3)*. These examples, with all the facilitated features of bases can be considered the starting set for any base or settlement on any planet. Of course, this starting set must be complemented or even multiplied by other service areas for scientists, who must be protected from the external environment in order to concentrate and carry out their scientific tasks. For the first company of such scientists, each incident will be unique and must be resolved promptly, professionally and without critical consequences for the continued use of the settlements.

Figure 3
Amundsen–Scott South Pole Station
Source: Wikipedia, Daniel Leussler, CC-BY SA 3.0

Reaching the limits of sustainable resupply of such Lunar bases from Earth is only a question of time. There must be parallel to all scientific research processes a secondary "back office" project, which prepares the base to turn into a self-sufficient habitat, where humans can be humans, men and women live together and form a tiny society with all the necessities of mankind. At that point, the supply connection between the colony's planet (not necessarily the Moon) and Earth would have only secondary meaning. The base can produce and supply most goods. Complete self-sufficiency would be of course much harder to attain.

Needless to say, a self-sufficient habitat complex cannot exist without a source with all the supplements needed for everyday life. The deliveries of all construction parts from Earth have already been completed, so any further expansion of a settlement depends on the properties of that explored planet humans choose to conquer. Suppose we check our timeline from the first skid container-like base to this sophisticated habitat complex, an undisturbed research program shall be discovered. This research program has one aim, and that is to find material in the vicinity which will be good enough to serve as construction material for the habitat.

By the time the built space for humans on a faraway planet reaches its limits, a lot of other scientific, social, legal, ethical, etc. questions must be solved. Only when questions, such as how the new society will look like, what kind of political system they have, are there religions or not, etc. have been answered, can humans live in that habitat long enough to start to use the new resources of the newly accommodated planet. To start a project which has a target that lies outside of the barriers of daily survival challenges, such as who is the leader, who makes decisions, what command routes to follow or is there enough energy reserves, a separated group of people shall exist, who can work independently. Their necessities for existence in an extraterrestrial environment must be provided by others, who can secure a surplus of any existential goods. This independent group of people can overcome the issue of new construction materials for the extension of the habitat without any supplement from Earth. To create a construction material from the surroundings, which can withstand all the challenges of that planet a well-equipped lab, some sort of a test site, lots of independent observation, time and most importantly, enough motivation is needed to continue despite all failures that are granted in any development program.

If we look around in our architectural world today, there are several building materials from which we can build our engineering environment. These materials come directly from nature, like wood and stone or from factories like masonry, concrete, steel or aluminium and their combinations. From this approximate list of materials, only wood and stone can be found as natural resources and these can be used immediately, only with limited additional preparation, as construction materials. That is why one of the first research programs shall be to find out the practical usage of any surrounding material on another planet.

There are programs and investments which are currently analysing the possibilities of using the Lunar regolith with in-situ methods as a construction material. Such investments include 3D printing or the methods used in the processes of the U.S. Army Corps of Engineers, according to a study by NASA focusing on space-based resources for deep space exploration (NASA 2024).

Back to the example of the simple Moon base with that modular vehicle. The vehicle could create a road between two sites (the landing site and home of the astronauts) or build a barrier from the soil of the planet against any currents, winds, etc. of the location. There is another way of using the surrounding regolith of a planet, which is selected for permanent habitat but has a harsh surface "weather" situation to dig into the soil. It is practical against high radiation arriving constantly from outer space. Unfortunately, it is not an optimal long-term solution but helps a lot to gain time for further research to find a way to build facilities on the surface. This version of the structure requires a high knowledge of the regolith or soil at a deeper level. It must be understood how this material will react if a hole is dug or how it reacts as soon as it gets a heavy load from an erected structure, all this in a long-term timeframe. In many cases on Earth, the soil will settle long after the structure is built and can cause damage in the building from a visible scratch to a fatal deformation in the load-bearing system. To handle these kinds of incidents, we have every knowledge and we can design every part of the endeavour to avoid these failures on Earth. Therefore, the regolith used for construction should be well known at the outset and there should be sufficient of that material nearby to be able to complete the project.

Considering all the factors mentioned above, the facility can also be excavated with mining machinery by digging into the deep as planned. In this case, the following issue shall be solved: the route of the mining machinery must be fixed with very massive supporters *(Figure 4).* In our everyday usage, it is concrete, wood or steel, but in a very large amount, so the newly dug path is safe against the collapse of the above layers.

Figure 4
An ordinary mine route supported with concrete arches
Source: DedMityay – stock.adobe.com

Another method to construct the new base on the surface (or half buried see *Figure 5*) and still use the protecting function of the regolith is the following: a load-bearing structure can be erected as a supporter, then the regolith can be added as a cover layer, as thick as it is needed for the radiation protection. The supporting structure shall be delivered from Earth, which must be strong enough to support the cover. Additionally, for this version of a belated construction of the protective soil layer, all elements of the base must have a radiation shielding layer, as opposed to the first version, where the base will be erected in the already protected tomb or tunnels.

Figure 5
A half-buried home
Source: Yiorgis Yerolymbos, Mold Architects (Barker 2022)

However, building structures and living continuously underground has significant biological and psychological side effects, and solving the problem of exclusion from sunlight can be as complex as finding a solution against radiation for building on the surface.

Apart from this initial use of the surrounding soil, for any other complex material, thorough research programs are needed to find possible and optimal solutions. According to our knowledge and everyday use, steel has very good properties, it is strong enough with relatively thin thickness and optimised geometrical cross-sections (I, U, L, etc.) to withstand torque, tensile or shear effects. Or reinforced concrete to withstand forces of high pressure because of its material consistency or also to withstand load-bearing moments or shear in any designed geometry an architect could imagine. But to be able to use these mentioned materials or create in situ such new building materials easily and readily, a very long and extremely complex parallel and independent development process must take place. These materials are available on Earth, but they are an end product of a very complex and sophisticated supply chain (or rather network) which takes a lot of time and effort to build and maintain. Establishing such a multi-layered and complex industrial base in situ will be extremely difficult if not impossible. Experience is also very important. On Earth, mankind has had to work on countless construction sites, where all the failures and negative properties have come to light and a wealth of experience has been accumulated. The Moon or any other planet has special circumstances and dealing with those with the limited resources available is a tremendous challenge.

Under ideal circumstances, in the first developing stages of extraterrestrial materials, the raw soil or stone samples would be transported to Earth, where scientists could create new construction materials and develop production processes optimised to the conditions of the planet. This includes all production steps from resource extraction, transport and manufacturing to energy supplies. The new materials would be the basis of any construction elements of any structural facility. These construction parts must be able to withstand the loads resulting from the load cases of simple building structures, taking into account local load factors, such as self-loading and additional dead loads (cladding, insulation, HVAC equipment, etc.), imposed loads such as variable loads resulting from the actual use of the structure, thermal loads depending on the circumstances of the new planet, fire loads or any accidental load that may occur during the lifetime of the structures (European Standards [s. a.]). Yet, humanity so far found it difficult to bring back samples for examination from distant planets. We have some samples from the Moon and asteroids, but none from Mars so far. To gather such samples is very expensive and takes a long time with our current technology. A more viable option could be to send robots to the location with onboard laboratories and analysing equipment and transfer the data back to Earth. The drawback is that these onboard laboratories may have a limited capacity and the replicated material created here on Earth would not be the same as on the other planet, it would not be subject to the same gravitational forces as on the other planet, etc.

After reaching the development level of manufacturing new construction materials and the possibility for wide-scale applications opens up, a planetwide construction project can be started. The essential attributes of those who will participate – or better said live – on that planet are the same as those who live on Earth. They need a place to live. After an exhausting shift spent in the research laboratories or their service facilities, these people also need a place where they can recharge for the next day or simply a place called home. Unlike in a scientific research laboratory where scientists only spend a certain time of their lives, these people on a planet will be born and die in those habitats and their lives will take as many twists and turns as those on Earth. These events also need facilities of similar quantity and variety to those on Earth. From a very small habitat base to a complex planetary city, there will be a need for residential areas, working places, health care and recreational places, culture centres, sports facilities, etc.

This base or independent base compounds connected via different routes will be so complex that implementing building regulations will become mandatory. The building regulations will be in power to minimise the risk to the safety of an individual living in the habitat and to annihilate all hazardous events which could lead to a malfunction of the base or turn it into a completely doomed space city.

To implement building regulations on these extraterrestrial habitats, the basic ideas of the regulations obtained on Earth can be used. In the everyday design process on Earth, the building is categorised according to the usage and planning and analysing the risk of having people inside or the importance of that building for the economy and public safety. A good example of such a complex facility is a building with different functions, an administrative building that shall be needed for housing more people. This kind of building scheme was developed in a project where the necessities of 1,000 people on Mars were the task *(Figure 6)*.

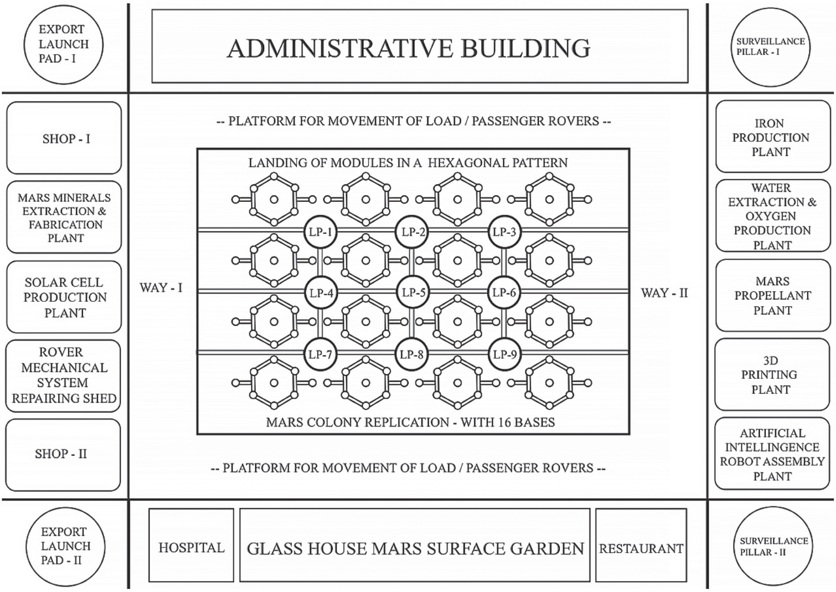

Figure 6
Facilities of a Martian colony
Source: Biswal et al. 2019

Knowing the extended boundaries for complex buildings is important for the detailed planning procedure and has a significant effect on the construction design. Such an example is to compare a single family house with a public building. The method to build a house for a family is based on their budget and the readiness and professional expertise of the construction company but it contains simple technical solutions and minimal living spaces. It is often built for a lifespan of approximately 50 years at most, but in this short lifetime, it needs to be renovated a couple of times. A public building with an expected capacity of 1,000 people has wider corridors, additional service spaces, greater rooms or an event hall which requires complex load-bearing structures. The extra housing services such as HVAC or electricity are also on a different scale and in all cases require additional spaces in the building. For such a structure all the required dimensions and building concepts are defined and with the correct execution, the building will have a much longer life-cycle. Similar and even more strict regulations will be needed when a large-scale construction or expansion starts on other planets.

After introducing the reader to some obstacles and basic principles of construction work, the chapter continues with the description of a possible solution for solving the weight and cargo space problem, while providing a good starting point for the base of operations at the early stages of a space colony.

INFLATABLE STRUCTURES IN SPACE EXPLORATION

Since the heroic age of space exploration, virtually every structure that has crossed the Kármán line and officially reached outer space has been built of metal. By the time of World War II, the durability, strength and lightness of aluminium and titanium alloys had supplanted almost all other materials in aircraft construction. Thus, when the first space technology developments were underway, all engineers and researchers naturally used these metal alloys to design and build spacecraft.

However, in the meantime, thanks to the progress of organic chemistry and plastic industry research, materials have become available that surpass these metals in many of their properties. Polymer plastics such as Kevlar or Dyneema are much lighter than the above metal alloys, but at the same time, their tensile strength is much higher than that of the metals. It is not surprising that these materials have found their way to space applications. However, they are currently used only as outer shells of metallic devices, where they act as a kind of "bulletproof vest" to protect the spacecraft from the damaging effects of micrometeorite impacts. Unfortunately, however, the protection cannot be perfect, as certain devices – solar panels or cooling radiators – cannot be covered with a cover made of such materials, as this would hinder their operation. However, reports of unprotected, and thus leaking cooling equipment clearly show that most spacecraft are effectively protected by these plastic covers.

Although even experienced pilots and astronauts are averse to structures made of plastic, development has now reached the point where the International Space Station has been boasting an inflatable plastic module for a few years now. The inflatable module of Bigelow Aerospace went into space in 2016 and docked with the space station. The largely empty module is serving mainly experimental purposes. On the one hand, the durability and pressure resistance of the structure can be checked during several years long use. On the other hand, this module also allows astronauts to get used to living in such structures when in space. In other words, the attachment of this module is intended to demonstrate that astronauts can safely use the volume provided by the inflatable modules for a long time and that their aversion to such an unconventional structure is just a habit that can be overcome.

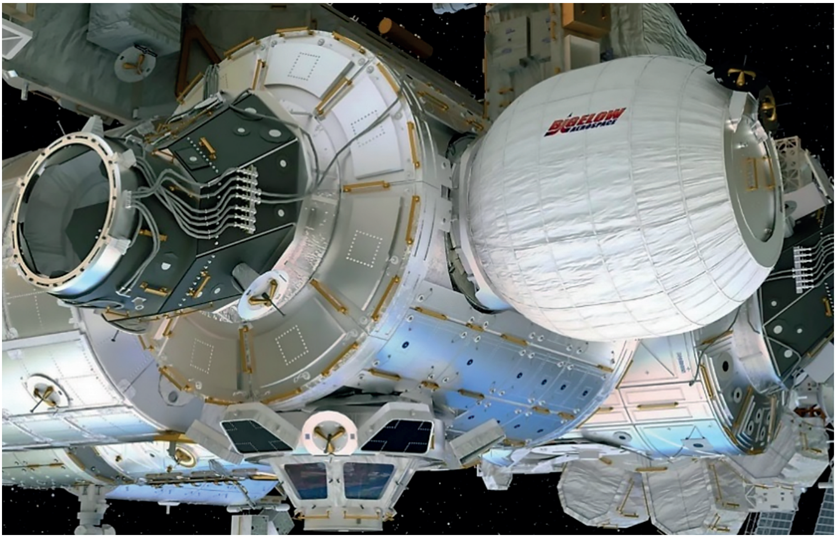

Figure 7
The inflatable module of Bigelow Aerospace docked at the ISS
Source: Foust 2022

Since the module of Bigelow Aerospace has been providing a stable and safe living space for ISS astronauts for 7 years, other private companies have also started to plan to launch such structures into space (Seedhouse 2014). When Bigelow Aerospace was liquidated due to the economic crisis during the Covid pandemic, a significant number of specialists were employed by the Sierra Space Corporation. So, it is not surprising that this company is planning to build the so-called Orbital Reef space station in partnership with the rocket manufacturer company, Blue Origin. This space station would consist largely of inflatable modules, with metal parts only in the structure connecting them. Sierra Space and Blue Origin plan to launch the parts of the space station into orbit in 2025 with Blue Origin's New Glenn rocket, which is supposed to be operational to that date (Williams–Mosher 2022).

The biggest concern regarding the use of inflatables is proper pressure retention. Since the air pressure in outer space is practically zero, and in the inflated module a pressure of at least 0.7–0.8 bar must be ensured for comfortable breathing, the wall of the module is subjected to enormous forces. At a minimum of 0.7 bar, 70 kN is exerted on each square meter of the wall, and at the usual atmospheric pressure – at 1 bar – even more, 100 kN/m^2, is exerted from the inside to the outside. For comparison, the same force would be exerted on the wall, if we put 7 or 10 tons of weight under normal earthly conditions to every square meter. The latter is equivalent to the weight of two adult elephants, on each single square meter of surface. The wall of the inflatable module should resist these enormous forces: the deformation of the elastic material counterbalances the force exerted by the air pressure. For example, in case of a module with a diameter of 5 m and an inner pressure of 1 bar, each meter-thick strip of the wall is pulled by a force of 500 kN in opposite directions (see *Figure 8*).

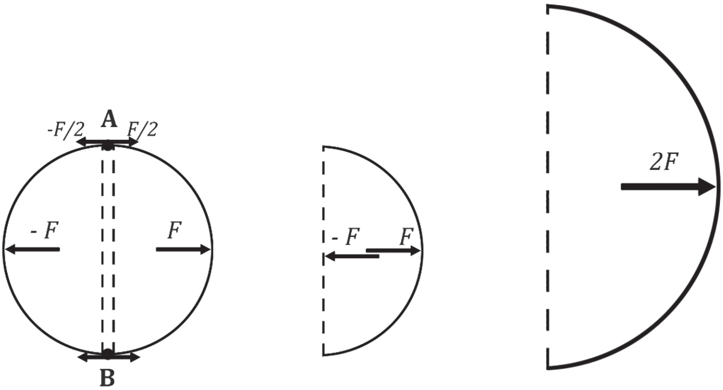

Figure 8
Pressure retention of inflatable modules in space
Note: The tensile forces arising in the wall of the cylindrical modules result from the difference between the internal and external pressure. Since the external pressure in space is practically zero, the internal "comfortable" air pressure creates enormous forces in the walls of the module. Only metals and plastics with high tensile strength can withstand these forces.
Source: Compiled by the authors

(If we imagine the inflated module shown in *Figure 8* to be cut in half between points A and B, then one half of the module is pushed to the right by the force F resulting from the internal air pressure, while an opposite but equal force $-F$ pushes the other half to the left. The material behind the A and line B points is pulled apart by an F/2 and $-F/2$ force pair. The middle picture demonstrates that in the half module, on the side opposite to the force F, a force $-F$ is generated due to the pressure.

In this case, however, the surface is flat, so it is easy to calculate that the force created by the air pressure is the product of the pressure [P] and the surface [A]: $F = P \cdot A$. But the surface created by cutting the module in half is the product of the length [L] and diameter [D] of the module: $A = L \cdot D$. Thus, the force is $F = P \cdot L \cdot D$, i.e. the product of pressure, length and diameter. This means that at a given pressure and given length, the magnitude of the force that pulls apart the walls will be proportional only to the diameter of the module. So, if we double the diameter the force is also doubled, and with three times the diameter, the force will be three times larger.)

Since the force arising in the wall increases with the diameter of the module, we might reach the tensile strength of the material in case of a large diameter module. Therefore, it is not common to design modules with a diameter larger than 5 meters for use in space. Of course, the same reasoning applies to modules made of metal, which is why metal spacecraft or space station modules are usually not more than 5 meters in diameter. But other pressure resistant containers, such as rockets used in space navigation, do not exceed 10 meters in diameter due to the cracks that occur due to the resulting tensile forces. Other pressurised vessels, such as rockets used in spacefaring, also do not exceed the 10 meters limit in diameter, since the tensile forces the pressure generates would cause the failure of the material (Bihari–Herzig 2021).

In science fiction literature, we often come across ideas in which the base built on other celestial bodies is covered by a dome, which protects the inhabitants of the base from external air pressure or the lack of air pressure, or even from a toxic atmosphere. Such a dome, however, is rarely a realistic construction. As the people living in a base covered by such a dome are used to a normal pressure of 1 bar, the internal pressure should be between 0.7 and 1.2 bar, so that too low or too high an air pressure does not cause breathing difficulties for the occupants. By changing the oxygen content of the air, it is possible to achieve different pressure values: for example, if the concentration of oxygen is increased from the usual 21% to 35%, breathing difficulties do not occur even at a relatively low pressure of 0.5 bar. But if the external pressure is practically zero, as in the case of Earth orbit or on the surface of the Moon or Mars, 0.5 bar pressure will only enable the construction of a dome with a diameter of 10 meters using the typical inflatable materials.

A large dome can only be feasible if the internal pressure is not significantly different from the external pressure. Such circumstances exist in the high atmosphere of Venus, where the air pressure is about 1 bar at an altitude of 50 km and the temperature is also acceptable, around 30°C. Here, we can think of an inflatable structure of almost any size since the air pressure can be the same outside and inside – the wall merely prevents the mixing of the external Venusian carbon dioxide atmosphere and the internal oxygen-nitrogen air. Another such possibility in the Solar System is Saturn's moon Titan, which has a surface pressure of 1.5 bar. On the surface of this moon, there are 5 km high mountains with a pressure of about 1.2 bar – still a comfortable pressure for humans. An inflatable structure of any size is therefore possible to build here, but since Titan's atmosphere is composed of nitrogen and methane, such an inflatable dome is needed to prevent the mixing of toxic external gases with the internal air.

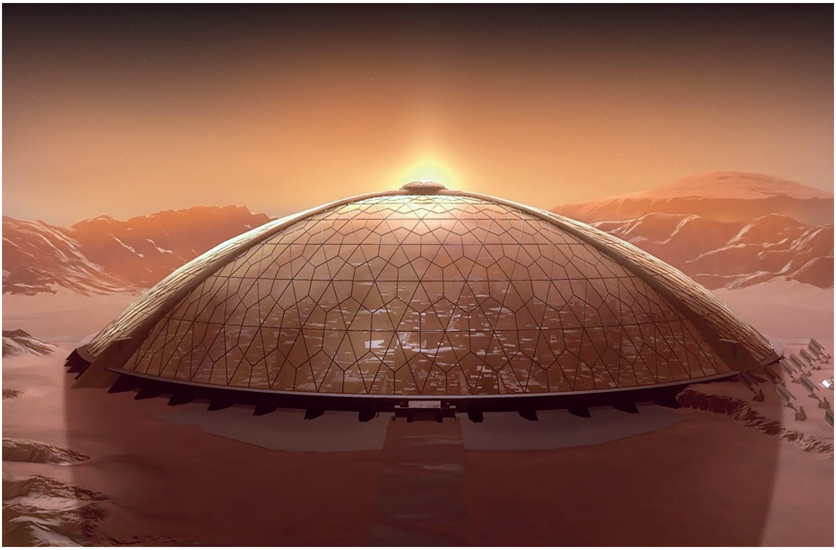

Figure 9
Protective domes in space
Note: On other celestial bodies, the construction of large domes is only realistic if there is a part of the celestial body where the air pressure is almost the same as the comfortable 1 bar pressure for us. Otherwise, enormous forces would be exerted on the dome, which would result in a large wall thickness and very large mass. However, such conditions prevail only in the upper atmosphere of Venus or on the surface of Saturn's moon Titan.
Source: Bihari – Herzig 2021

However, on other well-known celestial bodies, such as the Moon, Mars, or Mercury and the moons of Jupiter, the surface pressure is zero or very low, so the forces generated by the internal air pressure limit the size of the structures that can be built, whether they are made of metal or some kind of durable plastic. For example, in case of a 100-metre-diameter dome, which is by no means large, only a wall about 10 cm thick could withstand the forces. However, taking into account the properties of the known materials, the weight of the dome would still be several hundred tonnes, which shows that such an idea is not realistically feasible in most cases.

***

In the next few decades, humanity is expected to return to the Moon and establish a permanent base there. The current political climate suggests that there will not be one such base on the Moon, but probably two, thanks to the renewed space race. One of these bases will be built by the U.S. space agency, NASA, and private U.S. companies such as SpaceX, Blue Origin and Sierra Space, in partnership with the European Space Agency and the space agencies of India, Canada and Japan. The other base will be built mainly by China and Russia, with several associated countries, Iran and other Middle Eastern countries.

The main reason for building a permanent lunar base will be to exploit the water ice reserves at the Moon's poles and the opportunities it offers. Previous studies have detected the presence of water ice, and the hydrogen of the water molecule using various methods, such as neutron backscattering, radar echo intensity analysis and the emission spectrum of the gas cloud produced by the impact of an artificial object. This water ice is expected to be found in craters close to the poles, the depths of which are never illuminated by sunlight. Due to the lack of illumination, these craters are among the coldest regions of the Solar System, where temperatures have been around –150 and –200 °C for billions of years (Lawrence, 2017).

While the depths of the craters in the north and south polar regions of the Moon are extremely cold, the protruding peaks of these areas are called the Mountains of Eternal Sunshine. On these mountain peaks and plateaus, the Sun can be seen almost continuously, since the Sun moves around the horizon in polar regions. This unusual natural phenomenon – the eternally dark craters and the constantly illuminated mountain peaks – provides a unique opportunity for mankind to establish the first outposts on the Moon. The energy supply of the base built in these permanently illuminated areas would be ensured by solar panels and unlimited sunlight. But continuous sunlight offers the possibility of plant cultivation as well. The deep craters shrouded in darkness, on the other hand, offer the possibility of mining water ice. Extraction of the latter would not only provide drinking water to the personnel of the base but would also supply the crew with oxygen – i.e. breathable air – and food through the irrigation of plants. The hydrogen and oxygen produced by splitting water could be used also as propellants for rockets.

All this means that the lunar water resources are of extreme strategic importance. Extracted water ice can be used to create a self-sustaining base on the Moon that can also produce rocket propellants. This will give the future lunar base a role as a kind of gas station. In other words, the lunar base is the springboard for exploring and colonising the rest of the Solar System. Any country or major corporation that is the first to mine ice on the Moon could gain a strategic advantage that could make it the winner of the space race and the sole ruler of Earth's economy in the 21st century.

***

When designing a human habitable structure on other celestial bodies, it is very important to consider the environmental hazards of outer space. Among these sources of danger, radiation is the most significant: numerous astronomical objects in our galactic environment shower us with a diverse array of radiation. While we are on the surface of the Earth, we are protected from the vast majority of cosmic rays by the Earth's atmosphere and magnetic field. The latter deflects electrically charged particles so that most of them are absorbed by the molecules of the atmosphere around the uninhabited poles of the Earth, creating the phenomenon of the aurora borealis and australis.

Particles deflected by the Earth's magnetic field create the Van Allen radiation belts around the Earth (see the chapter on space weather.) Everything below these belts is largely protected from radiation since these high-energy particles can no longer get down there. Since space stations in low Earth orbit are also below the Van Allen belts, astronauts are still protected by the Earth's magnetic field. In the belts and above the belts, however, astronauts are exposed to the full spectrum of cosmic radiation, whether these are the solar wind protons, or X-rays from the Sun, or even high-energy particles from distant quasars. If we want to create a habitable space for humans anywhere in space beyond the Earth's magnetic field, we need to isolate that habitable space from the radiations of outer space with thick radiation shields.

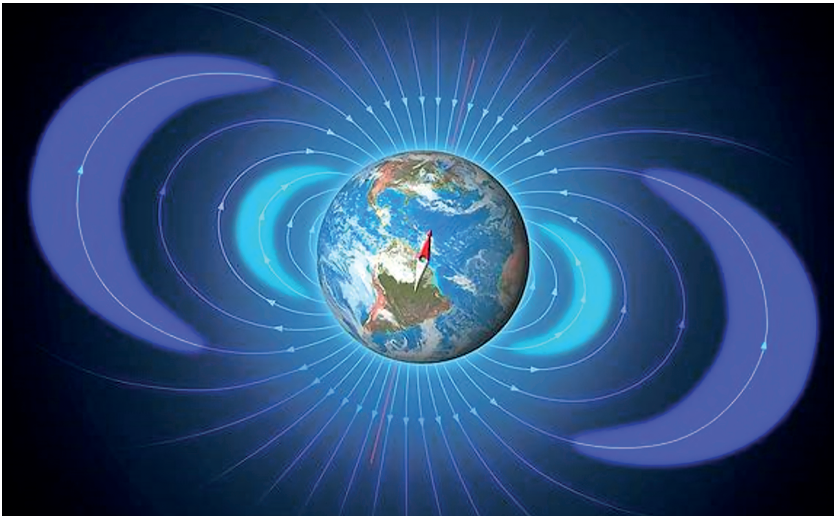

Figure 10
The Van Allen radiation belts around the Earth, shown to scale
Note: In the immediate vicinity of the Earth, at an altitude of only a few hundred kilometres from the surface, space station crews are largely shielded from the radiations by the Earth's magnetic field, although the dose rates are higher than those at the surface, where the atmosphere also has a shielding effect. However, this magnetic protection disappears further away from Earth.
Source: Evans 2018

Micrometeorites are another very serious source of danger in outer space. These tiny dust particles are usually very small, and most of them fall into the microgram range. They are usually released when comets disintegrate or when larger meteorites collide. Their velocity relative to a human habitable base to be defended can be very high, whether it is a space station orbiting the Earth or a building on another celestial body. Comets can reach speeds of up to 40–50 km/s in their orbits close to the Sun, which means that any dust grain that break away from them and move in a similar orbit will have the same speed and significant kinetic energy. For example, a grain with a diameter of less than a millimetre and a mass of a milligram can have tens of kilojoules of kinetic energy at this speed – the energy of the most powerful armour-piercing and sniper rifle projectiles.

Thus, in space architecture, the limiting factor is not only the material strength and the forces that arise from the large pressure difference but also the harmful levels of radiation and the danger of impacting micrometeorites. All these factors are threatening the living organisms in the building. On most celestial bodies – especially those without a significant atmosphere, such as the Moon or Mars – all three factors need to be taken into account during the design.

***

As we have seen, the size of inflatable structures is severely limited by the thin external atmosphere, i.e. the lack of external air pressure, and the tensile strength of the materials known today. It is possible to improve the tensile strength of inflatable membranes to some extent by using special high-tensile strength ropes, but the size limit is still in the region of 5–10 m in diameter. With such a size limit, the spherical shape allows for only a relatively small interior volume. Contrary to this, the cylindrical shape sets the size in only two directions: in the longitudinal direction of the cylinder, in principle, there is no limitation to the size. In other words, instead of a spherical shape, the elongated tubular shape, which can even be closed in on itself in the form of a ring, allows much larger living spaces to be created.

In this way, the spaces to be formed can be created using three main shapes or any combination of them. Adjoining spheres, cylindrical tubes and toroidal ring shapes can be used to create interiors of varying sizes and shapes. Concentric rings or parallel tubes can even be used to create very large habitable spaces on other celestial bodies.

Due to the restrictions on the diameter, there are only three main shapes that can be useful in the design process – all buildings should be created by any combination of these. Spheres, cylindrical tubes and toroidal ring shapes should be fitted together to create interiors of varying sizes and shapes. For increasing the size, concentric rings or parallel tubes can be used, thus creating very large habitable spaces on other celestial bodies.

A key advantage of inflatable structures over traditional metal structures is their large size, despite their lightness. Considering the same weight, the inflatable structure can be an order of magnitude larger than the structure made of metal. If, for example, we have to build a structure with a mass limit of 10 tonnes, this structure, when built of metal, would be no larger than a space station module, even with relatively thin walls: it could be around 4–5 metres in diameter and 6–8 metres long. In case of inflatable structures, the diameter is also limited to about 5 metres, but for linear tubes, the length can be up to 100–150 metres. The floor area of such an inflatable structure can reach 600–700 m^2 without exceeding the mass limit of 10 tonnes.

However, there is a serious disadvantage of inflatable structures compared to traditional metal structures: they offer much less protection against the external hazards mentioned above. In low Earth orbit, this poorer protection is still a relatively acceptable compromise, since the Earth's magnetic field already provides significant protection against most of the radiation. While against the impact of micrometeorites – as in the case of Bigelow Aerospace's inflatable module – a multi-layer cover based on Kevlar fabric protects the interior.

However, for deep space applications beyond low Earth orbit, we need to provide much more effective protection for the inflatable structure itself, and for the inhabitants or even the plants grown inside. To provide the same level of radiation protection inside as we are used to on the Earth's surface, we need to protect the structure with a layer of several metres thick dense material. In terms of radiation protection, the thickness of the Earth's atmosphere is equivalent to about a 10 metres thick layer of water or a 3–4 metres thick layer of rock.

Of course, it is possible to make a compromise and use a thinner radiation protection layer to reduce the difficulties and costs of construction – thereby accepting the risks associated with higher radiation exposure and shortening the service time for astronauts. Since the radiations from the Sun and mainly the effect of the relatively low-energy solar wind are eliminated by a layer of material even only half a meter thick, and the danger caused by micrometeorites is also eliminated, the radiation protection layer is no thicker than half a meter in case of most inflatable structures. The radiation exposure in such a building is much higher than it would be on the surface of the Earth, but even such limited protection still allows a quite long service time of 1 to 2 years for the personnel.

There are already numerous plans on how to build the first outposts on the Moon or Mars. All the designs using inflatable structures agree that only the inflatable structure is transported from Earth to the celestial body in question, and the protective layer against radiation and micrometeorites is built around the inflatable structure in situ, with the help of locally available materials.

There are special designs that would use unconventional materials to form the radiation shielding layer around the inflatable module. In case of Mars, for example, some designs would use local water ice to build a protective layer. Of course, such solutions can only work if the temperature at the building site is constantly below freezing. Below –20 °C to be precise, because above such temperatures ice can melt due to an increase in pressure, whereas in the case of the lower layers of the ice building, the weight of the upper layers can create this pressure increase. In other words, such an ice dome can survive for long only in very cold climates, even on Mars.

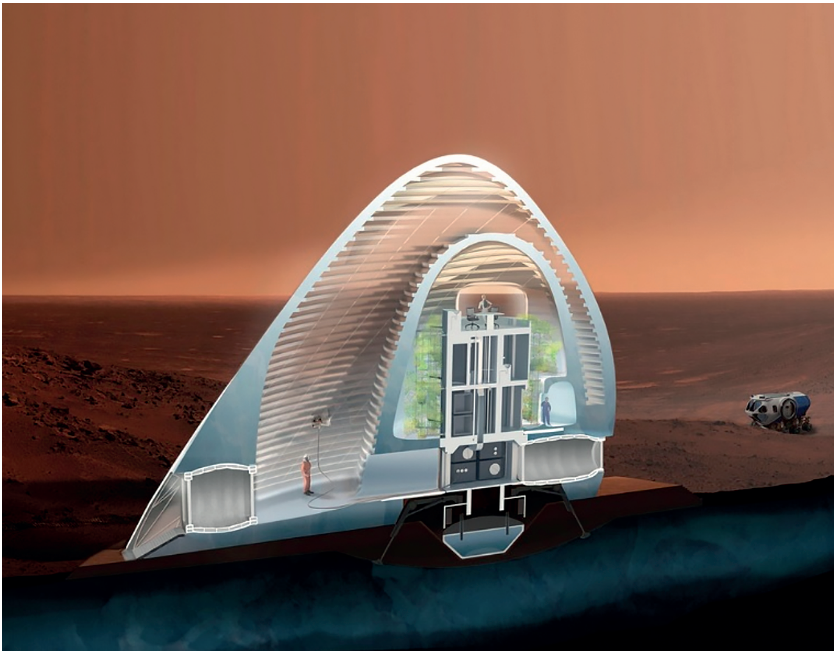

Figure 11
The 3D printed Martian ice house: inside the outer ice envelope there is also an inflatable structure
Source: www.spacexarch.com/mars-ice-house

Already for the water ice outer shell, the possible use of modern technology, the building with 3D printing has been raised. Since ice is relatively easy to melt, a 3D printer head can form an outer shell of almost any shape around the inflatable, pressure resistant part.

According to designers, 3D printing can also be a useful method for building external covers made of other materials. Local dust and rock debris that make up the lunar or Martian regolith can be the raw material for the protective wall of inflatable modules using various methods. Some methods would solve the transformation of local rock rubble into a concrete-like material with the help of additives transported from the Earth. Such additives can be special binding compounds, cement or even organic resins. Some designs even suggest that the cementing material could be available locally: on Mars, for example, gypsum (calcium sulphate) deposits may be present in accessible surface areas and this material may be suitable as a cementing material. However, if we could establish agricultural colonies on some celestial bodies, it becomes possible to produce certain plant-based organic resins, i.e. the binder material, in situ. Indeed, there are even plans to turn locally quarried debris into brick-like blocks using the threads of fungi to produce building materials.

However, lunar or Martian dust can be used to build solid walls even without binders. By heating the local dust to 1,000–1,200 °C, a ceramic-like material can be produced, which, even without additives, has sufficient strength to be used as bricks on celestial bodies with lower gravity than Earth. However, some specialists have the highest hopes for designs that plan to melt the rocky materials to create the walls. In this case, the previously mentioned 3D printing method can also be used to build the walls. The only drawback of such designs is that melting the rock requires a very large amount of energy. However, it is possible that this high energy requirement could be solved by solar energy: according to such ideas, sunlight concentrated by mirrors would directly melt the lunar or Martian rock dust into glass (Prater et al. 2018).

The question arises, of course, whether it is really necessary to build solid walls during construction on another celestial body. After all, the building of these solid walls would require considerable effort. It is not these solid rock walls that create the habitable space, but the inflatable structures and their flexible plastic walls. The solid walls would be built around the inflatable structure only for radiation protection and mechanical protection against micrometeorites. Not a surprise then, that there are designs, which would simply pile up local rock debris and dust around the inflatable structure, thus significantly simplifying the work of protecting the inflatable building and its inhabitants.

Figure 12
Design of a 3D printed outpost planned for Mars
Note: The inflatable structure would be surrounded by walls made of a glass-like material obtained by melting local rock dust. However, such an outpost would not be self-sustaining due to the lack of large-scale agricultural production, meaning that it would imply a huge construction and maintenance cost for the builder.
Source: PRATER et al. 2018

***

Research into the future methods of space architecture is currently ongoing. Today, we do not yet know exactly which methods will be the most effective on the celestial bodies we will visit in the future. However, it is almost certain that inflatable structures will play a significant role in the construction of humanity's first outposts and bases. The relatively small mass of the inflatable elements that make up the framework of these future bases can be put into orbit by relatively small launchers. We do not know of a more efficient solution:

inflatable structures enable the construction of large-scale buildings at low cost, especially if the necessary radiation protection and mechanical protection can be provided by the use of locally available materials.

Nevertheless, the protective outer layer can also be an obstacle to achieving one of our most important goals. For an outpost built on another celestial body to be self-sustaining, each member of the crew needs 0.5–0.7 kg of oxygen, 1–2 kg of food and 2–3 litres of clean drinking water per day. The simplest way to achieve this is to install large greenhouses. It has already been calculated by experts that each crew member needs at least 800 kg of living biomass in the greenhouses to produce the required amount of oxygen and food. This 800 kg of vegetal biomass needs a greenhouse with a floor area of at least 120–150 m^2: in other words, a greenhouse of this size is necessary for supporting each crew member.

Most of the designs propose hydroponic and aeroponic plant cultivation and artificial lighting. In this case, the greenhouses are filled with racks on which the plants grow vertically on several levels. The roots absorb the nutrients from the fertilizer solutions sprayed on them. In this case, the light required for photosynthesis is provided most effectively by LED lighting that emits light with only those wavelengths that are usable for plants. Of course, running such a greenhouse requires a lot of electricity. Since the energy requirement for the LED lighting of a greenhouse with a floor area of 120–150 m^2 is at least 20–30 kW, a solar panel park with an area of 120–150 m^2 – that is, approximately the same size as the greenhouse – would also need to be installed.

Due to the problem of such high energy demand, a solution that does not use artificial light for plant cultivation has also been proposed. In this case, mirrors project natural sunlight into the interior of the inflatable greenhouses. The use of mirrors is necessary as the greenhouse needs to be protected from the Sun's radiation by a protective cover – of course, the protective layer shields the greenhouse preferably from all directions, but most of all from the direction of the Sun. Fortunately, the mirrors do not transmit harmful radiation into the greenhouses, only the sunlight that is necessary for the photosynthesis of the plants.

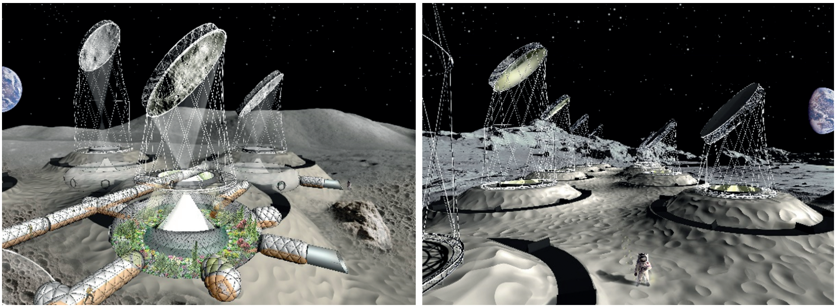

Figure 13
Plan of a lunar base consisting of inflatable elements
Note: The ring-shaped inflatable greenhouses are covered with a several meter thick layer of lunar dust. Since the Sun goes around the horizon in the lunar polar regions, we can use large, rotating mirrors to project the light into the underground greenhouses.
Source: https://pneumocell.com/pneumo-planet-moon-habitat/

One such solution is shown in *Figure 13* above. In this plan, the first outpost on the Moon would be made of inflatable elements. The ring-shaped greenhouses, the adjacent corridors and other living and working spaces are covered with a thick layer of debris, providing both radiation and mechanical protection. The whole structure is open at only a few points: above the ring-shaped greenhouses. The mirrors are placed here, which are made of stretched plastic membranes with a reflective layer and placed on lightweight towers. These mirrors continuously follow the movement of the sun and project the natural sunlight onto another, cone-shaped mirror through a funnel that leads underground. The latter mirror scatters the light in all directions, providing almost continuous illumination in the underground greenhouse (Herzig et al. 2022).

Since these large mirrors project very intense light into the inflatable greenhouse – up to 50–100 kW of radiative power, depending on the mirror's surface area – the greenhouses would quickly overheat without cooling. Therefore, a cooling system should be installed in each greenhouse, with cooling radiators that radiate the excess heat to space. These horizontal black cooling panels can be seen around the debris mound covering the greenhouse.

Another similar solution plans to start growing crops on Mars, which is vital for self-sufficiency, as we have seen before. In the Moon's polar regions, the Sun goes very low along the horizon, which is well utilised by the mirror that revolves around its axis and reflects the light into the ring-shaped greenhouse underneath. However, on the equatorial regions of Mars, it is better to think in terms of linear greenhouses with side mirrors to reflect the light of the Sun high above in the sky (Benaroya 2018).

Unfortunately, Mars has a very thin atmosphere – only about 1% as dense as that of Earth – so it offers little protection against cosmic radiation or micrometeorites. Therefore, also on Mars, we have to cover the inflatable structures with some kind of protective layer. The structure shown in *Figures 14–16* are protected from above by the debris piled on top of the inflatable structure. The plastic inflatable sidewalls are protected by mounds of debris that run along the length of the greenhouse. These mounds are also used to hold the stretched mirror foils, which reflect the sunlight into the greenhouse.

The weight of the debris layer is of course much smaller than the uplifting force that pushes the ceiling up, due to the internal air pressure. The Martian gravity is only a third of that on Earth, so even a 4 metres thick layer of debris weighs only 20 kN – equal to the weight of 2 tons on Earth – per square meter on the roof. The internal pressure, on the other hand, even with the previously mentioned 0.5 bar pressure and high oxygen concentration air, pushes the ceiling upwards with a force of 50 kN per square meter. This means that even in case of an accident and sudden decompression, it takes a considerably long time until the building starts to collapse. The crew has to leave the compartment due to the decreasing pressure and the resulting breathing difficulties, not because of the collapse of the roof. Collapsing only begins when 70% of the air has already escaped. Until then, the building is safely standing and does not hinder evacuation.

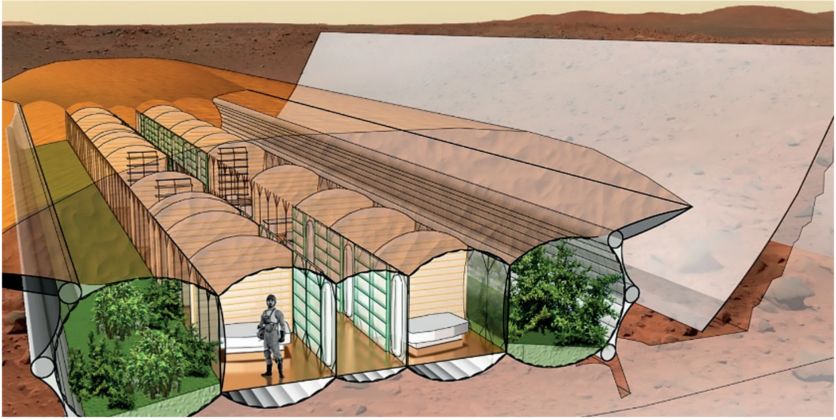

Figure 14

The building structure of a Martian settlement

Note: The basic element of a Martian settlement could be a long, inflatable greenhouse that produces the necessary oxygen and food for the crew. This design uses natural sunlight, and side mirrors to project the light into the greenhouses, the top of which is covered with Martian rock debris as a protective layer.

Source: https://marshabitat.space/

Figure 15

Image of the Martian settlement, consisting of greenhouses and residential parts similar to the one in Figure 14

Source: https://marshabitat.space/

Figure 16
Interior view of an inflatable habitation unit at the above Mars base
Note: The internal structure of the building is fixed by inflatable dividing walls and ropes. The inflatable walls are complemented by a floor of lightweight plastic elements, shelves and furniture.
Source: https://marshabitat.space/

REFERENCES

Barker, N. (2022): Ten half-buried houses hidden from the outside world. *deezen.com,* 7 January 2022. Online: https://www.dezeen.com/2022/01/07/buried-houses-hidden-underground/

Benaroya, H. (2018): *Building Habitats on the Moon. Engineering Approaches to Lunar Settlements.* Cham: Springer. Online: https://doi.org/10.1007/978-3-319-68244-0

Bihari, G. – Herzig, T. (2021): Space Nomad: An Easy-to-Build Mars Habitat Design. *Journal of the British Interplanetary Society,* 74, 6–20.

Biswal, M. K. – Vs, V. – Murugavel, S. – Kumar, D. S. (2019): *Human Mars Mission Architecture. Plan to Settle the Red Planet with 1000 People.* Kalapet: Pondicherry University. Online: https://doi.org/10.48550/arXiv.1904.01389

DedMityay: *Underground ruined and abandoned chalk mine tunnel or industrial corridor with perspective view.* Online: https://stock.adobe.com/images/underground-ruined-and-abandoned-chalk-mine-tunnel-or-industrial-corridor-with-perspective-view/188615620

European Standards [s. a.]: *Eurocode EN 1991*. Online: https://eurocodes.jrc.ec.europa.eu/EN-Eurocodes/eurocode-1-actions-structures

Evans, J. (2018): Studying the Van Allen Belts 60 Years After America's First Spacecraft. *NASA.gov,* 31 jan 2018. Online: http://www.nasa.gov/solar-system/studying-the-van-allen-belts-60-years-after-americas-first-spacecraft/

Foust, J. (2022): Bigelow Aerospace transfers BEAM space station module to NASA. *Spacenews.com,* 21 January 2022 Online: https://spacenews.com/bigelow-aerospace-transfers-beam-space-station-module-to-nasa/

Hein, A. M. – Welch, C. – Hirai, M. (2014): *Autonomous Space Colony Construction*. International Astronautical Congress, Toronto, Canada, 29 September – 3 October 2014. Online: www.academia.edu/16745374/Autonomous_Space_Colony_Construction?email_work_card=title

Herzig, T. – Kömle, N. I. – Macher, W. – Bihari, G. – Gläser, P. (2022): Site Selection, Thermodynamics, Environment and Life Support Analysis for the Pneumoplanet Inflatable Lunar Habitat Concept. *Planetary and Space Science,* 224. Online: https://doi.org/10.1016/j.pss.2022.105595

Johnson, R. D. – Holbrow, C. (1977): *Space Settlements. A Design Study.* Washington, D.C.: National Aeronautics and Space Administration.

Lawrence, D. J. (2017): A Tale of Two Poles: Toward Understanding the Presence, Distribution, and Origin of Volatiles at the Polar Regions of the Moon and Mercury. *Journal of Geophysical Research: Planets,* 122(1). Online: https://doi.org/10.1002/2016JE005167

NASA (2024): *Using Space-Based Resources for Deep Space Exploration*. Online: www.nasa.gov/overview-in-situ%20resource%20utilization/

Oilfield Service Company (2020): *Skid-mounted metering device for oil/gas separation is widely used*. Online: https://www.hcpetroleum.hk/news-detail/108?

Prater, T. – Kim, T. – Roman, M. C. – Mueller, R. P. (2018): *NASA's Centennial Challenge for 3D-printed Habitat: Phase II Outcomes and Phase III Competition Overview.* AIAA Space and Astronautics Forum 2018, AIAA 2018-5405. Online: https://doi.org/10.2514/6.2018-5405

Seedhouse, E. (2014): *Bigelow Aerospace. Colonizing Space, One Module at a Time*. Cham: Springer. Online: https://doi.org/10.1007/978-3-319-05197-0

Williams, V. A. – Mosher, T. J. (2022): *Orbital Reef: A Low Earth Orbit Destination for Commercial Exploration Demonstration*. Ascend 2022 Conference, AIAA 2022-4366. Online: https://doi.org/10.2514/6.2022-4366

Zsolt Hetesi[1] – Zsófia Biró[2]

Bon Voyage: Sources of Energy for Space Exploration and Its Current Regulatory Insights

Except for a brief mention at the beginning, the paper deals with the technical and legal aspects of space exploration and, to a lesser extent, the energy sources used in the conquest of space. The idea of energy from space is not new. As early as 1923, Konstantin Tsiolkovsky envisioned a system based on mirrors placed in space to send amplified sunbeams back to Earth. A bit later, in 1941, the famous science fiction writer Isaac Asimov came up with a similar idea (ESA 2022a), and in 1975, the physicist Gerard K. O'Neill took the idea one step further, bringing it even closer to the present day: he had already written that "manufacturing facilities in high orbit could be used to build satellite solar power stations from lunar materials" (O'Neill 1975: 943). If we look at the 20th century space science fiction literature, we can see that the various ways of producing energy that appeared in novels, which seemed impossible and futuristic at the time, are beginning to materialise, or are already partially operational. It might be worth picking up today's science fiction literature to get a more accurate picture of our own future. This paper has a similar goal: to show what kind of energy production and supply opportunities will exist during the exploration and eventual colonisation of space at different locations and distances.

[1] University of Pécs, Faculty of Natural Sciences; Ludovika University of Public Service, Faculty of Water Science; ORCID: https://orcid.org/0000-0002-4250-4050; e-mail: hetesi.zsolt@uni-nke.hu

[2] University of Pécs, Faculty of Law; ORCID: https://orcid.org/0000-0001-8372-4896; e-mail: dr.biro.zsofia@gmail.com

DOI: https://doi.org/10.36250/01209_06

POSSIBLE ENERGY SOURCES IN AND FROM OUTER SPACE AND PHYSICAL BACKGROUND

The energy sources that have been and may be used in the future to explore space are characterised by diversity, the complexity of the challenges and the evolution of technology. Among the challenges, the energy density of the propellant, the long distances and the need to overcome large potential fields are all tasks that have only just begun in the little more than six decades of space exploration. Future space missions, whether human or automated, will go much further, faster and more efficiently than ever before, but they will require several technical leaps that, for the present, exist more in science fiction literature than on the drawing board. The next two sections define the basic concepts needed to understand the rest, in terms of distance and speed scales, and the following ones the ways and means of using energy.

Distance and velocity basics

Space is characterised by distances that are simply too great for human experience, since for most of us, journeys of a few hundred or a few thousand kilometres are not an everyday occurrence, the current human record being the Moon, with an average distance of 384,000 km from Earth. However, this distance is also small compared to one of the most expressive units of measurement in the solar system, namely the AU, the average Earth–Sun distance, or 149,600,000 km. While the Moon is 0.002 AU from the Earth, the Kuiper Belt, for example, which follows the planets of the Solar System, is about 50 AU away, while the Oort cloud, which lies at the boundary[3] of the Solar System, is between 2,000 and 200,000 AU away. The distance to the nearest star, Proxima Centauri, is so large that it is not practical to express it in AU, about 268,770 AU. Therefore, light years are used for distance measurements in interstellar space, even though

[3] In a strict sense, the boundary of the Solar System can be defined in several ways. One of the most commonly accepted is the heliopause, the boundary where the interstellar medium stops the solar wind.

the light year is small at intergalactic distances, it is still common and has not evolved into a larger unit, unless *parsec* counts as one.

Table 1
Average distances to some celestial bodies

Celestial body	Km	AU	Light year
Moon	384,000	0.002	1.3 light seconds
Sun	150,000,000	1	8 light minutes
Jupiter	602,890,000	4.1	33.5 light minutes
Proxima Centauri	40×10^{12}	268,770	4.3 light years

Source: Compiled by the authors

Of all the man-made objects, the Voyager 1 spacecraft has gone the furthest, currently travelling at a distance of 160 AU, and 4 other man-made objects have exceeded the third cosmic velocity, Pioneer 10 and 11, Voyager 2 and New Horizon.

The spacecraft can be divided into Earth orbiting, interplanetary and interstellar groups based on the location of the mission. This is essentially the same if the objective is not only a mission but also the establishment of a base around the Earth (e.g. the International Space Station), on the Moon (which is not yet considered interplanetary space) or on other planets. The exploration of interstellar space can be regarded as purely theoretical for the time being.

Addendum. Speeds required to explore space: The escape velocities

The force that organises the cosmos on a macroscopic scale is gravity. Therefore, getting into space means, first of all, investing the energy to accelerate the spacecraft to the first cosmic velocity for orbital insertion, the second for interplanetary missions and the third for interstellar missions – although the latter is not entirely true, see later.

Table 2
Cosmic velocities

Cosmic velocity	Velocity [km/s]	Note
First	7.9	Orbit
Second	11.2	Earth leaving orbit
Third	42.1	Orbit out of the solar system

Source: Compiled by the authors

The first cosmic velocity, or escape velocity, means that at least this speed is required to leave the surface of the Earth (interpreted as a cannon shot with a velocity at least equal to the fall towards the surface of the Earth's curvature). At the second cosmic velocity, the speed of the device would decrease to 0 at an infinite distance from the Earth, and at the third cosmic velocity, at an infinite distance from the Sun. The latter two mean that the device would escape from the potential of the Earth or the Sun, because its velocity would decrease to zero at the infinitely distant point from the centre of attraction, i.e. its kinetic energy would be "consumed". It follows from this interpretation that all three velocities are different from planet to planet.

To calculate the velocity required for an orbital path, the centripetal force and the force of gravity must be equated because this path can be formed if the only force acting is gravity, and that is the force that keeps the object in orbit:

$$\frac{mv^2}{R} = G\frac{Mm}{R^2} \rightarrow v_{c1} = \sqrt{\frac{GM}{R}} \quad ,$$

where M is the mass of the planet and *R* is its radius. The way to calculate the second and third cosmic velocities is the same, one has to write down the mechanical energy at an infinite distance from the centre of gravity (second cosmic velocity: Earth, third: Sun). Assume that the kinetic energy resulting from the minimum escape velocity at infinity will be 0, the minimum velocity at which you can travel infinitely far:

$$\frac{1}{2}mv^2 = G\frac{Mm}{R} \rightarrow v_{c2} = \sqrt{\frac{2GM}{R}} \quad .$$

For the second cosmic velocity, M is the mass of the Earth, for the third cosmic velocity, the mass of the Sun and R is the radius of the corresponding celestial body's orbit (NASA 2000).

The third cosmic velocity does not necessarily have to be reached during the launch, and a device can still leave the Solar System even if it was launched from Earth at a lower velocity. An example is Voyager 1, mentioned earlier, which was able to gain extra speed by taking advantage of the gravity assist effect of the outer gas planets.

Similarly, the Earth's rotation helps launches, where the energy required to launch the device into space as close as possible to the equator is significantly less because the Earth's rotation "helps". The famous launch sites are therefore as close as possible to the equator: Kourou (ESA), Baikonur (Russia–Kazakhstan) and Cape Canaveral (USA).

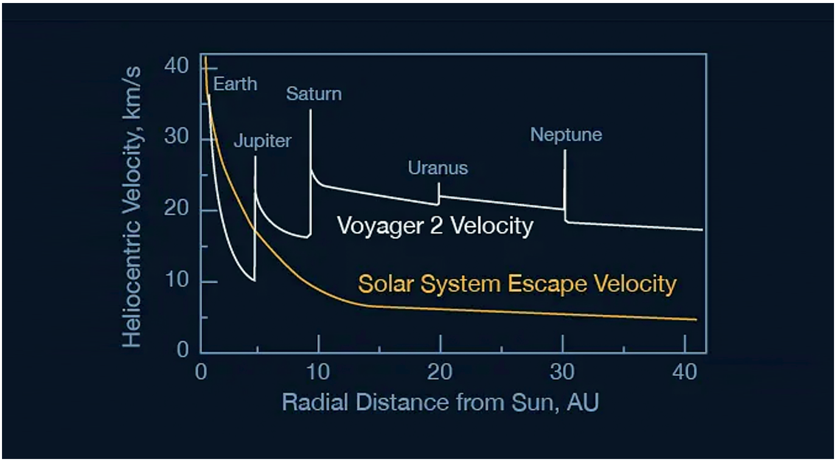

Figure 1
Gravity assist during the Voyager 1 mission
Note: It can be seen that encounters with giant planets increased the probe's speed to well above the third cosmic velocity.

Source: NASA s. a.

Environmental criteria for energy source design

Understanding the space environment and its impact on space devices is fundamental to the successful design and operation of solar cells for various space missions. Moreover, the extreme conditions of space, and the almost total absence of conditions for life, make it difficult to launch instruments or even astronauts. Plans for a permanent human presence on the Moon or a mission to Mars in the not-too-distant future, although technically feasible, are still at the limits of humanity's capabilities.

The development of technology is usually not linear because of the leaps that follow a major discovery, but rather almost stagnant, then bouncing back and so on. At the beginning of the space age, the first space devices (Sputnik 1, early Apollo programme) did not have integrated circuits, and the computer for the moon landing was a very rudimentary device by today's standards. Technological progress in the last period was not so much in launch technology as in the electronics and information technology of the operating system.

Table 3
Challenges of space exploration and technological responses

Challenge	Technological response
Overcoming long distances	New engine types, new propellant, taking into account NASA TMA principles and TLR scale
Long-time flights	Hibernation, dehibernation systems to maintain life functions that can last for centuries
Hostile environment	Life support systems, spacesuits, space stations, colonies

Source: Compiled by the authors

According to a summary from the Johns Hopkins University Applied Physics Laboratory (JHUAPL 2018), in the near future, the speed of smaller devices could be accelerated by a factor of 4, reducing the travel time to 17,500 years, instead of the current technology's travel time of about 75,000 years. More importantly, the material suggests a target of 20 AU/year in the not-too-distant future.

Another important area where progress needs to be made to overcome technological barriers is in reducing the mass ratio. By definition, mass ratio is the ratio of wet mass (rocket + propellant + payload) to dry mass (rocket + payload):

$$\frac{m_{wet}}{m_{dry}}\ .$$

The less propellant required to deliver the same payload (rocket body + payload) to the target, the smaller the number. For multi-stage rockets (see later), this number is between 8 and 20. It is worth noting that this means that between 12.5 and 5% of the mass of the rocket is non-fuel, i.e. the residual mass of the rocket plus the payload.[4]

All the technologies that are classified by NASA Technology Readiness Level (hereinafter TRL) as TRL 1-5 are not yet the subject of a scientific discourse that would make them part of space exploration in the foreseeable future. This includes energy sources and propulsion systems that exist only on paper, not even on a semi-industrial scale or ideas from science fiction literature. Examples include the fusion reactor, travel through wormholes and bending space.

A permanent base on the Moon or Mars, for example, presents a different technological challenge. In both cases, energy supply is probably the least problem, because the solar constant on the Moon is practically the same as on Earth, and there is no atmosphere to limit the radiation, yet on Mars it is 40% of that on Earth (Appelbaum–Flood 1989). The much greater difficulties here are food, clean water and filtering cosmic radiation, among others.

According to the NASA Marshall Space Flight Center, the space environment shall be described with seven main components: neutral thermosphere (atmospheric density, density variations, atmospheric composition), thermal

[4] The definition of the mass ratio is a consequence of the Tsiolkovsky equation, which indicates the maximum velocity that can be achieved by the thrust of the outflowing gas jet.

(solar radiation, radiative transfer, atmospheric transmittance), plasma (ionospheric plasma, auroral plasma, magnetospheric plasma), meteoroids–orbital debris (distribution by size, mass, velocity and directionality), solar (solar physics and dynamics, geomagnetic storms, solar activity predictions, solar–geomagnetic indices, solar constant, solar spectrum), ionising radiation (trapped proton–electron radiation, galactic cosmic rays, solar particle events) and geomagnetic field (natural magnetic field). In addition to this: gravitational field and mesosphere (Bedingfield et al. 1996: 2).

Looking at each environmental factor one by one, it can be concluded that plasma, which is the flow of charged particles ejected from the solar corona, poses a serious threat to the long-term operation of space devices, as it can cause surface charge, electrostatic discharge, energy loss and short circuits in electronic and photovoltaic components. Furthermore, when the solar wind reaches the Earth, it interacts with the magnetic field, so incoming charged particles tend to get trapped in the region called Van Allen radiation belts. It is therefore obvious that space devices orbiting at such altitudes must be able to withstand such conditions, i.e. the effects of radiation. Likewise, the dangers associated with indirect ionising radiation are also problematic for the stability of space assets, as they can release charged particles in materials. The next factor responsible for space-induced degradation is thermal fluctuations. Thermal cycling is very dangerous for the materials and devices of space assets, as it can cause thermal stresses and eventually cracking of some components or detachment of several layers. The factors discussed so far are also seriously influenced by the activity of the Sun. It is also necessary to mention the neutral atmosphere, which affects the service life of space device components primarily due to the presence of atomic oxygen and high vacuum. Finally, meteors and space debris, which pose a threat to space devices due to the disastrous consequences of possible collisions, should be mentioned as a final but important factor (Verduci et al. 2022: 6).

ENERGY SOURCES BY TYPE

Rocket propulsion, and motion in space in general, is facilitated by propulsion based on Newton's third axiom of action–reaction, where the motion of the device is caused by matter flowing out of the device at high speed, and thus the device is subject to thrust due to the action–reaction principle.

In the earliest phase of the space age, the challenge was to get spacecraft out of the atmosphere, initially using only chemical propellants. Even the earliest rocket propellants were based on a chemical reaction, using Chinese gunpowder propelled firecrackers.

For chemical propellants, the exhaust velocity out of the rocket can be between 3,000 and 5,000 m/s,[5] for a single stage the top speed at which the rocket can run out of fuel is high if a significant part of the launch mass is fuel, but it is obvious that the mass ratio (m_{wet}–m_{dry}) is limited, so the top speed is limited. If a single stage rocket is to reach interplanetary space (where a velocity of $v = 11.2$ km/s is required, see earlier), the mass ratio should be around 13 for an exhaust velocity of 4,500 m/s. To give an example, for a hen's egg the mass ratio of the shell to the yolk and protein of the egg is 10, and for a bag of cereal 100, so it can be seen that it is almost impossible to reach interplanetary space with a single stage rocket, leaving a meaningful mass to be placed. To add to the rocket's velocity ratios, the Tsiolkovsky equation must be supplemented by the velocity-reducing effect of the Earth's gravity field, which makes the situation even worse.

Multi-stage rockets were invented to solve this problem, where the first stage and later the second stage are ejected from the launcher during the launch and fall back into the Earth's atmosphere (or to the surface of the Earth), where they burn up. This can increase the relative size of the payload that can be delivered by up to a factor of ten, compared to the single stage rocket.

[5] German A4 rocket's outflow speed was 2,100 m/s.

Chemical propellants

Chemical propellants are generally two components in their operating principle, i.e. they burn a fuel and an oxidising agent together. In the first rockets, because they operated in the atmosphere, the propellant was gunpowder (one component), but later a mixture of ammonium perchlorate (oxidiser) + aluminium powder (fuel) was developed, but solid propellants were not widely used in space exploration because of their low specific burning rate.

For chemical propellants, the following are important considerations: specific thrust, fuel density, combustion temperature, combustion stability and fuel toxicity. While thrust is important for the maximum achievable speed, density affects the design of the rocket, exhaust velocity and heat of combustion affect the design of the engine and nozzle.

Liquid propellants have a higher outflow rate and have been used in practice from the first space rockets until today. One of the most common is hydrazine (N_2H_4). Stable at room temperature, it decomposes almost explosively at higher temperatures and can exhaust at 4.5 km/s with a properly designed nozzle. Both hydrogen peroxide and kerosene + liquid oxygen are used. Kerosene was mainly used in Soviet rockets and its environmental impact is less severe than that of hydrazine. Hydrazine is a very dangerous and toxic compound. It is a carcinogenic and irritating substance, highly toxic when released into the environment, and its replacement has become a major issue of our time. Several attempts have been made to make the propellant "green", one of the most promising being the liquid methane + liquid oxygen two-component propellant. Efforts are being made to ensure that methane does not come from fossil sources but is renewable in origin.

Electromagnetic reactive propulsion

In case of electric propulsion, there are several types of ionised propellants that work on several principles: electrostatic, electrothermal and electromagnetic.

In the case where the reactive force is based on the Coulomb repulsion, we speak of electrostatic propulsion. In this case, the mechanism can be, for example, an ion engine (one of the most common). In the engine, gas is ionised and the ions are accelerated by an electric field parallel to the direction of travel. Electrons stored in the spacecraft are injected into the outgoing ion stream so that the outgoing cloud is neutral. While the engine uses only Coulomb separation, it is purely electrostatic. The ion engine of Deep Space has achieved an exhaust speed of 4.5 km/s. However, the typical thrust is less than that of chemical propulsion, and this type of propulsion works in space.

In electromagnetic, or plasma, propulsion, the acceleration of the ions is done by the Lorentz force, so that the electric field is perpendicular to the outflow. In these devices, the exit velocity is high, 20–50 km/s, but the thrust is relatively small. Devices of this type are typically used in a vacuum.

In summary, ion and plasma thrusters are not suitable for enabling lift-off from a planet, but they can operate efficiently in space because little material needs to be transported to generate thrust (the mass ratio is small). *Figure 2* shows the specific impulse as a function of thrust for different engines and propellants. Specific impulse measures how efficiently a reactive engine uses propellant: in effect, it measures how many seconds it would take for a given propellant to accelerate the initial mass of a given engine to 1 g.

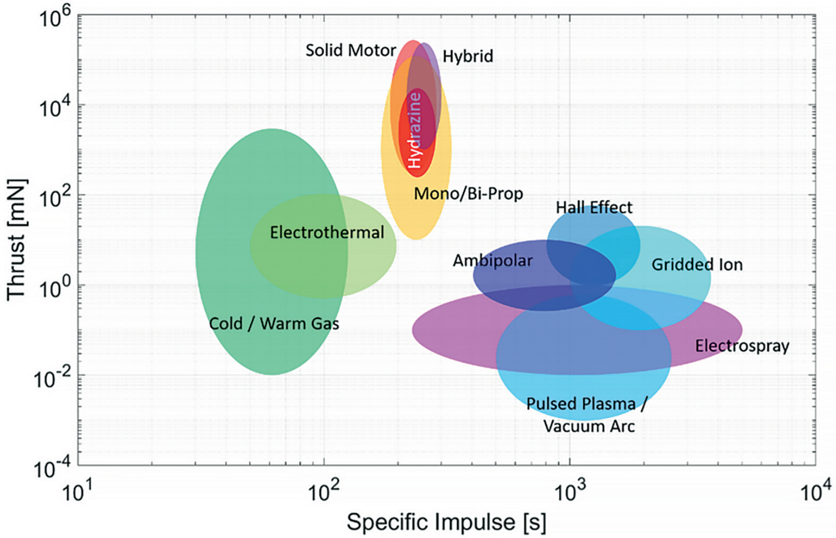

Figure 2
Current chemical propellants (left and top centre) and electricity-based propulsion (ion and plasma)
Source: NASA 2023

Nuclear energy

Radioisotope Thermoelectric Generator (hereinafter RTG) has been the main power source for the U.S. space programme practically since the beginning. The high decay heat of plutonium-238 (0.56 W/g) enables its use as an electricity source in the RTGs of spacecraft and satellites. Because of the mainly intense alpha decay process with negligible gamma radiation, no significant shielding is required because the alpha radiation is practically absorbed by a sheet of paper. Americium-241, with 0.15 W/g is another source of energy used by the European Space Agency, though it has high levels of relatively low-energy gamma radiation, so requires more shielding.

The next step is the reactor-powered propulsion system, which so far only exists in concrete design, is based on the fact that the heat provided by the reactor heats up a working gas, typically hydrogen, which flows through a nozzle into space, creating thrust. Since reactors are compact devices, the mass ratio can be as low as 7, compared to 10–20:1 for chemical rockets. Because the energy source is efficient, the outflow rate is high, partly because the gas medium is hydrogen and the molecular weight of hydrogen is small.

Both Soviet and American technology have been at the forefront of compact reactor construction since the beginning, and such reactors have powered nuclear submarines. Developed by Los Alamos National Laboratory, Heat Pipe Power System (hereinafter HPS) fast reactors operate at 400 kW(t) of power, coupled with 100 kW(e) of electricity generation, using a Stirling or Brayton power cycle. Here (e) stands for electric and (t) for thermal power. These reactors can be used not only to power rockets or interplanetary spacecraft but also to power colonies. This latter use is obvious because photovoltaic power generation alone will not be sufficient for the Moon or Mars, and geothermal (not in the strict sense of "geo") power is not available either, for lack of planetary volcanism. The Moon has 14 days of night due to its tidal locking, and at Mars's distance, the solar constant is 40% of that on Earth.

Small modular reactor (hereinafter SMR) technology, which refers to reactors that are smaller than conventional reactors, can be assembled from parts and easily scaled up, allowing for rapid replacement, easy repair and reliable operation for decades. Progress in the management of nuclear waste is also encouraging, as Russian technology has come close to completing the fuel cycle for the Beloyarsk BN-600 reactors, which means that there is essentially no or much less spent fuel.

The question of the fusion energy of the He-3 isotope will be discussed later. In the following, we will look at the regulation of nuclear energy in space law, and then return to the analysis of other energy sources.

Energy-related regulations in international space-related treaties

If we take an interdisciplinary approach, the Outer Space Treaty and the Moon Agreement, as well as the Artemis Accords are inescapable. Article IV of the 1967 Outer Space Treaty already states that nuclear weapons must not be placed in orbit around the Earth, placed on celestial bodies or otherwise kept in outer space. (By the way, this is also stipulated in Article 3 of the Moon Agreement concerning the Moon, orbits around the Moon and orbits leading to it.) This, of course, does not exclude the use of nuclear energy as a resource in space, since this type of energy (RTG) has also been used on deep space missions, such as Voyager 1–2 (Petrocelli et al. 2023: 9).

Principles Relevant to the Use of Nuclear Power Sources in Outer Space and the Safety Framework for Nuclear Power Source Applications in Outer Space

The United Nations Office for Outer Space Affairs (hereinafter UNOOSA) implemented the decisions of the Committee on the Peaceful Uses of Outer Space (hereinafter UN COPUOS). UNOOSA recognises "that for some missions in outer space nuclear power sources are particularly suited or even essential owing to their compactness, long life and other attributes" and "that the use of nuclear power sources in outer space should focus on those applications which take advantage of the particular properties of nuclear power sources". It has adopted a set of principles (see in next paragraph) applicable "to nuclear power sources in outer space devoted to the generation of electric power on board space objects for non-propulsive purposes", for radioisotope systems and fission reactors as well (World Nuclear Association 2021).

Session 47/68 of 1992 Principles Relevant to the Use of Nuclear Power Sources in Outer Space acknowledged the essential importance of nuclear energy in space missions, which should always be based on a thorough safety assessment. Furthermore, in the preamble, the document provides its own revision for the future, since the number of solutions based on nuclear energy will increase. As this study demonstrates, that time has come, because of the possibilities outlined in Principle 3, point 2 about where nuclear reactors can operate (such as in interplanetary missions, sufficiently high orbits and in low Earth orbits if they are stored in sufficiently high[6] orbits after the operational part of their mission). The regulations also state that nuclear reactors shall use only highly enriched Uranium-235 as fuel.

In 2009 the UN COPUOS Scientific and Technical Subcommittee and the International Atomic Energy Agency (hereinafter IAEA) jointly published a document on the Safety Framework for Nuclear Power Source Applications in Outer Space, having regard to the fact that "nuclear power sources (hereinafter NPS) for use in outer space have been developed and used in space applications where unique mission requirements and constraints on electrical power and thermal management precluded the use of non-nuclear power sources. Such missions have included interplanetary missions to the outer limits of the Solar System, for which solar panels were not suitable as a source of electrical power because of the long duration of these missions at great distances from the Sun" (UN COPUOS – IAEA 2009: 1).

The Safety Framework for Nuclear Power Source Applications in Outer Space focuses on the safety for relevant launch, operation and end-of-service phases of space applications using NPS. It provides high-level guidance on programming and technical aspects of security, including the design and application of NPS in space. However, the detailed implementation of these guidelines depends on the specific design and application. The implementation of guidance in the safety framework would complement existing standards that address other aspects of space NPS applications (UN COPUOS – IAEA 2009: 2).

As space exploration has gained momentum since 2009 and human missions could take us beyond Mars by the end of the century, the wider use of nuclear energy sources has become indispensable. Therefore, on 15 February 2023, in

[6] The definition of "sufficiently high" is rather vague, and it would be a desirable solution if this concept were clarified in a legal source or an international treaty, and to make the legal definition meet the practical criteria of astronautics.

Vienna, U.S. Representative Kevin Conole at the U.S. Mission to International Organizations in Vienna highlighted the significance of the 2009 document and presented that the United States calls on Member States and international intergovernmental organisations that are considering the use of space NPS to implement the joint Safety Framework developed in 2009. The need for this is clear: "Use of NPS for in-space propulsion of spacecraft is a potential technology for crew and cargo missions to Mars, and scientific missions to the outer solar system, enabling faster and more robust human and robotic missions. Expanding into a new era for space exploration depends on mass-efficient, high-energy solutions[7] to power deep space vehicles, operate in harsh environments, and increase mission flexibility" (Conole 2023).

The above-mentioned Principles from 1992 and the Document from 2009 were also cited by the UN COPUOS in 2018 in the Guidelines for the Long-term Sustainability of Outer Space Activities. According to Guideline A.2 2. (e) in developing, revising or amending, as necessary, national regulatory frameworks, States and international intergovernmental organisations should implement the guidance contained in the Safety Framework for Nuclear Power Source Applications in Outer Space and satisfy the intent of the Principles Relevant to the Use of Nuclear Power Sources in Outer Space through applicable mechanisms that provide a regulatory, legal and technical framework that sets out responsibilities and assistance mechanisms, prior to using nuclear power sources in outer space.

Solar energy

Solar power has always been an important element in the operation of satellites and space probes, and this will not change in the future for planetary missions, but solar power is typically enough to power or contribute to the operation of the probe's instruments. In the outer parts of the solar system, the solar constant

[7] From a physical point of view, the correct wording would actually be "of high energy output", i.e. there is a huge difference between high-energy physics and an energy source with high energy output.

is so reduced that it can only be used as an auxiliary power source. The table shows that the outer part of the solar system receives less than a thousandth of the irradiance of the Earth.

If solar cells are to be used to some extent to power planetary colonies, it is important to bear in mind that the already low power density of solar cells will only allow them to be used if they can be manufactured on the planet, or at least the largest possible parts can be produced. In this respect, the use of photovoltaic films and surface materials such as paints is a good step forward.

Table 4
Solar irradiance at the distance of the planets (mean value for Mercury, Mars and Pluto)

Planet	Distance (in 10^9 m)	Mean solar irradiance (W/m^2)	Irradiation compared to the Earth's
Mercury	57	9116.4	6.673
Venus	108	2611	1.911
Earth	150	1366.1	1.000
Mars	227	588.6	0.431
Jupiter	778	50.5	0.037
Saturn	1,426	15.04	0.011
Uranus	2,868	3.72	0.003
Neptune	4,497	1.51	0.001
Pluto	5,806	0.878	0.001

Source: Compiled by the authors

An alternative use of solar energy is the solar sail, which uses the radiation pressure of the solar radiation. The first successful solar sail probe was the Japanese IKAROS.

In the following, we will look at the energy sources according to where they are used.

ENERGY SOURCES BY PLACE

Energy in orbit around the Earth

In general, the type of energy source and energy production method used depends on the distance from Earth and the Sun and the type of mission: its energy intensity and length (Datas–Martí 2017: 285; Miller et al. 2016: 197). In orbit around the Earth, we find mostly solar-based solutions: its great advantage in space is that the solar radiation performance at the top of the atmosphere is more than ten times stronger than on the Earth's surface, there are no clouds and there is no change of time of day (ESA 2022c; Nagy 2018: 67). For short missions, chemical energy production is usually used in the form of non-rechargeable batteries or fuel cells (Verduci et al. 2022: 2).

Chemical energy production can also be a feature of the very small CubeSats that have become fashionable (and cost-effective) today: since very little energy is produced by the solar cells on them, their propulsion and thrust must consume as little energy as possible. A joint development by MIT and NASA could be a solution to this, for which the idea was taken from plants, whose water absorption is based on porous and capillary effects. Plants absorb water through capillary pores at the root level, which travels through smaller and smaller capillaries through their trunks to branches and then to leaves, where it evaporates. The invention consists of a porous layer of tiny peaks through which ionic liquid is sucked all the way to the outer surface of the peaks, where the liquid can be expelled as a spray under the influence of electrical voltage between two electrodes. The ionic liquid spray flows out of the pores like a propeller, moving the nanosatellite in the opposite direction to the flow. According to measurements, for example, 500 porous tips can produce 50 micronewtons of thrust, which is capable of moving a device weighing up to 1.5 kg in space. The voltage value applied to these peaked inserts can also be used to change the driving force of the outflowing ion spray, allowing precise control. The invention was called the Ion Electrospray Propulsion System (Braun 2018: 97).

For longer missions, photovoltaic rechargeable batteries are the most common choice. A possible alternative to solar panels is solar heat generation through generators that allow heat storage at very high energy densities, but these systems have only been experimentally studied and flight experiments have not yet been conducted. Nuclear power generation is used for deep space and interplanetary missions because there the intensity of solar power is already too low (Datas–Martí 2017: 285).

Thanks to technological advances, in the late 2010s there were efforts to radiate solar energy produced in space to Earth (Nagy 2018: 68). One of the unresolved problems is how to put such a huge structure into Earth orbit. To be effective, the size of the space solar power plant could reach ten square kilometres (1,400 football fields), so it is necessary to work with extremely light materials since the most expensive part of the whole project would be to launch the device into orbit itself. One proposal, widely supported, is to build a solar power plant out of thousands of smaller satellites equipped with solar panels that would assemble in space into one large structure. What is certain, is that such solar power plants orbiting the Earth could be realised in the coming decades. So far, only China has a concrete plan for this, which in 2016 presented plans for a solar power plant that could produce 2 gigawatts of energy. The SSPS-OMEGA (Space Solar Power Station via Orb-shape Membrane Energy Gathering Array) is planned to be operational in 2050 and could replace the full capacity of more than six million terrestrial solar panels at maximum capacity (Hughes–Soldini 2020). OMEGA can be thought of as a modular, spherical system concept in which sunlight is collected by the main reflector and energy is produced in a series of PV cell arrays. Electricity is supplied to microwave devices using electrical cables and conductive joints (Yang 2016: 53).

One such attempt is CASSIOPeiA (Constant Aperture, Solid-State, Integrated, Orbital Phased Array), which is a new format microwave antenna. According to its creators, when combined with a space-based solar system, it will serve as the basis for a satellite that will be able to partially meet the growing terrestrial energy demand at high specific power. By using an appropriate orbit (the best would be geosynchronous – in this case, there is no need for several ground stations, one is enough), the technology would be in sunlight 24 hours a day, and if several ground receiving stations were in its field of view at the same time, the generated energy could be continuously radiated to the ground station with minimal atmospheric loss at frequencies below 10 GHz (Cash 2019: 170–171; Zhang et al. 2021: 2). The same Space-Based Solar Power (hereinafter SBSP) solution will be offered by ESA's SOLARIS project: "The goal of SOLARIS is to prepare the ground for a possible decision in 2025 on a full development programme by establishing the technical, political and programmatic viability of SBSP for terrestrial clean energy needs" (ESA 2022b). True, even though almost all the equipment and techniques required for a Space Solar Power Station (hereinafter SSPS) or SBSP are already well developed, both the launch infrastructure and the huge costs of ground stations are not affordable, which is why it remains a significant obstacle to achieving viable economic performance. (Solar panels currently designed for use in space have a very high price of around $500/W; taking efficiency into account, a power plant providing 1 GW of electricity on the surface would require 11.2 GW of solar panels. A price of $250/W seems achievable in the foreseeable future, but it would still cost $2,800 billion for solar panels alone) (Zhang et al. 2021: 3; Nagy 2018: 70). But this does not deter innovators, in 2021 ESA finally highlighted 16 ideas out of 85 received on the topic "Solar Power from Space" that could be put on the path to implementation (ESA 2021).

By the way, successful attempts have already been made: the electrical energy generated in space with solar panels was converted into microwaves and beamed down to Earth, where it was converted back into electric energy (Perkins 2023). So, science fiction of the 20th century is actually starting to become a reality.

Possible power supply of the future lunar base

Future lunar bases could not only offer the possibility of energy sharing between lunar-based energy communities, but the Moon could also be a possible point from which the solar energy generated there, but not used locally, could be beamed to Earth in the future. Not only with the help of satellites but also with the help of the Moon – taking advantage of the correspondence between its rotation period around its axis and its orbital period around the Earth – the base load of electricity worldwide could be complemented by the beamed energy from there. What is more, the isotope ^{3}He is located on the Moon, which, together with deuterium, provides fuel for fusion energy. According to some calculations, if fusion power plants could operate on the moon, only 20 tons of isotope ^{3}He would be needed to meet the entire annual electricity demand of the United States. It is another matter, of course, that although the Moon consists of 30% machinable metals, 20% silicon and 40% oxygen, which can help build a power plant locally with the help of robots (Lior 2001: 1772–1773), the question arises whether this is the more economical solution or transporting isotope ^{3}He to Earth.[8]

Fleith and co-workers offer a solution for storing energy produced on the Moon and then used locally: One of the biggest challenges of exploring the Moon is storing the energy needed for missions. Due to the prohibitive costs of transporting materials from Earth, In-Situ Resources Utilization (hereinafter ISRU) is necessary for energy production and storage. If batteries were used for energy storage, their number would be at least two orders of magnitude larger than that used on the International Space Station, leading to a dramatic increase in the mass to be launched from Earth. Fortunately, lunar poles are regions that receive prolonged exposure to sunlight due to the low inclination of the Sun and local topography. Therefore, photovoltaic panels could be used over long periods of time, which would reduce the amount of energy to be stored during dark periods. Regarding energy storage, ISRU's approach as a means

[8] Other useful materials are also "by-products" of the mining of isotope ^{3}He, which can contribute to sustaining local life.

of energy supply is to use lunar regolith to store thermal energy, similar to the concept of underground thermal energy storage used on Earth. On the Moon, a cold working fluid would pass through the heat mass and absorb heat, which could be used as a source for a heating system. Heat masses could be produced using sintered regolith on the Moon (Fleith et al. 2020: 1–3).

Energy to Mars

The average distance between the Sun and Earth is about 150 million kilometres, while the average distance between the Sun and Mars is 228 million kilometres (ELTE s. a.) and the irradiation of the Sun between the Sun and Mars is 40% of the terrestrial value (as it was mentioned before), therefore, especially at the beginning of colonisation and infrastructure construction, nuclear energy will be needed due to the high energy demand.

NASA's Kilopower fission surface power project – initially planned for 10 kilowatts – could offer a solution in the late 2020s. The project has developed preliminary concepts and technologies for an affordable nuclear fission power system enabling long-term stays on the planetary surface. Following the successful completion of The Kilopower Reactor Using Stirling Technology (KRUSTY) experiment in March 2018, the Kilopower project team has started to develop the mission concepts for the lunar demonstration. The lunar demonstration, part of the current fission surface power project, will pave the way for future fission surface power systems. The technology could enable the establishment of human outposts on the Moon and Mars, including mission operations in harsh environments (Mohon 2017).

For those who think even bigger, Saturn's largest moon, Titan, is one of the most interesting places in the Solar System, with a dense atmosphere, surface and subsurface oceans and complex topography. Paluszek and co-workers present a conceptual design for a fusion-powered system to explore Titan and enable the use of powerful instruments. The plan includes a fusion-powered orbital transfer vehicle and an electrically powered aircraft. The Direct Fusion Drive (hereinafter DFD) could put the spacecraft into orbit around Titan in less than two years. A second fusion reactor would be used to power the electric aircraft. Both reactors are based on the Princeton Field-Reversed Configuration concept, a technical solution that uses a novel radio-frequency plasma heating system and deuterium-helium-3 fuel. The electric aircraft would be propelled into Titan and then be able to fly at subsonic speeds anywhere on Titan. The DFD-powered transfer vehicle would allow the transfer stage in orbit to change inclination as needed to cover different areas of the surface (Paluszek et al. 2023: 82–93). The exploration of Mars, and especially further afield, also raises the need for settlements and colonies in space. Let us now examine the energy aspects of these communities from the point of view of energy communities.

The future opportunity of shared energy production in space

Returning to the Outer Space Treaty, Articles 9 to 12 regulate cooperation between States Parties to the Treaty on the Moon and other celestial bodies, but it is Article 12 that actually states: "All stations, installations, equipment and space vehicles on the Moon and other celestial bodies shall be open to representatives of other States Parties to the Treaty on a basis of reciprocity." This cooperation may already raises the possibility of sharing energy sources, energy production and use, and consuming jointly produced energy locally if the individual bases are sufficiently close since locally produced and consumed energy is the most economical solution. Furthermore, Article 4 of the 1979 Moon Agreement states that "due regard shall be paid to the interests of present and future generations" – this statement may be familiar concerning sustainable development in terrestrial terms, and indirectly about energy use. Also, Article 4 point 2 states that "States Parties shall be guided by the principle of co-operation and mutual assistance in all their activities concerning the exploration and use of the moon", which reciprocity could also be valid and economical for energy production and use, especially considering that Article 9 could soon become a reality and lunar base(s) could be established. When these are established, they will be able to generate energy and feed themselves even with the help of natural resources found on the Moon, i.e. it will be necessary to establish the international regime referred to in Article 11, points 5–7 of the Moon Agreement, which according to the agreement will regulate a) the orderly and safe development of the natural resources of the moon that will be based on b) the rational management of those resources and c) the expansion of opportunities in the use of those resources. Last but not least, d) an equitable sharing by all States Parties in the benefits derived from those resources, whereby the interests and needs of the developing countries, as well as the efforts of those countries which have contributed either directly or indirectly to the exploration of the Moon, shall be given special consideration.

Of course, all these need to be adapted to today's prospects, which the Artemis Accords partially did, and also the number of its signatories should be higher than in the case of the Moon Agreement, with special attention to those States who have an interest in establishing a lunar base. Point 2 of Section 10 on space resources states that "the Signatories affirm that the extraction of space resources does not inherently constitute national appropriation under Article II of the Outer Space Treaty" – nothing could demonstrate this better in practice than sharing the resources extracted and used locally for energy production or sharing the energy produced. At the same time, Section 11 on deconfliction of space activities: point 7 refers to the so-called "safety zone", which refers to an "area wherein this notification and coordination will be implemented to avoid harmful interference". In other words, the Signatories will likely want to establish safety zones around their own facilities, so isolation from each other may make distributed energy production and use more difficult.

As it is recently recognised, (e.g. MacKay 2008: 231–255) the most economical and nature-friendly method of energy production and use on Earth is always locally produced and used, even optimally shared with smart devices. Presumably, this will be no different in space for bases established on individual celestial bodies. In other words, community energy production and use serve not only sustainability, which is considered important in space contracts and treaties but also economic operation, which is one of the primary considerations for an extremely expensive industry.

Possible parallels between energy communities on Earth and future energy communities in space

In terrestrial environments, community energy production and use are currently implemented by energy communities, which are still in their infancy but are developing rapidly, with several pilot projects underway throughout the European Union and around the globe. As regards the EU regulation, Directive 2019/944/EU (about the internal electricity market) already deals extensively with energy communities, paragraph (44) of the Preamble states that any legal entity may be a member of energy communities, but that the decision-making power of the Community can only be exercised by members who do not engage in extensive commercial activities or who do not carry out their main economic activities in the energy industry.

It can be seen that the regulation was designed for terrestrial relations, i.e. about natural and legal persons, and there is no international legal basis on which the individual cooperating nations could build when establishing a space base, and later a space and planetary colony. That is why bilateral international treaties may be the simplest solution initially.

One thing is for sure, under Article 2 (11) point b) of Directive 2019/944/EU, the energy community is a legal entity whose primary objective is not to make financial gains, but to provide environmental, economic and social community benefits to its members or shareholders or local areas under its operation – has some echoes with the provisions of the Outer Space Treaty on the shared use of outer space.

Point c) of the same article defines the concept of energy community as a legal entity which may participate in energy production, including renewable sources, energy distribution, energy supply, energy consumption, aggregation, energy storage or energy efficiency services, or provide services for the recharging of electric vehicles, or provide other energy services to its members or shareholders. In addition, Article 16 highlights that participation in energy communities should be based on a voluntary decision, which should be an open opportunity for all, also members should subsequently be entitled to leave the community (Biró 2022: 21), which also parallels the Outer Space Treaty, as it is an opportunity open to all.

However, while regulatory sandbox has been the possible solution for energy communities and related innovations on Earth, this is unlikely to be feasible in a highly regulated environment such as space. The essence of the regulatory sandbox, as stated by the Council of the European Union, is that it is increasingly used in a range of sectors, for example in finance, health, legal services, aviation, transport and logistics as well as energy, often including the use of new, emerging technologies or the innovative use of existing technologies (Council of the European Union 2020). In other words, the operation of energy communities that may be created in space in the future will not be characterised by free development, but their operation will be limited by strict regulations, which should be based on the application of the most serious and secure technological developments, and not on the subsequent regulation of freely emerging, experimental developments.

CONCLUSIONS

Overall, the paper reviewed what kind of conclusions could be drawn from the current legal regulation on energy use in space and examined the possible energy sources belonging to missions planned at different distances that are the most likely to be applicable at the moment. Based on the discussed international space-related treaties, legal documents and recommendations, it can be concluded that the legitimacy of NPS applications is recognised, as they are essential, given that the opportunities for interplanetary missions are about to open up for humanity. Moreover, as soon as technological solutions not only theoretically but also practically enable long-distance missions, NPS applications and other possible solutions outlined in this paper that may seem futuristic today, such as HPS and SMR and nuclear fusion, will need to be regulated in detail as well. On the other hand, it is also conceivable that there will be technological breakthroughs in the energy production methods currently used in orbit, in which case new regulations will be needed, where the mentioned SSPS and SBSP technologies are expected to be among the first. Space exploration and technological progress have been on a mutually reinforcing path in the past, we can assume the same in the future, and it is likely that if we can rise above our challenges on Earth, science fiction can become a reality.

REFERENCES

Appelbaum, J. – Flood, D. J. (1989): *Solar Radiation on Mars.* NASA Technical Memorandum 102299. Online: https://ntrs.nasa.gov/api/citations/19890018252/downloads/19890018252.pdf

Bedingfield, K. L. – Leach, R. D. – Alexander, M. B. (1996): *Spacecraft System Failures and Anomalies Attributed to the Natural Space Environment.* NASA Reference Publication 1390. Alabama: Marshall Space Flight Center. Online: https://ntrs.nasa.gov/api/citations/19960050463/downloads/19960050463.pdf

Biró, Zs. (2022): The Current EU and Hungarian Legislation of Energy Communities and Possible Future Directions. In Garayová, L. (ed.): *Budúcnosť práva – Právo budúcnosti II. Zborník príspevkov z online vedeckej konferencie – The Law of the Future – The Future of Law II. Conference Proceedings.* Bratislava: Paneurópska vysoká škola, Fakulta práva. 165–185.

Braun, T. (2018): Rubik-kockával a világűrkutatásban. Ionos folyadékokkal hajtott nanoműholdak. *Magyar Kémikusok Lapja,* 73(3), 96–99. Online: https://doi.org/10.24364/MKL.2018.03

Cash, I. (2019): CASSIOPeiA – A New Paradigm for Space Solar Power. *Acta Astronautica,* 159, 170–178. Online: https://doi.org/10.1016/j.actaastro.2019.03.063

Conole, K. (2023): *U.S. Statement as Prepared for U.S. Representative Kevin Conole.* U.S. Mission to International Organizations in Vienna. Online: https://vienna.usmission.gov/u-s-statement-agenda-item-15-use-of-nuclear-power-in-outer-space-60th-session-of-the-stsc-of-copuos/

Council of the European Union (2020): Council Conclusions on Regulatory sandboxes and experimentation clauses as tools for an innovation-friendly, future-proof and resilient regulatory framework that masters disruptive challenges in the digital age. 12683/1/20 REV 1. Brussels, 16 November 2020, 13026/20.

Datas, A. – Martí, A. (2017): Thermophotovoltaic Energy in Space Applications: Review and Future Potential. *Solar Energy Materials and Solar Cells,* 161, 285–296. Online: https://doi.org/10.1016/j.solmat.2016.12.007

ELTE (s. a.): *A Naprendszer adatai.* Online: http://sterni.web.elte.hu/anyag/ora2.html

ESA (2021): *Clean Energy – New Ideas for Solar Power from Space.* Online: https://ideas.esa.int/servlet/hype/IMT?documentTableId=45087625530300097&userAction=Browse&templateName=&documentId=514a8db636ea637f6e27069183966350

ESA (2022a): *SBSP History.* Online: www.esa.int/Enabling_Support/Space_Engineering_Technology/SOLARIS/SBSP_history

ESA (2022b): *SOLARIS.* Online: www.esa.int/Enabling_Support/Space_Engineering_Technology/SOLARIS

ESA (2022c): *Space-Based Solar Power Overview.* Online: www.esa.int/Enabling_Support/Space_Engineering_Technology/SOLARIS/Space-Based_Solar_Power_overview

Fleith, P. – Cowley, A. – Canals Pou, A. – Valle Lozano, A. – Frank, R. – López Cordóba, P. – González-Cinca, R. (2020): In-situ Approach for Thermal Energy Storage and Thermoelectricity Generation on the Moon: Modelling and Simulation. *Planetary and Space Science,* 181, 1–12. Online: https://doi.org/10.1016/j.pss.2019.104789

Hughes, A. J. – Soldini, S. (2020): Solar Power Stations in Space Could Be the Answer to our Energy Needs. *The Conversation,* 19 November 2020. Online: https://theconversation.com/solar-power-stations-in-space-could-be-the-answer-to-our-energy-needs-150007

JHUAPL (2018): *Interstellar Probe: Study for Upcoming Heliophysics Decadal Survey.* Presentation. Online: https://interstellarprobe.jhuapl.edu/

Lior, N. (2001): Power from Space. *Energy Conversation and Management,* 42(15–17), 1769–1805. Online: https://doi.org/10.1016/S0196-8904(01)00040-1

MacKay, D. J. C. (2008): Sustainable Energy – Without the Hot Air. Cambridge: UIT Cambridge. Online: www.withouthotair.com

Miller, T. F. – Paul, M. V. – Oleson, S. R. (2016): Combustion-based Power Source for Venus Surface Missions. *Acta Astronautica,* 127, 197–208. Online: https://doi.org/10.1016/j.actaastro.2016.05.006

Mohon, L. (2017): *Kilopower.* Online: www.nasa.gov/directorates/stmd/tech-demo-missions-program/kilopower-hmqzw/

Nagy, I. (2018): Naperőművek föld körüli pályán. *Repüléstudományi Közlemények,* 30(2), 67–74.

NASA (2000): *Explanatory Supplement. Chapter 7: Fundamentals of Orbital Mechanics.* Online: https://spsweb.fltops.jpl.nasa.gov/portaldataops/mpg/MPG_Docs/MPG%20Book/Release/Chapter7-OrbitalMechanics.pdf

NASA (2023): *In-Space Propulsion.* Online: www.nasa.gov/smallsat-institute/sst-soa/in-space_propulsion/

NASA [s. a.]: *Basics of Space Flight. Chapter 4: Trajectories.* Online: https://science.nasa.gov/learn/basics-of-space-flight/chapter4-1/

O'Neill, G. K. (1975): Space Colonies and Energy Supply to the Earth. *Science,* 190(4218), 943–947. Online: https://doi.org/10.1126/science.190.4218.943

Paluszek, M. – Price, A. – Koniaris, Z. – Galea, C. – Thomas, S. – Cohen, S. – Stutz, R. (2023): Nuclear Fusion Powered Titan Aircraft. *Acta Astronautica,* 210, 82–94. Online: https://doi.org/10.1016/j.actaastro.2023.04.029

Perkins, R. (2023): *In a First, Caltech's Space Solar Power Demonstrator Wirelessly Transmits Power in Space*. Online: www.caltech.edu/about/news/in-a-first-caltechs-space-solar-power-demonstrator-wirelessly-transmits-power-in-space

Petrocelli, A. – Bettinger, R. A. – Kutz, N. C. – Hartsfield, C. (2023): Atlas of Historical and Proposed Nuclear Devices and Power Systems in the Earth–Moon System and Wider Solar System. *Progress in Nuclear Energy,* 164, 1–19. Online: https://doi.org/10.1016/j.pnucene.2023.104857

UN COPUOS – IAEA (2009): *Safety Framework for Nuclear Power Source Applications in Outer Space.* United Nations Committee on the Peaceful Uses of Outer Space – International Atomic Energy Agency.

VERDUCI, R. – ROMANO, V. – BRUNETTI, G. – YAGHOOBI NIA, N. – DI CARLO, A. – D'ANGELO, G. – CIMINELLI, C. (2022): Solar Energy in Space Applications: Review and Technology Perspectives. *Advanced Energy Materials,* 12(29), 1–24. Online: https://doi.org/10.1002/aenm.202200125

World Nuclear Association (2021): *Nuclear Reactors and Radioisotopes for Space.* Online: https://world-nuclear.org/information-library/non-power-nuclear-applications/transport/nuclear-reactors-for-space.aspx

YANG, Y. – ZHANG, Y. – DUAN, B. – WANG, D. – LI, X. (2016): A Novel Design Project for Space Solar Power Station (SSPS-OMEGA). *Acta Astronautica,* 121, 51–58. Online: https://doi.org/10.1016/j.actaastro.2015.12.029

ZHANG, T. – LI, Y. – CHEN, Y. – FENG, X. – ZHU, X. – CHEN, Z. – YAO, J. – ZHENG, Y. – CAI, J. – SONG, H. – SUN, S. (2021): Review on Space Energy. *Applied Energy,* 292, 2–23. Online: https://doi.org/10.1016/j.apenergy.2021.116896

Further legal documents

The Artemis Accords. Principles for Cooperation in the Civil Exploration and Use of the Moon, Mars, Comets, and Asteroids for Peaceful Purposes

Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 on Common Rules for the Internal Market for Electricity and Amending Directive 2012/27/EU

Guidelines for the Long-term Sustainability of Outer Space Activities A/AC.105/2018/CRP.20

Moon Agreement. 34/68 Agreement Governing the Activities of States on the Moon and Other Celestial Bodies

Outer Space Treaty. 2222 (XXI). Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies

Resolution 47/68 of 1992. Principles Relevant to the Use of Nuclear Power Sources in Outer Space

Róbert Marc[1]

Robotic Pioneers: Helping to Create a Sustainable Presence in Space

INTRODUCTION

Since the very first satellites in space, robotics and automation have played an important role in meeting challenging space mission requirements. Robotic technologies enable the completion of tasks in environments where human presence is non-viable. Many of our most important space missions – one only has to think about the James Webb Space Telescope (JWST), the Voyager missions, or any of the Mars rover missions – are aimed at helping us to understand our universe and answer fundamental questions motivating space research, such as: Where do we come from? Where are we heading? These missions often require operation in the most hostile and distant environments where we cannot send humans and may never be able to do so. Instead of astronauts, however, we can send robotic probes and rovers. Therefore, robotics and robotic platforms are instrumental in meeting some of the most important aims of space research.

Space exploration – the mere act of uncovering what is around us even before conducting science with further goals – has consistently propelled humanity beyond Earth's boundaries and into the expansive cosmos. The allure of space travel and the aspiration for a permanent human presence in space have always sparked wonder and optimism, and it is increasingly evident that robotics stands as an indispensable catalyst in transforming these aspirations into tangible realities. The transformative power of robotic innovation has

[1] AOCS/GNC department, Airbus Defence and Space Ltd., United Kingdom, robert.v.marc@gmail.com, ORCID: https://orcid.org/0009-0007-2036-2083

DOI: https://doi.org/10.36250/01209_07

reshaped the landscape of space exploration, opening avenues for a sustainable human presence in space – formerly relegated to the realms of science fiction.

This article delves into the pivotal role of robotics in the pursuit of establishing a lasting human presence in space. Through a historical lens, we explore how robots have played a vital role in enhancing our comprehension of the universe and enabling exploration of distant celestial bodies. We scrutinise the merits of incorporating robots into space missions, ranging from their cost-effectiveness to their resilience in facing the extreme conditions of space.

In the pursuit of establishing a lasting human presence beyond Earth, robots transcend their role in exploration. Their significance extends to becoming essential contributors in constructing and maintaining space habitats for humans, optimising resource utilisation and executing pivotal experiments. These multifaceted tasks lay the groundwork for achieving a self-sustainable presence in space.

This paper is organised as follows: the first few sections summarise a historical perspective of space exploration, including the International Space Station (ISS). The following two sections focus on past and future Mars exploration missions. In the second part of the article, we discuss the various elements regarding the advantages of robots used in space exploration and the collaboration between humans and robots, next we examine the topic of habitat creation. Finally, we conclude by highlighting the future roadmaps of robotic exploration and summarising the main points of the article.

TYPES OF SPACE ROBOTIC ASSETS

Space robotic platforms are specially designed systems that can function in hostile environments. Their complexity and capabilities vary greatly and their purposes are diverse. To make some sense of all these variables, here the author arbitrarily designates a few broad classes of robotic systems according to the missions they are intended to perform. To be noted that some of the missions could be classified into several categories. In terms of taxonomy, space robotics can be broadly categorised into manipulator systems (i.e. robotic arms), mobile systems (i.e. rovers), lander systems (i.e. static probes) and robotic space probes. This taxonomy highlights the diverse roles and functionalities of space robots, each tailored to specific mission requirements.

The first category is robotic arms, which are manipulative structures equipped with joints and end-effectors. These arms are versatile tools used for tasks such as sample collection, maintenance and assembly. They are prominently featured on rovers, landers and space probes to enhance their functionality.

Rovers represent another group of space robotics, serving as mobile platforms equipped with wheels or legs for navigation. These vehicles are designed to traverse planetary surfaces, capturing images and collecting data. Rovers play a significant role in scientific exploration, conducting in-situ experiments and analysing terrain to broaden our understanding of celestial bodies.

The objective of a lander spacecraft is to successfully touch down on the surface of a target planet and then operate autonomously or semi-autonomously to gather and transmit valuable data back to Earth. This data often includes crucial insights into the planetary composition, atmospheric conditions, geological features and other specific scientific parameters.

Finally, space probes are equipped with varying degrees of autonomy, and constitute another integral component of space robotics. These probes are deployed for remote sensing, data collection and analysis. Advanced autonomy allows them to make decisions based on predefined algorithms, adapting to changing conditions without direct human intervention.

BRIEF HISTORY OF SPACE EXPLORATION

Since 1957, when the Soviet Union successfully launched the Sputnik 1 satellite, humans have consistently dispatched robotic emissaries into space, serving as pioneers in the exploration of the vast cosmos beyond Earth. Throughout the years, various forms of robotic spacecraft, including probes, rovers and landers, have journeyed to every planet in our solar system and even ventured into the interstellar medium (Angelo 2007).

In December 1962, the Mariner 2 mission achieved the historic milestone of becoming the world's first robotic space probe to successfully complete a Venus flyby (NASA 2023). It collected measurements based on which it became known that the solar wind streams continuously, it helped to further refine the mass of Venus and noted the high temperatures of the atmosphere of the planet (500 Celsius). The Mariner missions helped to highlight the significant environmental differences between Earth and Venus, and such space agencies became focused on other planets.

In 1970, the Soviet spacecraft Venera accomplished the remarkable feat of landing on the surface of Venus. This marked the first instance of an unmanned probe successfully touching down on another planet and transmitting surface data back to Earth. Due to the conditions prevailing on Venus, attention was turned towards the Moon and Mars and thus space agencies started to optimise for robotic exploration.

One year after the United States' (U.S.') Moon landing, the Soviet Union achieved the first successful deployment of a robotic lunar rover named Lunokhod in 1970. Operating remotely from November 1970 until the summer of the following year, Lunokhod covered almost 10 km across the lunar surface in teleoperation mode (Siddiqi 2018). The Lunokhod Programme pushed the boundaries of rover design, technology, manufacturing and teleoperation.

The NASA Viking mission, commencing in 1968, witnessed successful landings on Mars in 1976. These missions were equipped with robotic technology similar to Mariners 4 and 6. Each Viking spacecraft comprised both a lander and an orbiter. The purpose of these mission series was to build up the knowledge and technology necessary to survive Martian orbit insertion, pass the Entry, Descent and Landing (EDL) stage successfully and deploy landers on the surface in a soft manner.

The list of the most significant robotic missions includes the Voyager probes, which flew by several planets. The probes, even after nearly 50 years, continue to transmit valuable data beyond the heliopause. Both of the spacecraft, Voyager

1 and 2, were launched in 1977, performed flybys of Jupiter and Saturn before Voyager 2 continued to Uranus and Neptune, offering unprecedented insights into the outer planets and their moons, making it the only spacecraft to have done so. Both Voyager crafts are currently journeying billions of kilometres from the Sun, studying particle and magnetic properties of interstellar space. In the summer of 2012, Voyager 1 flew beyond the heliopause and entered interstellar space, the first ever human made object to reach such a feat (NASA Jet Propulsion Laboratory [s. a.]).

Since the early 1970s, the United States and the former Soviet Union undertook challenging missions, sending a plethora of spacecraft to explore neighbouring planets. The list of most prominent missions of this era, of course, has to include the Apollo missions, which primarily focused on human exploration of the Moon, but were equipped with robotic components to help interplanetary travel. These instances exemplify the versatility and far-reaching ambitions enabled by robotic technologies in space exploration initiatives. These missions were characterised by challenging flyby manoeuvres around neighbouring celestial bodies, demonstrating the technological skills of the era.

Despite their limited timelines, the missions achieved remarkable scientific returns. Examples like the Pioneer 10 and 11 missions conducting flybys of Jupiter and Saturn underscore the importance of exploration and discovery that defined the initial phase of interplanetary exploration. These missions, by gathering valuable data about the planets of the solar system, exemplify the adventurous spirit that laid the foundation for subsequent human spaceflight endeavours around the lower Earth orbit and beyond.

ROBOTICS ON THE ISS

Assembly of the International Space Station (ISS) commenced in 1998, marking the beginning of the construction of the most expensive space asset to date (ESA [s. a.]a). Positioned in Low Earth Orbit (LEO), the ISS holds the title of the largest space station ever constructed. Its construction involved a remarkable effort involving most major space agencies, encompassing over 250 Extravehicular Activities (EVAs), commonly known as astronaut spacewalks.

Integral to the assembly process was the utilisation of Canadarm2, a robotic asset developed by the Canadian Space Agency (CSA). Canadarm2 played a crucial role in manoeuvring and assembling various modules of the ISS. Simultaneously, the European Space Agency (ESA) made substantial contributions to the ISS project by investing in developing the Columbus module and its own space-qualified robotic arm. After more than three decades of dedicated work and overcoming substantial delays, the European Robotic Arm (ERA) achieved a significant milestone when it was successfully launched in 2021 (ESA [s. a.]b). Following its launch, ERA underwent in-orbit commissioning the next year, solidifying its role as a valuable addition to the robotic infrastructure of the ISS.

This collaborative effort by multiple space agencies demonstrates the international cooperation and technological advancements that have propelled the construction and operation of the ISS, showcasing the capabilities of both human and robotic assets in the challenging environment of space.

MARTIAN EXPLORATION

Traditional rovers from various space agencies such as NASA's Sojourner, twin rovers Opportunity and Spirit, later on, Curiosity and Perseverance have enabled great discoveries on Mars, but have limitations when it comes to other celestial bodies (e.g. Moon, Phobos, asteroids). We are focusing in this chapter on the Martian case which is of great interest for various reasons: closeness to Earth, vaguely similar temperature and atmospheric conditions.

Sojourner, the inaugural U.S. robotic rover on Mars, touched down on 4 July 1997, and explored the flat terrain of Ares Vallis near its landing site of the Pathfinder Lander. During its brief operational span of two months, Sojourner transmitted 550 images of Mars and collected valuable data on soil composition, wind patterns and weather conditions (Siddiqi 2018). In 2004, NASA's Jet Propulsion Laboratory (JPL) successfully deployed two identical rovers, Spirit and Opportunity, equipped with cameras, computers and specialised scientific instruments. Beyond their expected three-month lifespan, both rovers made groundbreaking discoveries, confirming the planet's past water presence. In 2011, Spirit identified that dust in the Gusev Crater was found to be magnetic, moreover, it also identified rock containing zinc and bromine, indicating the past flow of heated water (Bertelsen et al. 2004). Opportunity transmitted its final data to NASA in June 2018, being operational for a total of 5,111 sols and traversing a total distance of 45.16 km (Platt 2019).

In the frame of NASA's Mars Science Laboratory's mission, Curiosity, a car-sized rover, which landed on Mars in August 2012, remains active after many years. Initially commissioned for a one Martian year mission duration and the capability to achieve at least 20 km, NASA extended Curiosity's tenure indefinitely just six months after landing. Designed to assess the habitability of Mars, Curiosity boasts the largest and most advanced suite of scientific instruments ever sent to the Martian surface (NASA Jet Propulsion Laboratory 2012); it also contains no less than 17 onboard cameras. These instruments can collect rock samples, analyse their composition and structure, and transmit the data back to Earth. The main challenges to its mobility capabilities included issues related to wheel wear, wheel entrapment and progressive wheel sinkage (Rankin et al. 2020).

Building on the previous successful missions, in July 2020, the Perseverance Rover embarked on its journey to the Martian surface. While resembling its predecessor, Curiosity, Perseverance boasts an enhanced wheel design and is equipped with a drill for collecting samples from Martian rocks and soil. Additionally, Perseverance carries the Ingenuity helicopter, the first vehicle to take flight on another planet. This small helicopter faces the unique challenge of flying in the atmosphere of Mars, which is only 1% as dense as Earth's. Enduring harsh conditions, including overnight temperatures plunging to −70 °C, Ingenuity was designed to conduct four planned 90-second flights. Perseverance landed successfully on Mars in February 2021, equipped with an array of technology, including 23 different cameras. Ingenuity is meant to be a 30-day technological demonstrator, originally designed for 5 flights at an altitude between 3–5 m. The successful performance in the challenging Martian environment is outnumbering any previous expectations: in January 2024, Ingenuity had its 72nd flight during which it suffered rotor damage on a featureless terrain (NASA Jet Propulsion Laboratory 2024).

Various static landers without mobile platforms have played a crucial role in advancing our scientific understanding of extraterrestrial environments. For instance, NASA's InSight mission made significant contributions by measuring Martian earthquakes, providing valuable insights into the interior structure of the Red Planet (Yana et al. 2023). Static landers, with their specialised and fixed functionalities, have emerged as indispensable instruments in deciphering the enigmas of celestial bodies within our solar system and farther afield.

The ExoMars Mission, spearheaded by the ESA and previously in collaboration with Roscosmos, has its goal set on exploring Mars and uncovering potential evidence of past or present life. This comprehensive mission consists of two integral components: the ExoMars Trace Gas Orbiter (TGO) and the ExoMars Rover, aptly named the Rosalind Franklin Rover. The TGO was launched in 2016 and it is a hybrid science and telecom spacecraft that serves as an orbiter around Mars. It is equipped with scientific instruments (i.e. NOMAD, ACS, CASSIS, FREND) to study the Martian atmosphere, particularly focusing on trace gases like methane.

The Rosalind Franklin Rover, being part of the second mission phase, is designed to search for signs of the origins of life on Mars. It carries a 2-metre-long drill instrument to collect samples from below the Martian surface. The rover is equipped with a large suite of scientific instruments, including infrared spectrometers, ground penetrating radar and high-resolution cameras, to analyse the composition of the Martian soil (Vago et al. 2017). As such, the ExoMars Rover was meticulously designed and engineered for navigating through highly demanding terrains relative to its platform's capabilities, all the while prioritising the rover's safety (Winter et al. 2015). The core scientific objectives of the ExoMars mission encompass comprehending the Martian environment, probing potential traces of past or current life, and delving into the planet's geological makeup. Focused on exploring a region of significant scientific interest, the rover leverages its mobility and drilling capabilities to augment the mission's capacity for acquiring vital data (Gao 2016). The ExoMars mission represented a collaborative effort between ESA and Roscosmos, the Russian space agency in the quest to unlock the mysteries of Mars. Unfortunately, the project was further delayed and ESA announced that the launch of the rover has been suspended and delayed to at least 2028 (ESA 2023).

Zhurong stands out as China's maiden Mars rover mission being an integral part of the Tianwen 1 orchestrated by the China National Space Administration (CNSA). Its journey commenced with a launch on 23 July 2020, culminating in a successful orbital insertion on 10 February 2021, and a well-executed soft landing on Mars on 14 May 2021. This historic achievement not only marked China as the third nation to achieve a Mars soft landing but also secured its position as the second country to deploy a rover, following in the footsteps of the United States. Exploration activities officially kicked off on 22 May 2021.

Designed for a 90-sol lifespan, Zhurong exceeded expectations, operating for 347 sols (356.5 days) after deployment. Unfortunately, it became inactive on 20 May 2022, due to approaching sandstorms and the onset of Martian winter.

SAMPLE RETURN MISSIONS

The NASA–ESA Mars Sample Return (MSR) Campaign is a response to the long-running scientific objective to better understand Mars. By acquiring and returning to Earth an uncontaminated set of Mars samples, scientists will have access to the extent of science instruments available in terrestrial laboratories, unlocking new possibilities in exobiology, interplanetary geology and supporting our search for the origins of life (Muirhead et al. 2020). The plan involves a multi-step approach that spans several missions over more than a decade. The proposal envisions collecting these samples using a series of small, cylindrical, titanium tubes – 43 in total.

As of September 2022, the NASA–ESA plan has received approval for implementation. The mission involves three key phases (Haltigin et al. 2022):

Sample collection mission

Perseverance rover, part of the Mars Sample Return campaign, serves as the sample collection mission.

It gathers the Martian samples and prepares them for retrieval.

Sample retrieval mission

- This mission involves several components, including a Sample Retrieval Lander, Mars Ascent Vehicle, Sample Transfer Arm and two Ingenuity-class helicopters.
- The lander facilitates the safe landing and deployment of necessary equipment.
- The Mars Ascent Vehicle lifts the collected samples from the Martian surface.
- The Sample Transfer Arm transfers the samples to the Earth Return Orbiter (ERO).

Return mission

- The ERO, a crucial part of the mission, is responsible for transporting the collected samples from Mars to Earth.
- The return is anticipated around 2033, marking a historic moment in planetary exploration.

NASA's OSIRIS-REx mission was specifically designed and constructed for the investigation and sample collection from the near-Earth asteroid Bennu. Launched in 2016, the spacecraft reached Bennu, conducted extensive observations (Barnouin et al. 2020), and acquired samples from the asteroid's surface which were later delivered to the surface of the Earth. Its primary objective was to contribute insights into the early solar system, the formation of planets, and the potential existence of life's building blocks in asteroids.

The Martian Moons eXploration (MMX) is a forthcoming robotic space probe, scheduled for launch in 2024 (Clark 2020), with the primary objective of bringing back the first-ever samples from the largest moon of Mars, Phobos. Primarily developed by the Japanese Aerospace Exploration Agency (JAXA) and officially announced on 9 June 2015, the MMX mission encompasses landing and collecting samples from Phobos, possibly once or twice. Additionally, it includes Deimos flyby observations and the monitoring of the climate of Mars. A notable component of the MMX mission is the inclusion of a rover named IDEFIX, representing a collaborative effort between the French Space Agency (CNES) and the German Space Agency (DLR). This rover, weighing less than 30 kg on four wheels, is designed to navigate and explore the surface of Phobos within its unique microgravity environment (Barthelmes 2023). The mission aims to enhance our understanding of the Martian moons, particularly Phobos, by analysing collected samples and conducting observations. The inclusion of the IDEFIX rover will further extend the mission's capabilities, providing valuable insights into the geological and environmental characteristics of Phobos. The MMX mission holds the potential to contribute significantly to our broader knowledge of the Martian system.

Further sample return missions such as Hayabusa and Chang'e underscore significant milestones, so they should not be omitted. Hayabusa, led by JAXA, successfully retrieved and delivered for the first time samples from asteroids Itokawa (2010) and Ryugu (2020), contributing to our understanding of the early solar system. Meanwhile, the Chinese Chang'e 5 mission, operated by CNSA, in December 2020 has returned lunar samples. These endeavours reflect the increased steps that national space agencies are taking in unravelling the mysteries of our solar system.

ADVANTAGES OF ROBOTIC SOLUTIONS

Robotic platforms prove useful in space applications and exploration where the environments are too extreme and offer unparalleled superiority, especially when venturing into environments too challenging and hazardous for human survival without extensive protection. Take the surface of Mars for instance, where temperatures fluctuating from −153 to +20 degrees Celsius, present a formidable challenge for future astronauts. That is why it is more practical to send remote assets first in order to investigate, assess and prepare for the arrival of future astronauts. Additionally, the vacuum of space and the relentless barrage of solar particles, known as solar radiation, create an environment that is deadly to human presence. To overcome these challenges, space assets are meticulously engineered, subjected to rigorous testing, and built with strict requirements and safety margins. This meticulous approach ensures their resilience in the face of harsh conditions, making scientific missions feasible despite the complexity and potential delays associated with developing cutting-edge technologies.

In contrast to robotic systems, human spaceflight introduces a myriad of complexities that significantly escalate mission costs. The fundamental need for life support systems becomes imperative to guarantee the safety and well-being of astronauts, whether stationed aboard the International Space Station (ISS), prospective lunar bases, or potential Martian missions. Unlike robots, humans demand protection against extreme temperature variations and radiation exposure. They rely on a stable and continuous supply of air and water, necessitating sophisticated life support infrastructure. Moreover, human habitats must meticulously maintain constant pressure and temperature, adding layers of intricacy to space missions. The delicate equilibrium between sustaining human life and the inherently harsh space environment markedly amplifies the financial investment required for human spaceflight endeavours.

Robotic systems, on the other hand, sidestep these intricate challenges associated with human missions. They operate in environments where humans would face insurmountable difficulties without extensive protection measures. Robots do not require life support systems or meticulous habitat conditions.

This inherent advantage allows for streamlined mission planning and execution, resulting in cost-effective exploration of space. The absence of ethical, political and certification considerations, which are inherent in human spaceflight, further contributes to the efficiency of robotic missions. As robots navigate and gather data in the frontiers of space, they simultaneously contribute to the advancement of knowledge that can be leveraged to make future human flights safer and more informed. The synergistic relationship between robotic exploration and human spaceflight endeavours ensures a strategic and complementary approach to unravelling the mysteries of the cosmos.

On the ISS, where there is constant human presence, robotic arms handle heavy lifting tasks, showcasing the efficiency and precision of operation manipulator systems. Cargo transportation is facilitated by various cargo spacecraft, including from ESA, Japan, the United States and the Russian Federation, further emphasising the integral role of robotic systems in the logistics and functionality of space exploration endeavours. The advantages of robotic platforms extend beyond cost-effectiveness to encompass enhanced safety, endurance and adaptability in environments hostile to human life.

Moreover, robots play a pivotal role in space exploration and other environments that are deemed harsh and inhospitable for human presence. Their ability to operate in these challenging conditions stems from several key advantages that are summarised hereafter.

Extreme temperatures

In space and on celestial bodies like Mars, temperatures can vary widely, ranging from scorching heat to bone-chilling cold. Robots are equipped with materials and components designed to withstand these extreme temperature fluctuations, having extensive thermal protection and insulation, but not in need of life support systems, which is a complex and highly costly system of any spacecraft.

Radiation exposure

The void of space is filled with cosmic radiation, including solar and cosmic rays. Research studies of exposure to various doses and strengths of radiation provide strong evidence that cancer and degenerative diseases are to be expected from exposures to galactic cosmic rays (GCR) or solar particle events (SPE). Robots are vulnerable to some extent to the adverse effects of radiation. Their electronic components can be shielded and hardened to withstand radiation, allowing them to operate for extended periods in environments where humans would face significant health hazards.

Microgravity and low-gravity environments

Robots are not affected by the physiological challenges associated with microgravity or low-gravity environments, such as those on asteroids or moons. Human bodies undergo changes in bone density, muscle mass and cardiovascular function in microgravity conditions, making long-term human presence challenging. Robots, on the other hand, can navigate and perform tasks without the constraints of these gravitational limitations.

Planetary mobility

Planetary surfaces, especially those of Mars or the Moon, can be rugged and difficult to traverse. Robots can be designed with advanced mobility systems, such as wheels, legs, or even hopping mechanisms, to navigate challenging terrains without the constant need for human intervention (Rubio et al. 2019). This adaptability enables them to explore inaccessible areas where human mobility would be restricted. It is envisaged that mobile platforms will greatly support astronaut missions on the surface of the Moon or Mars (O'Shea 2023), similar to the Lunar Roving Vehicles (LRV) during the Apollo missions. LRVs allowed human explorers to cover more terrain and increased the range of science activities.

Harsh atmospheric conditions

Environments with corrosive atmospheres, such as the acidic clouds of Venus, would pose significant challenges to human survival. Robots can be constructed using materials resistant to corrosive elements, allowing them to endure and operate effectively in atmospheres that would be detrimental to human health.

Long duration missions

Robots can operate for extended periods without the need for life support systems, food, or rest. This endurance is particularly valuable for missions requiring prolonged exploration or monitoring, where human presence would be logistically challenging and economically impractical. For example, the most optimised transfer from Earth to Mars is about 9 months, during which there are several issues which needs to be solved for future astronauts to travel to the surface of Mars: shielding and protection for humans against radiation from the Sun, the psychological effects of long-term travel, and bringing enough supplies for a return mission.

Precision and repetitive tasks

Robots excel at performing precise and repetitive tasks with unwavering accuracy. In environments where monotony or precision is required, robots can outperform humans, contributing to efficient data collection, assembly, or maintenance tasks. Martian rover missions (e.g. Mars Exploration Rover missions, Curiosity) have been constantly conducting repetitive tasks, including drilling, sample collection and analysis.

By leveraging these advantages, robots become indispensable tools for space exploration and other applications in environments hostile to human life. Their versatility and adaptability make them ideal candidates for pushing the boundaries of scientific and engineering discoveries.

SAFETY ASPECTS

Safety stands as a paramount consideration in the planning and execution of exploration missions, especially as humanity embarks on groundbreaking Artemis Accords: a NASA led mission with major partner agencies such as JAXA, U.K. Space Agency (UKSA), United Arab Emirates Space Agency (UAESA), Canadian Space Agency (CSA) and Italian Space Agency (ASI). As of today, Artemis I (2022) was the successful uncrewed test of the SLS and Orion and was the first test flight for both crafts. The Artemis I mission involved placing Orion into lunar orbit before its return to Earth. These crewed missions, scheduled for 2024–2029, mark a historic return to the Moon's orbit after a hiatus of over 50 years. The overarching goal is to not only revisit lunar space but to advance human exploration by laying the groundwork for future lunar surface missions.

The safety protocols implemented in the Artemis Mission are comprehensive and multifaceted. They encompass rigorous spacecraft design, meticulous pre-launch testing and robust emergency contingency plans. Space agencies, in collaboration with private entities like SpaceX, prioritise the well-being and security of astronauts throughout the mission, considering the inherent challenges of space travel and lunar exploration.

As Artemis progresses, the subsequent phase aims to achieve another significant milestone: setting foot on the lunar surface, underscoring the commitment to safety as a fundamental aspect of the mission. Lunar surface operations pose unique challenges, including the abrasive nature of the lunar regolith, the potential for extreme temperature variations, and the need for life support systems in a hostile environment.

The lessons learned from past missions, such as the Apollo program, contribute to the ongoing refinement of safety measures. Advancements in technology, coupled with a wealth of experience, enable space agencies to enhance spacecraft reliability, astronaut training and mission preparedness.

In addition to lunar missions, the emphasis on safety extends to future endeavours, including crewed missions to Mars and beyond. Each step in space exploration is meticulously planned, integrating state-of-the-art safety features to mitigate risks and ensure the well-being of astronauts as they venture into the cosmos as projects that are funded by governmental agencies became risk-averse over the last few decades. The commitment to safety underscores the responsible approach taken by space agencies as humanity ventures into the future frontiers of space exploration.

HUMAN–ROBOT COLLABORATION

Several successful missions have been performed in the last decades within the human-robot interaction topic: such as ESA's teleoperation missions from the ISS. The Multi-Purpose End-to-End Robotic Operation Network (METERON), represents a forward-looking initiative gearing up for the future of space exploration (eoPortal 2020).

NASA has made significant investments in advancing human-like robotics projects, exemplified by initiatives like Robonaut: a dexterous anthropomorphic robotic system (Ambrose et al. 2000). These endeavours aim to integrate humanoid robotics into space exploration activities, capitalising on the dexterity and adaptability of human-like robotic systems. Robonaut, in particular, represents a cutting-edge venture developed by NASA in collaboration with technology partners. Projects such as Robonaut stress the commitment of space agencies to enhancing the capabilities of robotic systems for human–robot collaboration for current and future space missions. By designing robots with humanoid features (e.g. arms, hands and a torso), it aims to create intelligent machines capable of performing tasks in a manner more similar to how humans operate in terrestrial and space environments, moreover, such humanoids can cooperate with astronauts onboard the ISS (Diftler et al. 2011). This includes tasks that demand fine motor skills, intricate tool manipulation and efficient interaction with the surroundings.

Furthermore, support for initiatives such as Robonaut plays a crucial role in propelling the frontiers of artificial intelligence, machine learning, and collaborative endeavours between humans and robots. The aim is to create robots that seamlessly integrate with astronauts, elevating the overall effectiveness and safety of space missions. In the dynamic landscape of evolving technology, the lessons drawn serve as invaluable knowledge, steering the course of next-generation humanoid space robots. This trajectory sets the stage for progressively advanced and adept robotic systems within the domain of space exploration.

HABITAT CREATION

Establishing habitats on other celestial bodies is a critical step in the prospect of future human settlements, and robotic technologies will play a pivotal role in preparing environments that shield astronauts from challenging external conditions, such as temperature variations and atmospheric pressure fluctuations.

As we envision human presence beyond Earth, automated cargo vehicles are anticipated to play a crucial role in transporting the necessary materials and equipment to the lunar and Martian surfaces. These robotic cargo missions will serve as precursors to human expeditions, carrying payloads that include construction materials, life support systems and other essentials for habitat creation.

However, a significant challenge lies in the limited cargo capacity of current launch vehicles available as of the end of 2023. The payload constraints necessitate innovative solutions to optimise resource utilisation and minimise the number of launches required. SpaceX's revolutionary reusable Starship rocket emerges as a promising solution to address this limitation. With an impressive lift capacity of 100 to 150 metric tonnes to orbit, Starship has the potential to substantially increase the payload capacity for cargo delivery to lunar and Martian surfaces.

The deployment of robotic technologies in habitat creation involves a multifaceted approach. Automated cargo vehicles, equipped with advanced robotic systems, can perform precise tasks such as excavation, construction and assembly. Robotic arms and tools, controlled either remotely or autonomously, will be instrumental in preparing the groundwork for human-friendly habitats.

Beyond construction tasks, robots will also be tasked with creating protective environments within habitats. This includes setting up life support systems, ensuring stable atmospheric conditions and establishing energy infrastructure for sustained human habitation. The autonomous nature of these robotic systems is advantageous in executing repetitive or hazardous tasks without the need for direct human intervention.

As technologies continue to advance, the integration of artificial intelligence and machine learning will further enhance the capabilities of robotic systems in habitat creation. These intelligent robots can adapt to dynamic environmental conditions, learn from their surroundings and optimise their operations over time.

In summary, the future of habitat creation on celestial bodies heavily relies on the collaborative efforts of robotic technologies and advanced launch capabilities. By leveraging innovative solutions like SpaceX's Starship and employing sophisticated robotic systems, we are taking essential strides toward establishing sustainable and habitable environments beyond Earth.

In situ resource utilisation (ISRU) emerges as a critical strategy in the pursuit of sustainable human settlements on other celestial bodies. ISRU could provide materials for life support, construction materials, propellants, or energy to spacecraft payloads or space exploration crews. The ability to harness and leverage local resources for habitat creation becomes imperative to overcome the constraints of limited cargo capacity and ensure long-term viability. Robotic technologies play a central role in implementing ISRU, as they can be equipped to autonomously extract, process and utilise available resources on the Moon, Mars, or other destinations. For instance, robots can mine and process regolith to extract essential materials, such as metals and minerals, for construction purposes. This not only reduces the dependency on Earth-sourced materials but also minimises the need for extensive cargo transport, making the establishment of human habitats more cost-effective and sustainable. Another typical proposal for ISRU is the use of a Sabatier process, to produce methane to be used as a propellant on the Martian surface.

Moreover, ISRU extends to the utilisation of local energy sources. Solar panels deployed and maintained by robotic systems can harness the abundant solar energy available on the Moon's surface or Mars, powering habitat operations and reducing reliance on external power sources. By strategically integrating ISRU with robotic technologies, we pave the way for self-sufficient and resilient human settlements on other celestial bodies, where local resources become the building blocks for sustainable habitation and exploration.

NASA is gearing up for human exploration of Mars, and the MOXIE investigation on the Mars 2020 mission addresses a crucial knowledge gap by showcasing ISRU technologies for oxygen production from the Martian atmosphere. MOXIE collects CO_2 from the atmosphere of Mars, uses electrochemical processes to split CO_2 into O_2 and CO, and then analyses the purity of the produced O_2 before releasing it, along with CO and other exhaust products, back into the Martian atmosphere (Hoffman et al. 2022).

FINANCIAL CONSIDERATIONS

Automated robotic assets often outperform initial mission requirements, hence providing further scientific returns for the same asset, as only the cost of operations needs to be covered. One could argue that such machines cost taxpayers substantial amounts of budget, in fact, however, the yearly ESA budget costs European taxpayers less than a cinema ticket per capita (ESA [s. a.]c).

In the first 50 years of space exploration, during the space race, it was entirely financed by states in order to achieve many records such as the first satellite or the first Moon landing. In the last few years, private investors have gained significantly bigger slices of space exploration. One notable example is SpaceX, which revolutionised the rocket market segment with reusable rocket boosters, lowering the unit price per kg across the industry.

Venture capital also reached space companies: in the past few years, significant investment has flowed into the space sector. Consider the year 2021, where both public and private markets injected $10 billion of new capital into space companies (Bland et al. 2022). Numerous leaders and innovators in the space industry have concentrated on fostering internal growth by financing in-house technology for the development and construction of cutting-edge products. As an illustration, SpaceX made substantial investments in the rapid development and launch of Starlink, recognising the opportunity to apply established capabilities from its launch business to establish a satellite-based broadband internet system. The present is a different kind of space race: growth and technology are leveraged by increased capital.

ROADMAPS

In mapping out their trajectory for the coming decades, major space agencies appear to be steering towards sustained exploration, blending both robotic and human-centric initiatives. NASA, distinguished for its dedicated ventures toward Mars, stands ready to further explore the Red Planet. The emphasis lies on elevated robotic missions, integrating sophisticated sampling and analytical capabilities. Extending beyond Mars, the agency directs its focus toward the distant realms of our solar system. Ambitious missions are under consideration to unravel the enigmas surrounding Jupiter, Saturn, Uranus and Neptune, with a detailed examination of their atmospheres and diverse moons on the agenda.

ESA, on the other hand, envisions a lunar future with its ambitious Moon Village concept and having European astronauts on the surface of the Moon by 2030 (ESA 2022), fostering international collaboration for a prolonged lunar presence. Robotic missions are slated to be instrumental in laying the groundwork and offering logistical support for human endeavours on the Moon. As part of ESA's broader scope, deep space beckons, prompting consideration of missions to asteroids, comets and other celestial bodies, opening avenues for groundbreaking discoveries.

JAXA, with its distinct lunar focus, is anticipated to persist in lunar exploration missions, building upon the successes of Kaguya and charting new territories. The prospect of sample return missions is on the horizon, with JAXA eyeing potential targets among asteroids and intercepting comets together with ESA for meticulous scrutiny back on Earth.

Meanwhile, CNSA of China charts a course that encompasses lunar and Martian horizons. Prolonged lunar exploration, with a potential for sustained lunar habitation, is a key facet. Concurrently, the agency contemplates extending its Martian endeavours, integrating robotic missions and pondering the logistics of sample return missions. For China, these upcoming missions are planned to be in a non-cooperative setup.

These trajectories, intricately woven with scientific pursuits, resource utilisation aspirations and preparedness for potential human undertakings, epitomise the evolving landscape of celestial exploration. Anticipated adaptations to these strategic roadmaps will be influenced by the assimilation of cutting-edge technologies, synergistic international collaborations, and novel revelations unveiled through rigorous scientific exploration.

CONCLUSIONS

The possibilities for space robotics reach far beyond its role in aiding human space exploration. It embraces vital functions in upcoming endeavours such as resource extraction from celestial bodies like the Moon and asteroids. Additionally, space robotics plays a pivotal role in conducting secure scientific investigations throughout our solar system with current and future robotic space probes. Achieving these distant objectives necessitates the technology development of sophisticated hardware, and software while scaling up and optimising robotic functionalities. This can be only met with a vast amount of funding from both private and public entities.

Space robotics assumes paramount importance in establishing a permanent presence beyond Earth, undertaking tasks such as scientific research, habitat construction, infrastructure maintenance and other endeavours too hazardous or costly for humans. Realising the full potential of space robotics requires addressing challenges like creating resilient robots capable of withstanding the harsh conditions of space, developing autonomous software for diverse tasks and establishing necessary supporting infrastructure.

In overcoming these challenges, the focus on advanced robot software for space exploration becomes crucial. Companies and institutions are actively engaged in this pursuit, aiming to empower robots for diverse tasks in extreme environments. As humanity ventures further into space, the role of space robotics stands indispensable, shaping the future of space exploration and enhancing our understanding of the universe.

REFERENCES

Ambrose, R. O. – Aldridge, H. – Askew, S. R. – Burridge, R. – Bluethmann, W. – Diftler, M. – Lovchik, C. – Magruder, D. – Rehnmark, F. (2000): Robonaut: NASA's Space Humanoid. *IEEE Intelligent Systems and Their Applications,* 15(4), 57–63. Online: https://doi.org/10.1109/5254.867913

Angelo, J. A. (2007): *Robot Spacecraft. Frontiers in Space.* [s. l.]: Facts on File Science Library. Infobase Publishing.

Barnouin, O. S. – Daly, M. G. – Palmer, E. E. – Johnson, C. L. – Gaskell, R. W. – Al Asad, M. – Bierhaus, E. B. – Craft, K. L. – Ernst, C. M. – Espiritu, R. C. – Nair, H. – Neumann, G. A. – Nguyen, L. – Nolan, M. C. – Mazarico, E. – Perry, M. E. – Philpott, L. C. – Roberts, J. H. – Steele, R. J. – Seabrook, J. – Susorney, H. C. M. – Weirich, J. R. – Lauretta, D. S. (2020): Digital Terrain Mapping by the OSIRIS-REx Mission. *Planetary and Space Science,* 180(1). Online: https://doi.org/10.1016/j.pss.2019.104764

Barthelmes, S. – Buse, F. – Chalon, M. – Hacker, F. – Langofer, V. – Sedlmayer, H.-J. – Skibbe, J. (2023): *Driving in Milli-G: The Flight Model of the MMX Rover Locomotion Subsystem and its Integration & Testing in the Rover.* Proceedings of 17th Symposium on Advanced Space Technologies in Robotics and Automation (ASTRA). Online: www.researchgate.net/publication/376714092_Driving_in_Milli-G_The_Flight_Model_of_the_MMX_Rover_Locomotion_Subsystem_and_its_Integration_Testing_in_the_Rover

Bertelsen, P. – Goetz, W. – Madsen, M. B. – Kinch, K. M. – Hviid, S. F. – Knudsen, J. M. – Gunnlaugsson, H. P. – Merrison, J. – Nørnberg, P – Squyres, S. W. – Bell 3rd, J. F. – Herkenhoff, K. E. – Gorevan, S. – Yen, A. S. – Myrick, T. – Klingelhöfer, G. – Rieder, R. – Gellert, R. (2004): Magnetic Properties Experiments on the Mars Exploration Rover Spirit at Gusev Crater. *Science,* 305(5685), 827–829. Online: https://doi.org/10.1126/science.1100112

Bland, R. – Brukardt, R. – Gangware, W. – Swartz, D. (2022): A Different Space Race: Raising Capital and Accelerating Growth. *McKinsey & Company,* 16 November 2022. Online: www.mckinsey.com/industries/aerospace-and-defense/our-insights/a-different-space-race-raising-capital-and-accelerating-growth-in-space

Clark, S. (2020): Phobos Sample Return Mission Enters Development for 2024 Launch. *Spaceflight Now,* 20 February 2020. Online: https://spaceflightnow.com/2020/02/20/phobos-sample-return-mission-enters-development-for-2024-launch/

Diftler, M. – Mehling, J. – Abdallah, M. E. – Redford, N. – Sanders, A. M. – Askew, R. S. – Linn, M. D. – Yamokoski, J. D. – Permenter, F. – Hargrave, B. K. – Platt, R. – Savely, R. – Ambrose, R. (2011): *Robonaut 2. The First Humanoid Robot in Space.* 2011 IEEE International Conference on Robotics and Automation, Shanghai, China. 2178–2183. Online: https://doi.org/10.1109/ICRA.2011.5979830

EoPortal (2020): METERON (Multi-Purpose End-to-End Robotic Operation Network). *EoPortal,* 13 October 2020. Online: www.eoportal.org/other-space-activities/meteron#meteron-multi-purpose-end-to-end-robotic-operation-network

ESA (2022): *Terrae Novae 2030+ Strategy Roadmap, June 2022.* Online: https://esamultimedia.esa.int/docs/HRE/Terrae_Novae_2030+strategy_roadmap.pdf

ESA (2023): *FAQ: The 'Rebirth' of ESA's ExoMars Rosalind Franklin Mission.* Online: www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/Exploration/ExoMars/FAQ_The_rebirth_of_ESA_s_ExoMars_Rosalind_Franklin_mission

ESA [s. a.]a: *How much does it cost?* Online: www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/International_Space_Station/How_much_does_it_cost

ESA [s. a.]b: *European Robotic Arm.* Online: www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/International_Space_Station/European_Robotic_Arm

ESA [s. a.]c: *ESA Facts.* Online: www.esa.int/About_Us/Corporate_news/ESA_facts

Gao, Y. (2016): *Contemporary Planetary Robotics. An Approach Toward Autonomous Systems.* Weinheim: Wiley–VCH.

Haltigin, T. – Hauber, E. – Kminek, G. – Meyer, M. A. – Agee, C. B. – Busemann, H. – Carrier, B. L. – Glavin, D. P. – Hays, L. E. – Marty, B. – Pratt, L. M. – Udry, A. – Zorzano, M.-P. – Beaty, D. W. – Cavalazzi, B. – Cockell, C. S. – Debaille, V. – Grady, M. M. – Hutzler, A. – McCubbin, F. M. – Regberg, A. B. – Smith, A. L. – Smith, C. L. – Summons, R. E. – Swindle, T. D. – Tait, K. T. – Tosca, N. J. – Usui, T. – Velbel, M. A. – Wadhwa, M. – Westall, F. (2022): Rationale and Proposed Design for a Mars Sample Return (MSR) Science Program. *Astrobiology,* 22(S1), S27–S56. Online: https://doi.org/10.1089/AST.2021.0122

Hoffman, J. A. – Hecht, M. H. – Rapp, D. – Hartvigsen, J. J. – Soohoo, J. G. – Aboobaker, A. M. – McClean, J. B. – Liu, A. M. – Hinterman, E. D. – Nasir, M. – Hariharan, S. – Horn, K. J. – Meyen, F. E. – Okkels, H. – Steen, P. – Elangovan, S. – Graves, C. R. – Khopkar, P. – Madsen, M. B. – Voecks, G. E. – Smith, P. H. – Skafte, T. L. – Araghi, K. R. – Eisenman, D. J. (2022): Mars Oxygen ISRU Experiment (MOXIE) – Preparing for Human Mars Exploration. *Science Advances,* 8(35). Online: https://doi.org/10.1126/sciadv.abp8636

Muirhead, B. K. – Nicholas, A. – Umland, J. (2020): *Mars Sample Return Mission Concept Status.* 2020 IEEE Aerospace Conference, Big Sky, MT, USA. 1–8. Online: https://doi.org/10.1109/AERO47225.2020.9172609

NASA (2023): *Mariner 2.* NASA's Solar System Exploration website. Online: https://science.nasa.gov/mission/mariner-2/

NASA Jet Propulsion Laboratory (2012): *Mars Science Laboratory/Curiosity.* Online: https://d2pn8kiwq2w21t.cloudfront.net/documents/mars-science-laboratory.pdf

NASA Jet Propulsion Laboratory (2024): *After Three Years on Mars, NASA's Ingenuity Helicopter Mission Ends.* Online: www.jpl.nasa.gov/news/after-three-years-on-mars-nasas-ingenuity-helicopter-mission-ends

NASA Jet Propulsion Laboratory [s. a.]: *Interstellar Mission.* Online: https://voyager.jpl.nasa.gov/mission/interstellar-mission/

O'Shea, C. (2023): *NASA Pursues Lunar Terrain Vehicle Services for Artemis Missions.* Online: www.nasa.gov/news-release/nasa-pursues-lunar-terrain-vehicle-services-for-artemis-missions/

Platt, J. (2019): *Opportunity's Mission Status.* Online: https://mars.nasa.gov/mer/mission/rover-status/opportunity/recent/all/

Rankin, A. – Maimone, M. – Biesiadecki, J. – Patel, N. – Levine, D. – Toupet, O. (2020): *Driving Curiosity: Mars Rover Mobility Trends During the First Seven Years.* 2020 IEEE Aerospace Conference, Big Sky, MT, USA. 1–19. Online: https://doi.org/10.1109/AERO47225.2020.9172469

Rubio, F. – Valero, F. – Llopis-Albert, C. (2019): A Review of Mobile Robots: Concepts, Methods, Theoretical Framework, and Applications. *International Journal of Advanced Robotic Systems,* 16(2). Online: https://doi.org/10.1177/1729881419839596

Siddiqi, A. A. (2018): *Beyond Earth. A Chronicle of Deep Space Exploration, 1958–2016.* Washington, D.C.: NASA History Program Office.

Vago, J. L. et al. (2017): Habitability on Early Mars and the Search for Biosignatures with the ExoMars Rover. *Astrobiology,* 17(6–7), 471–510. Online: http://doi.org/10.1089/ast.2016.1533

Winter, M. – Barclay, C. – Pereira, V. – Lancaster, R. – Caceres, M. – McManamon, K. – Nye, B. – Silva, N. – Lachat, D. – Campana, M. (2015): *ExoMars Rover Vehicle: Detailed Description of the GNC System.* Proceedings of the 13th Advanced Space Technologies in Robotics and Automation (ASTRA). Online: www.researchgate.net/publication/326698356_ExoMars_Rover_Vehicle_Detailed_Description_of_the_GNC_System

Yana, C. – Lapeyre, R. – Gaudin, E. – Hurst, K. – Lognonné, P. – Rochas, L. (2023): Deployment and Surface Operations of the SEIS Instrument Onboard the InSight Mission. *Acta Astronautica,* 202, 772–781. Online: https://doi.org/10.1016/j.actaastro.2022.10.010

Antonio Carlo[1]

Satellite Communications: An Objective Lunar Base and Beyond

The following chapter discusses the challenges and opportunities of utilising satellite telecommunications for space and Moon exploration. It also examines the critical role of communication satellite constellations in providing essential services for future space communications.

The paper comprehensively analyses the critical technical, economic and operational factors that affect the design and development of a lunar telecommunications system, as well as the security and defence risks and challenges.

In this scenario, various elements are highlighted that lead to the emergence of the need for multilateral cooperation between various actors, such as public and private, national and international, to promote the development of a sustainable, safe and advantageous lunar telecommunications system for everyone.

SATELLITE CONSTELLATIONS FOR LUNAR COMMUNICATIONS

Satellite constellations for communications are the backbone required by critical infrastructures to provide fundamental services on Earth. The other necessary parts are global navigation and Earth observation systems. A disruption of navigational and communication services would simultaneously affect transportation services, broadcasting services, the power grid and banking transactions, among others. Due to the increasing interest of New Space businesses in the cislunar[2] economy, it would not be premature to investigate the gap hindering

1 Tallinn University of Technology; e-mail: Antonio.Carlo@taltech.ee
2 Volume within the Moon's orbit, or a sphere formed by rotating that orbit.

DOI: https://doi.org/10.36250/01209_08

the establishment of a secure and reliable satellite communication system orbiting the Moon rather than the Earth. This is especially true if the cislunar economy will soon enable the growth of lunar settlements and manned lunar missions.

The lunar economy[3] is a rapidly growing sector that offers opportunities for scientific, commercial and strategic development. In recent years, governments, space agencies and private companies have invested in the exploration and exploitation of the Moon's resources. These investments are expected to increase in the near future in view of possible human missions and greater international cooperation.

The most important artificial satellites are NASA's Lunar Reconnaissance Orbiter, which has been studying the lunar surface since 2009; China's Chang'e 5, which brought lunar samples to Earth in 2020; India's Chandrayaan 2; and Israel's Beresheet (Guruprasad et al. 2023).

The following governmental investments are among the most significant:

- The National Aeronautics and Space Administration (NASA)'s Artemis program aims to bring American astronauts to the lunar surface by 2027 (NASA 2022) and establish a sustainable presence by 2028. The programme also includes the construction of an orbital station around the Moon called Gateway, which will serve as support for lunar and Martian missions. The estimated cost of the programme is approximately USD 28 billion (Smith et al. 2020).
- China's Chang'e Project (or the Chinese Lunar Exploration Program) has already conducted five robotic missions to the Moon, including the first far-side moon landing in 2019 and in 2020 the first collection of lunar samples since 1976. The project has two more missions planned by 2024, with the goal being to build a research station on the lunar surface. The estimated cost of the programme is approximately USD 8 billion (Zuo et al. 2021).

[3] Lunar economy refers to all "economic activity associated with the production, use and exchange of lunar resources on the Moon's surface, in lunar orbit and on Earth" (Scatteia 2021).

In addition to private investment:

- The Lunar X Prize programme is an international competition sponsored by Google to encourage the development of private space technologies. USD 30 million will be awarded to the first team that lands a rover on the Moon, makes it travel at least 500 metres, and transmits images and data back to Earth. Thus far, while no team has managed to win the prize, some have announced a plan to launch their mission in the coming years (Smart 2018).

In fact, PwC estimated the interest and investment in the lunar economy to exceed €142 billion by 2040 (Scatteia 2021). The interest and investment are focused on the following three types of lunar activities: transportation, lunar data and in-situ resource utilisation (ISRU).

This article aims to provide a qualitative overview of the technological challenges faced by the satellite communication services that will support all lunar activities through the creation of a communication network to connect all stationary bases in situ and in orbit. The remainder of this paper is organised as follows: An introduction to the lunar economy and the future of the Lunar Gateway; the current scenario of the moon satellites; an overview of the future of lunar satellite system architecture as well as an overview of communication and possible challenges and risks as a result of the asset's criticality for security and defence. Lastly, the article identifies the need for cooperation in both the public and private sectors and in national and international environments.

THE LUNAR ECONOMY: NASA'S LUNAR GATEWAY

The first step to enabling the lunar economy is to establish a reliable and recurrent Earth–Moon transportation system. This step has been enabled by NASA's Artemis program, which is directly supported by its Lunar Gateway program. In particular, the Lunar Gateway program aims to develop a communication network around the Moon to support Artemis and beyond.

Lunar Gateway is an international project that aims to build a space station around the Moon to facilitate missions to the Moon and other planets. NASA is the leader of the programme, which also involves the space agencies of Canada, European countries and institutions, Japan and Russia. The space station will comprise various modules dedicated to housing different scientific, and logistical functions. The modules will be launched and connected between 2024 and 2030. Lunar Gateway aims to explore the Moon in a more in-depth and sustainable manner, experimenting with new technologies and paving the way for future explorations of Mars and beyond (Silva-Martinez et al. 2023).

While the NASA programs aim to transport and host human crews, several concepts have been proposed for transporting cislunar cargo only. Current cislunar transportation systems are targeted at large-scale transportation of cargo with a mass of 2–8 tonnes, which includes logistics resupply services for Lunar Gateway, the transportation of modules for expanding the station, as well as lunar landers. Based on Gateway Logistics Services contracts, the potential market over 15 years is estimated to have a value of €398 million.

The aforementioned contracts are awarded by NASA to various space companies to provide logistics services to the Gateway orbital station, which will be positioned in lunar orbit (LO), between 3,000 and 70,000 km from the satellite according to a near-rectilinear halo orbit (ESA 2019), compared to the 408 km of the ISS. These services include the transport of payloads, equipment, materials and supplies for the Gateway and Artemis missions, which foresee the return of astronauts to the Moon by 2027. The contracts have a duration of 15 years and a total value of USD 7 billion. The companies selected by NASA are SpaceX, Sierra Nevada Corporation, Northrop Grumman and NanoRacks. Each company will use its spacecraft to make deliveries to the Gateway, which will serve as a staging and transit point for lunar and Martian exploration (Nakamura et al. 2023).

As an example, Moonport proposes a commercially viable cislunar transportation system based on a refuellable space tug. It will meet the conditions set out in NASA's Commercial Lunar Payload Services (CLPS) contracts, which focus on frequent large-scale cargo transportation within cislunar space.

CLPS contracts are a series of contracts awarded by NASA to various American companies for the transport of payloads to the lunar surface. These contracts have a term of 10 years (i.e. until November 2028) for a value of USD 2.6 billion (NASA 2019). The goals of CLPS are to exploit commercial capabilities to explore the Moon, test technologies, conduct scientific experiments and demonstrate the potential for future human missions. CLPS contracts require the selected companies to provide all services necessary for integrating, transporting and operating NASA payloads, including launch vehicles, lunar landers, surface systems and Earth re-entry vehicles. To date, eight missions have been awarded under the CLPS programme, which excludes one mission for which the contract was revoked after it was awarded and another for which the contract was cancelled after the company went bankrupt. The first commercial deliveries were scheduled for 2023 (Giordano et al. 2023).

Once cislunar transportation has been established, the second step will be to transport capabilities for the creation of lunar bases to support research and eventually tourism. Some concepts include versatile transportation systems that could act as carriers for human crew and cargo, whose structure could subsequently be repurposed as a lunar base. An example is SpaceX's horizontal Starship Human Landing System placed at the lunar south pole on the rim of the Shackleton crater. Interestingly, this is the same crater where the Chang'e 7 mission is scheduled to land.

Furthermore, several hotspots have been located on the Moon, which would require a solid communication system between lunar bases or between lunar bases and LO vehicles. For instance, the presence of ice at the Moon's south pole could provide water resources in situ for longer crew missions as well as the resources for producing hydrogen fuel for liquid rocket engines. Another potential hotspot is the Moon's far-side equatorial region, which could potentially host massive radio telescopes. However, the far side of the Moon implies radio silence with Earth as it (as well as large portions of the polar regions) has no direct line of sight to Earth. Even on the side of the Moon that faces Earth, hills and crater walls could block communications.

THE CURRENT SCENARIO

Lunar orbiting satellites are artificial devices that orbit around the Moon. They have various functions, such as data transmission, navigation, scientific exploration and surveillance. Some satellites have been launched by national or international space agencies, while others have been launched by private or commercial entities. Currently, there are approximately 50 satellites in LO, of which 20 are operational and 30 are deactivated or lost.

Regarding the precise number of satellites currently orbiting the moon, the number is relatively low if one considers only artificial satellites (i.e. those launched by man for scientific or technological purposes). However, if one also considers natural satellites, meaning the celestial bodies that orbit the Moon due to its gravitational pull, then the number is considerably higher. A cloud of dust called the lunar exosphere surrounds the moon, which contains thousands of microscopic particles. These particles are considered natural satellites because they follow a stable orbit around the Moon; however, their size and distance make observing and counting them difficult.

The first of the Moon's artificial satellites was launched in the 1960s during the space race between the United States and the Soviet Union. The first satellite to reach the Moon was the USSR's Luna 1 in 1959, but it did not enter orbit and continued into interplanetary space. The first satellite to enter LO was the USSR's Luna 10 in 1966, which transmitted data on the Moon's gravity and magnetic field. The first satellite to land on the Moon was the USSR's Luna 9 in 1966, which sent the first images of the lunar surface.

Since then, many other countries have launched satellites to the Moon for different purposes, such as geological exploration, topographic mapping, scientific research and preparation for future human missions. Countries that have sent satellites to the Moon include the United States, China, India, Japan and Israel, as well as European countries.

Artificial satellites that orbit the Moon serve to improve our knowledge of this celestial body, which has a large influence on life on Earth. Through satellites, the physical and chemical characteristics of the Moon can be studied along with its climate, environment, origin and evolution. Satellites also assist in the discovery of natural resources on the Moon and the evaluation of possibilities to exploit them in the future (Carlo–Salmieri 2021). In addition, these satellites have allowed important information to be obtained on the geology, topography, climate and resources of the Moon; new technologies to be tested; and future human missions to be prepared for.

CISLUNAR INFRASTRUCTURE

To create a lunar satellite system architecture, several technical, economic and operational aspects must be considered. First, the main technical factors include the choice of orbit; the type and number of satellites; communication, navigation and observation capabilities; and the launch, deployment and maintenance requirements. Second, the key economic factors include the cost of developing, manufacturing, launching and operating the system; sources of financing; and market opportunities. Third, the key operational factors include end-user needs and priorities, space regulations and policies, as well as security and sustainability challenges and risks. A lunar satellite system architecture must therefore be designed in a way that balances these aspects and guarantees the achievement of set objectives.

In this scenario, the core functionality for lunar and cislunar infrastructure would be enabled by a reliable real-time communication system in cislunar orbit. This would ensure that Security Operational Centres and the operation commands are alerted promptly when critical vulnerabilities are found. Crucially, such a system would not rely on a direct link to ground stations on Earth.

Cislunar infrastructures are infrastructures found in the space between the Earth and the Moon. Space stations, satellites, probes, vehicles and other elements can facilitate the exploration and exploitation of lunar resources as well as communication and cooperation between various space agencies. Cislunar infrastructure is considered crucial for the development of a permanent human presence on the Moon and for the preparation of missions to Mars and beyond (Fowler 2023).

Some examples of cislunar infrastructures are the Gateway, a lunar orbital station that will be built by NASA in collaboration with other international partners; the Lunar Orbital Platform-Gateway (LOP-G), a space station that will stably orbit the Moon to allow the transfer of payloads and astronauts between Earth and the lunar surface; and the Lunar Communication and Navigation Services (LCNS), a telecommunications and navigation system that will provide coverage and support for lunar operations.

The LOP-G space station is designed to host human and robotic crews as well as science and technology experiments. LOP-G is an integral part of NASA's Artemis program, which aims to establish a sustainable presence on the lunar surface and set the stage for future missions to Mars. Its telecommunications system is the Power and Propulsion Module (PPE) a solar-powered electric propulsion module developed by Maxar Technologies: it is specially developed for NASA: this module will be one of the main components of the Lunar Gateway and its launch is scheduled for May 2024, which will provide electrical power, communications and orbital manoeuvres; the habitation module (HALO) will provide living and working space for astronauts. The logistics module will transport supplies, equipment and spacecraft; and finally, the robotic arm (RA) will assist in extravehicular operations and docking. LOP-G will be able to support long-duration missions to the Moon as well as serve as a transit point for missions to Mars and other celestial bodies. Moreover, LOP-G will have an elliptical orbit with an apogee of approximately 70,000 km and a perigee of approximately 3,000 km, offering a unique view of the far side of the Moon (Freeman 2023).

The LCNS project aims to provide communication and navigation services for lunar missions. The project involves the development of a network of satellites in LO, which will transmit data, images, video and commands between lunar missions and control centres on Earth; ground stations; and spacecraft terminals. Space platforms are the systems that host spacecraft, such as capsules, landers, rovers and orbital stations. LCNS satellites are designed to be flexible, reliable and compatible with different space platforms. They are able to communicate with each other, with ground stations, and with spacecraft in orbit or on the lunar surface. The purpose of LCNS is to facilitate data, voice and video transmission between the Earth and the Moon; support lunar exploration operations; and contribute to scientific research. The LCNS project is an international collaboration between several space agencies, including NASA, the European Space Agency (ESA), the Japan Aerospace Exploration Agency (JAXA) and the China National Space Administration (CNSA) (Molli et al. 2023).

COMMUNICATIONS

Earth–Moon telecommunications occur between the Earth's surface and a satellite or probe in LO or on the lunar surface. These communications are critical for space missions that explore our natural satellites, both manned and unmanned (Carlo 2021). Earth–Moon telecommunications are based on systems of antennas, transmitters and receivers that operate at different electromagnetic frequencies, depending on the transmission needs and conditions. The main challenges of Earth–Moon telecommunications are distance, latency, interference, propagation and signal security.

First, to reduce the negative effects of distance, repeaters can be used in terrestrial or lunar orbit, which amplifies and retransmit the received signals. The use of repeaters in terrestrial or lunar orbit for satellite communications between the Moon and Earth offers several advantages to reduce the negative effects of distance. This includes the reduction of propagation delay, increase in signal power, better reliability of the connection, greater flexibility, energy efficiency and possibility of lunar exploration. The choice of using repeaters in Earth or lunar orbit depends on several factors, such as the distance between the Earth and the Moon, the frequency of the radio signal and the power available to transmit the signal. Generally, repeaters in Earth orbit are easier to install and maintain, but repeaters in lunar orbit offer better propagation delay reduction and higher link reliability.

Second, to reduce latency, communication protocols suitable for managing delays in data transmission can be used. Third, to reduce interference, signal coding, modulation and filtering techniques can be used, which increase the signals' robustness and quality. Fourth, to improve propagation, directional antennas can be used, which concentrate the signals towards the target. Lastly, to guarantee signal security, encryption, authentication and data protection systems can be used that prevent interception or manipulation by third parties (Mortensen–Withee 2023).

Noteworthily, the creation of satellite constellations for communications in LO would require a lower payload class. For instance, lunar relay spacecraft for satellite communications often belong to the CubeSats class. One example is the Argotec satellite concept, which has dimensions of $44 \times 40 \times 37\ cm^3$ with solar panels and antennas stowed and a wet mass[4] of only 55 kg (Iess et al. 2023).

For lunar telecommunications, extremely demanding environmental challenges will be faced, requiring dedicated satellites. These satellites must be able to withstand the high radiation, temperature variations, and electromagnetic interference that characterise LO. The Van Allen belt does not offer any protection and the Moon does not have anything similar. Furthermore, they must be equipped with cutting-edge propulsion, navigation and communication systems to guarantee orbit stability and signal quality.

Moreover, the altitude at which they operate will depend on the type of orbit chosen and the operational needs. A low LO (LLO) offers the benefits of decreasing data transmission delay and improving image resolution, but it will require more satellites to cover the entire lunar surface. A high LO (LHO) will instead allow for greater coverage with fewer satellites, but it will imply greater delay and lower resolution. A possible solution could be to combine both types of orbits, thus creating an integrated network of lunar telecommunications satellites (Bhamidipati et al. 2023).

[4] Total mass including all propellants on board.

For lunar telecommunications, different types of satellites can be used depending on the needs and technical challenges. Some possible types of satellites that could be used are listed and described as follows:

- LLO satellites: These satellites orbit at a distance of a few hundred kilometres from the lunar surface and can provide direct and fast coverage between Earth and lunar bases. However, they have a limited useful life due to gravitational disturbances mainly caused by Earth and solar radiation. Therefore, they require a network of multiple satellites to ensure continuous communication.
- Medium LO satellites: These satellites orbit at a distance of a few thousand kilometres from the lunar surface and can provide wider and more stable coverage between Earth and lunar bases. While they have a longer useful life than LLO satellites (thanks to less exposure to radiation, less atmospheric resistance, a longer orbital period and a greater distance from Earth), they require greater power to transmit and receive and are more vulnerable to electromagnetic interference.
- Satellites in geostationary LO: These satellites orbit at a distance of approximately 60,000 km from the lunar surface and maintain a fixed position concerning the Moon. They can provide constant global coverage between Earth and Moon bases; however, they require highly advanced and expensive technology and are exposed to a high level of cosmic radiation.
- Satellites in Lagrangian orbit: These satellites orbit at one of the five points of gravitational balance between the Earth and the Moon, which are called Lagrangian points. They can provide reliable, long-distance communication between Earth and Moon bases; however, they require precise synchronisation and control and are subject to orbital variations due to disturbances from celestial bodies.

A critical choice when defining a concept of operations (ConOps) for satellite communications in a circular economy is the bandwidth of data to be transmitted. For lower bandwidth applications (e.g. text and voice messages), one satellite would be sufficient for collecting and aggregating data streams for relay elsewhere. For higher bandwidth applications (e.g. radio telescopes), an individual satellite is likely to reach its capacity with high data production.

Lunar satellite communications are a form of wireless telecommunications that use artificial satellites orbiting the Moon to transmit information between the Earth and the Moon or between different points on the lunar surface. Such communication entails the problem of signal latency, which refers to the time delay between sending and receiving data signals due to the distance between the transmitter and the receiver as well as the speed of light. Signal latency in lunar satellite communications limits the quality and efficiency of data transmissions between the Earth and the Moon. In the case of lunar satellite communications, the average distance between the transmitter and receiver is approximately 384,000 km; thus, the signal takes approximately 1.28 seconds to travel at the speed of light (300,000 km/s). Signal latency in lunar satellite communications can range from approximately 120 ms to 2.8 s depending on the relative position of the Earth and Moon. This delay can cause synchronisation problems, data loss, interference and signal degradation. It can also impact the performance and reliability of applications that require real-time communication or rapid response, such as navigation, remote control, or emergencies (Louca et al. 2023).

Lunar satellite communications are a technological and scientific challenge that requires constant development and innovation to ensure optimal and reliable performance. To solve the latency problem, several strategies can be adopted, such as the following:

– Using satellites in LLO: This strategy reduces the distance and therefore the signal propagation time. However, it requires more power to transmit as well as greater pointing accuracy of the antennas.
– Using more efficient modulation and coding techniques: This increases the capacity and robustness of the communication channel. However, it requires greater device complexity and bandwidth.
– Using communication protocols suitable for high-latency conditions: Such protocols include error control, retransmission and data buffering mechanisms. However, this requires more memory and greater delay tolerance.

Moreover, some projects are currently in place or under development for solving the problem of signal latency. One of these projects is the Lunar Communications Relay and Navigation System (LCRNS), a system of three lunar geostationary satellites that will allow continuous, low-latency coverage of the lunar surface. The LCRNS was proposed by NASA in 2018 as part of its Artemis program for human exploration of the Moon (MURATA et al. 2022).

A cislunar satellite transmission system is a system that allows communication between the Earth and the Moon, or between two points on the lunar surface, using artificial satellites that orbit natural satellites. This type of system is useful for supporting human or robotic space missions that aim to explore the Moon as well as for transmitting scientific or commercial data.

A cislunar satellite relay system is composed of three main elements: a ground station on Earth, one or more cislunar satellites and a lunar station. The Earth station is the point of origin or destination of the signal, which can be modulated in different ways depending on the needs. The signal is sent to the nearest cislunar satellite, which receives it with a dish or slot antenna and retransmits it to the lunar station or another cislunar satellite. The lunar station is the end or starting point of the signal, which can be received by a lander, rover, astronaut, or other device on the lunar surface.

Noteworthily, a cislunar satellite transmission system faces several technical challenges, such as the aforementioned distance between the Earth and the Moon, electromagnetic interference, temperature variations, solar and cosmic radiation, reduced gravity and occultations caused by the movement of the Moon. To overcome these challenges, high frequencies (e.g. the S, X, or Ka bands), coding and error correction systems, resistant and lightweight materials, solar panels and batteries for power supply, thrusters for altitude and orbit control and thermal control systems (PASQUALE et al. 2022) can be employed.

When a cislunar relay is used, the communication distance is shorter, which means that a powerful terminal is not required to maintain a low-data-rate link[5]

[5] It is a type of data link that has limited data transmission capacity (a data rate of less than 100 kbps), often used for applications that send small amounts of data at regular intervals, such as IoT sensors, monitoring devices and security systems (RAZA et al. 2022).

with Earth. Direct communication to Earth would require some seconds in both directions. Furthermore, direct Moon–Earth communication requires a powerful communications terminal with a large antenna or a high-wattage amplifier.

The ultimate goal of lunar communications systems would be to establish 5G capabilities for the entire Moon. Moreover, 5G technologies should be further standardised for in-space and cislunar use wherever possible, thus enabling, for example, the installation of cell sites on the Moon to supplement the relay arrangement. This approach would allow devices to be connected to a lunar network, such as low-power Internet of Things sensors and autonomous vehicles (Kodheli et al. 2022).

Yet, how can this ultimate goal be achieved? Many researchers and engineers working on the Artemis project ask this question. Artemis is NASA's space programme for returning astronauts to the lunar surface by 2024 and building a permanent base there. 5G wireless communications technology offers very high data speeds, low latency and greater reliability than previous generations. Therefore, 5G could significantly improve scientific and logistical operations on the Moon, allowing astronauts to communicate with each other and with Earth, remotely control rovers and drones, transmit high-resolution data and images, and exploit artificial intelligence and cloud computing. However, building a 5G network on the Moon presents several technical and logistical challenges.

First, the Moon's extreme environmental conditions must be considered, such as high temperature variations, solar radiation, electrical dust storms and the lack of an atmosphere. These factors can negatively impact the performance and lifespan of the devices and infrastructure necessary for 5G. Second, the distance between the Moon and the Earth makes a real-time connection difficult to establish. Finally, the problem of resource scarcity on the Moon must be addressed, both in terms of energy and materials. Notably, 5G requires a large amount of energy to function, but the availability of solar energy on the Moon is limited as it depends on the Moon's position and the lunar cycle. Furthermore, transporting materials from Earth to the Moon has high economic and environmental costs.

To overcome these challenges, researchers and engineers are studying several innovative and sustainable solutions, one of which is to use satellites in LO to create a 5G network that covers the entire lunar surface. The satellites could communicate with each other via lasers and provide connectivity to astronauts and vehicles on the Moon via radio waves. This solution would have the advantage of reducing the number of antennas and base stations required on the Moon, thus limiting the infrastructure's environmental impact and energy consumption. Another solution is to exploit the Moon's local resources to produce the materials required for 5G. For example, lunar regolith, the surface layer of dust and rock that covers the Moon, could be used to fabricate electronic components through 3D printing or other techniques. This solution would have the advantage of reducing dependence on Earth as well as transport costs (Raza et al. 2022).

In conclusion, establishing 5G capabilities for the entire Moon is an ambitious but feasible goal that requires international collaboration between various players in the space, telecommunications and industrial sectors. 5G may not only open new frontiers of scientific research and space exploration but also offer new economic and security opportunities.

PROJECTS

There are multiple ongoing projects, including a collaboration between NASA, Jet Propulsion Laboratory (JPL) and the Italian company Argotec proposes the realisation of relay satellites to support the bandwidth required for lunar and manned activities (Amoroso et al. 2022). The proposed Andromeda constellation is composed of 24 satellites, which are divided evenly among four different orbits. The relay network concept uses a class of stable orbits – so-called frozen orbits. Stable orbits make it easy to keep the satellites in their assigned orbits for a minimum of 5 years of operation. Each satellite is equipped with three different antennas to establish communications with Earth as well as the lunar surface. The K-band would be used for Earth-to-satellite connections since it has more bandwidth available compared with other bands used for space communications. Another reason is that for antennas of the same size, K-band frequencies have higher antenna gain; in other words, K-band antennas more efficiently convert the received signals into electrical power. However, the relay satellites would require an additional power margin to ensure that the link remains stable due to the weather sensitivity of K-band antennas. Currently, no standard protocol exists for communications between a relay satellite and a lunar user in the S- and K-bands. Standardisation, policy and regulations for lunar activities are crucial topics that must be developed in parallel.

ESA is also investigating the possibility of placing three or four satellites in highly eccentric orbits focused on the Moon's south pole through the Moonlight Initiative. The main goals would be to pinpoint geolocations on the surface of the Moon and to ensure high-speed data transmission back to Earth (Giordano et al. 2022).

Moreover, NASA's Space Communications and Navigation (SCaN) programme has developed the LunaNet architecture, a set of cooperating networks that provide interoperable communications and navigation services for users on and around the Moon. Briefly, each LunaNet Service Provider (LNSP) designs its own set of orbits. The Earth–Moon links would be dedicated to low-rate Telemetry, Tracking and Command (TT&C, X band) and high-rate mission data transmissions (Ka band), with the primary links being within cislunar systems. The baseline demand without human presence has been estimated as a data rate of 110 Mbps and a data volume of 600 GB/day. With the addition of Lunar Gateway at full capacity, the projections increase to 375 Mbps and 8.2 Tb/day, respectively. The increasing bandwidth demand due to human presence in lunar proximity would cause a congestion of RF bands, requiring optical communications to be tested and operational within this decade. Furthermore, optical capabilities would tighten avionics requirements for transferring the higher rate efficiently as well as increase pointing and stability requirements. The introduction of optical communication would also be required for future Mars activities (Giordano et al. 2023).

Other projects concern the development of new technologies and techniques for improving lunar satellite communications, such as the use of high-frequency radio waves, the use of lasers to transmit data at high speed, the adoption of adaptive and resilient network protocols, the creation of optical or radio intersatellite links, and deployment of wireless sensor networks on the lunar surface.

RISKS AND CHALLENGES

Lunar satellite telecommunications are also a critical asset for the security and defence of the moon installations. However, they are also exposed to various types of risks, including physical and cyber ones. To defend them, it is necessary to adopt a series of preventive and reactive measures that involve both technological and organisational aspects (Salmieri–Carlo 2021).

Generally, a broad understanding exists of the possible causes of disruption to the service of satellites in Earth orbit (EO), which vary from cyberattacks and space weather conditions to space debris and anti-satellite weapons. In principle, the same conditions apply to the LO, but with different severities and/or likelihoods of occurrence. For example, congested orbits like specific low EOs are absent in LO; thus, the likelihood of collisions with space debris is significantly reduced if one excludes meteorites from the equation. Furthermore, space weather events could have an even greater impact on cislunar systems. The Moon has neither a global intrinsic magnetic field – which causes direct charged particles to reach systems in LO and the lunar surface – nor a thick atmosphere – which enables the Earth's magnetosphere to directly impact the lunar surface for three to four days every month, even if the effect is very weak (Malinowska et al. 2023).

Additional challenges related to satellite constellations in LO are linked to the complexity and longevity of space systems, which require frequent updates or patches. Harsh space environments, which are characterised by radiation and microgravity, will impact the performance and durability of security systems. Last but not least, maintenance in LO would be more complicated than in EO. In both cases, once a satellite is deployed, physical maintenance becomes challenging and hazardous.

To prevent physical risks, it is advisable to design satellites with resistant and shielded materials, equip them with control and manoeuvre systems, constantly monitor their orbit and state of health, and plan for possible replacements or repairs (Cetin et al. 2023).

Moreover, among the cyber risks are cyberattacks aimed at intercepting, altering, or blocking satellite communications, or at damaging or destroying the satellites themselves. To prevent these attacks, it is necessary to adopt robust and up-to-date security protocols, encrypt transmitted and received data, protect infrastructures on the ground and in space from physical or logical intrusions, and develop capabilities for detecting and combating cyber threats (Marsili et al. 2023).

To create the cyber architecture of a lunar satellite system, it is necessary to follow some fundamental steps. First, the objectives and functionality of the system must be defined, taking user needs and environmental challenges into consideration. Second, the communication network between the satellites and Earth must be designed, with the most suitable methods, frequencies and protocols selected. Third, software and security systems must be developed to ensure the operation, control and data protection of the system.

Furthermore, to create a lunar satellite system cyber architecture, it is necessary to consider several aspects, including security, resilience, scalability and interoperability. First, security concerns the protection of data and communications from cyberattacks, which could compromise the functionality and integrity of the system. Second, resilience refers to the system's ability to resist and recover from adverse events, such as failures, interference, or sabotage. Third, scalability implies the possibility of adapting the system to operational needs and available resources, both in terms of the number of satellites and performance. Lastly, interoperability means the ability to communicate and cooperate with other satellite systems, both terrestrial and space-based.

Additionally, cyber threats can be of a technical, human, or environmental nature. Technical threats exploit vulnerabilities in software, protocols, or networks to alter or interrupt the functioning of the system; human threats come from malicious agents, such as hackers, crackers, or terrorists, who attempt to access, manipulate, or destroy the system; and environmental threats depend on external factors, such as solar radiation, space debris, or atmospheric conditions, which can affect the quality and reliability of communications (Sawik 2023). To address the aforementioned threats, it is necessary to adopt a series of physical and digital systems that guarantee the protection, monitoring and control of the lunar satellite system. Among the physical systems are encryption devices, sensors, transmitters and receivers, which allow data to be encrypted, transmitted, and received in a secure and robust manner. Among the digital systems are antivirus software, firewalls, intrusion detection and prevention systems, authentication and authorisation protocols, which allow cyberattacks to be identified, blocked and countered.

NEED FOR COOPERATION

For an effective defence of lunar satellite telecommunications, cooperation between the various actors involved – both public and private as well as national and international – is essential. Here, Europe is a prime example of cooperation with many projects, such as the Copernicus Programme for Earth observation, the GOVSATCOM programme for government communications, and the Quantum project for secure communications based on quantum mechanics (Carlo 2021). These initiatives aim not only to strengthen European space capabilities for security and defence but also to promote shared space governance and a culture of responsibility among space users (Prest–Bonifazi 2023).

The creation of a lunar satellite telecommunications system involves several regulatory and political challenges – both international and national. At the international level, it is necessary to define a legal framework that regulates the access to, use of, and management of cislunar space and its resources in accordance with the principles of space law and international law. At the national level, it is necessary to harmonise national regulations that relate to the licencing, frequencies, safety and liability of space activities, considering the interests and needs of the various actors involved, such as space agencies, private companies, scientific organisations, and civil society. These challenges require multilateral cooperation and dialogue between various stakeholders to promote the development of a lunar satellite telecommunications system that is sustainable, safe and beneficial to all (Keles 2023).

Next, this section examines the initiatives that have been taken to address the regulations and policies for establishing a lunar satellite telecommunications system. A lunar satellite telecommunications system is undoubtedly an ambitious project that requires various actors to collaborate, including space agencies, governments, companies and international organisations. To realise such a system, regulatory and political challenges in terms of security, sovereignty, accountability, resource sharing and cooperation must be addressed. Some steps that have been taken in this regard are described as follows:

– The Artemis Accords: This international agreement is promoted by the United States to establish principles and rules for the exploration and peaceful use of the Moon, Mars, asteroids and other celestial bodies. The treaty is named after the Artemis program, which aims to land the first woman and first black man on the lunar surface. It was signed by 36 countries, including Italy, on 13 October 2020 (U.S. Department of State 2023). The Artemis Accords builds on the 1967 Outer Space Treaty, which prohibits the militarisation of space and recognises that space exploration is in the common interest of humanity. The treaty also requires space activities to be conducted transparently, responsibly, and in compliance with international law and safety standards. Furthermore, it stipulates that participating countries must share scientific information and data obtained from their missions, protect the historical and cultural heritage of space, preserve the space environment and prevent the creation of space debris. The Artemis Treaty has been welcomed by many countries that see space exploration as an opportunity for scientific, technological and economic development. However, the treaty has also attracted some criticism from other countries, such as Russia and China, who see it as an attempt to impose a unilateral vision and exclude other actors from exploiting space resources. Some experts have also raised doubts about the treaty's compatibility with the principle of the nonappropriation of space enshrined in the Outer Space Treaty (Renshaw 2023).

– The Lunar Communications Architecture Working Group (LCAWG): This working group is composed of experts from different space agencies, industries, universities and nongovernmental organisations. They collaborate to identify the needs, challenges and opportunities for effective and reliable communication between the Earth and the Moon and aim to define the technical and operational standards for lunar communications. The LCAWG is responsible for defining and developing a communications network for lunar missions. It aims to create a shared vision and roadmap for the lunar communications architecture based on the principles of interoperability, standardisation, modularity and sustainability. The group meets periodically to discuss progress, best practices and recommendations for the future of lunar communication (Muff et al. 2023).
– Participation in the Moon Village Association (MVA): The MVA is a nongovernmental organisation that promotes international cooperation for the development of a sustainable human presence on the Moon. This includes the creation of a lunar telecommunications network for a permanent community there. The MVA is based on the 'Moon Village' concept proposed by the ESA in 2015, which involves a series of lunar activities and projects by various actors, both public and private, for scientific, commercial, or exploratory purposes. It refers to a vision of a sustainable, long-term human presence on the Moon, based on cooperation between different partners and sectors. This is not a specific project or a precise location but rather a general idea that encourages the development of lunar activities and infrastructure for various purposes,

such as scientific research, exploration, resource exploitation, tourism and culture. The MVA aims to facilitate dialogue and collaboration between stakeholders, to provide information and advice on the opportunities and challenges posed by the human presence on the Moon, and to support public education and awareness of the importance of the Moon for the future of humanity (Kansra 2023).

– In addition to these, there are also various private consultations with national and international regulatory authorities. This is necessary for obtaining the necessary authorisations for the launch and operation of lunar satellites, considering current regulations regarding frequencies, orbits, interference and space debris. Said authorisations are governed by a series of international and national regulations that aim to ensure the safety, sustainability and responsibility of space activities. At an international level, the main references are the 1967 Outer Space Treaty, the 1975 Convention on the Registration of Objects Launched into Outer Space and the 2007 United Nations Guidelines for the Reduction of Space Debris. Nationally, each state that intends to launch a lunar satellite system or put one into orbit must obtain a licence from its regulatory body, which may be the country's national space agency, its Ministry of Defence, or another competent body. The licence establishes the technical, legal, and financial conditions and requirements that the applicant must satisfy to conduct the operation. Additionally, the applicant must provide detailed information on the satellite system, launch vehicle, intended orbit, mission objectives, and measures taken to prevent or mitigate the generation of space debris. Depending on the complexity and sensitivity of the mission, the authorisation process can take several months or even years (Lee 2023).

CONCLUSIONS

Satellite telecommunications play a crucial role in the exploration and utilisation of the Moon. Since satellite technology constantly evolves, new advancements can enhance lunar communication capabilities. By utilising satellite constellations, we can establish a resilient and flexible infrastructure for lunar communications. However, the distance between the Earth and the Moon causes significant propagation delays, and the harsh lunar environment can damage satellites. Additionally, lunar communication technologies are still in the development stage. To address these issues, humanity is developing new technologies to reduce propagation delays and designing satellites that can withstand the lunar environment. This effort requires significant public investment in research and development of advanced lunar communication technologies.

This paper analyses the role of satellite constellations for communications as the backbone of critical infrastructure to provide fundamental services for the future of space communication. Satellite communications are fundamental to realising the presence of man on the Moon and beyond, as they allow data, images, audio and video to be transmitted between the Earth and other celestial bodies. Without satellite communications, it would not be possible to coordinate space missions, monitor the health of astronauts, receive scientific and technical information from experiments and spacecraft, and share the discoveries and excitement of exploration with the public. Satellite communications require a complex network of ground stations, artificial satellites, interplanetary probes and orbital relays, which must be synchronised and protected from interference and obstacles. It is, therefore, necessary to develop a strategic plan for lunar telecommunications and promote international cooperation for space and Moon exploration. Satellite communications pose technological, logistical, political and mental challenges, but they are also an indispensable resource for expanding the frontiers of knowledge and human adventure in space.

REFERENCES

Amoroso, M. – Pirrotta, S. – Impresario, G. – Zinzi, A. – Miglioretti, F. – Di Tana, V. – Simonetti, S. – Cotugno, B – Della Corte, V. – Dotto, E. – Yannoni, M. – Gai, I. – Capannolo, A. (2022): *Italian Cubesats for Moon and Asteroid Imaging.* 73rd International Astronautical Congress: IAC Proceedings, 1–10. Online: https://re.public.polimi.it/handle/11311/1223387

Bhamidipati, S. – Mina, T. – Gao, G. (2023): A Case Study Analysis for Designing a Lunar Navigation Satellite System with Time Transfer from the Earth GPS. *Navigation: Journal of the Institute of Navigation,* 70(4). Online: https://doi.org/10.33012/navi.599

Carlo, A. (2021): Cyber Threats to Space Communications: Space and Cyberspace Policies. In Froehlich, A. (ed.): *Outer Space and Cyber Space. Similarities, Interrelations and Legal Perspectives.* Cham: Springer. 55–66. Online: https://doi.org/10.1007/978-3-030-80023-9_4

Carlo, A. – Salmieri, A. (2021): Legal Solutions for the Peaceful, Sustainable and Strategic Utilization of Lunar Resources. *NATO Legal Gazette,* 42(1), 165–177.

Cetin, G. – Kurt, G. K. – Vazquez-Castro, A. (2023): *Secure and Robust Communications for Cislunar Space Networks.* Online: https://doi.org/10.48550/arXiv.2310.09835

Creech, S. – Guidi, J. – Elburn, D. (2022): *The Artemis Program: An Overview of NASA's Activities to Return Humans to the Moon.* 2022 IEEE Aerospace Conference, Big Sky, MT, USA. 1–7. Online: https://doi.org/10.1109/AERO53065.2022.9843277

ESA (2019): Angelic Halo Orbit Chosen for Humankind's First Lunar Outpost. *Phys.org,* 19 July 2019. Online: https://phys.org/news/2019-07-angelic-halo-orbit-chosen-humankind.html

Fowler, E. E. – Paley, D. A. (2023): Observability Metrics for Space-Based Cislunar Domain Awareness. *The Journal of the Astronautical Sciences,* 70(2). Online: https://doi.org/10.1007/s40295-023-00368-w

Freeman, R. H. (2023): In-Space Assembly of the Gateway-Lunar Surface Development and Protection: Lunar Operations Conceptual Design I. *Journal of Space Operations and Communicator,* 19(2). Online: https://opsjournal.org/DocumentLibrary/Uploads/JSOC%20Q2_2023_Extended%20Abstract_LOP_Gateway_RHF.pdf

Fullera, S. – Lehnhardt, E. – Connell, D. – Zaid, C. – Halloran, K. (2022): Gateway Program Status and Overview. *Journal of Space Safety Engineering,* 9(4), 625–628.

Giordano, P. – Malman, F. – Swinden, R. – Zoccarato, P. – Ventura-Traveset, J. (2022): *The Lunar Pathfinder PNT Experiment and Moonlight Navigation Service: The Future of Lunar Position, Navigation and Timing.* Proceedings of the 2022 International Technical Meeting of the Institute of Navigation, Long Beach, California, 632–642. Online: https://doi.org/10.33012/2022.18225

Giordano, P. – Swinden, R. – Gramling, C. – Crenshaw, J. – Ventura-Traveset, J. (2023): *LunaNet Position, Navigation, and Timing Services and Signals, Enabling the Future of Lunar Exploration.* Proceedings of the 36th International Technical Meeting of the Satellite Division of the Institute of Navigation (ION GNSS+ 2023), Denver, Colorado, 3577–3588. Online: https://doi.org/10.33012/2023.19345

Guruprasad, B. R. – Nagappa, R. – Mukherjee, A. – Dasgupta, U. – Siddhartha, V. (2023): *Moon Missions: The Way Ahead.* Bengaluru: National Institute of Advanced Studies.

Iess, L. – Di Benedetto, M. – Boscagli, G. – Racioppa, P. – Sesta, A. – De Marchi, F. – Cappuccio, P. – Durante, D. – Molly, S. – Plumaris, M. K. – Tartaglia, P. – Santi, F. – GéoAzur, A. F. – Linty, N. – Sosnica, K. – Belfi, J. – Giordano, P. – Swinden, R. – Ventura-Traveset, J. (2023): *High Performance Orbit Determination and Time Synchronization for Lunar Radio Navigation Systems.* Proceedings of the 36th International Technical Meeting of the Satellite Division of the Institute of Navigation (ION GNSS+ 2023), Denver, Colorado, 4029–4050. Online: https://doi.org/10.33012/2023.19428

Jawin, E. R. – Valencia, S. N. – Watkins, R. N. – Crowell, J. M. – Neal, C. R. – Schmidt, G. (2019): Lunar Science for Landed Missions Workshop Findings Report. *Earth and Space Science*, 6(1), 2–40. Online: https://doi.org/10.1029/2018EA000490

Johnson, S. K. – Mortensen, D. J. – Chavez, M. A. – Woodland, C. L. (2021): *Gateway – A Communications Platform for Lunar Exploration.* 38th International Communications Satellite Systems Conference (ICSSC 2021). Online: https://doi.org/10.1049/icp.2022.0544

Kansra, D. (2023): From Global to Planetary: Standards for the Conduct of Sustainable Lunar Activities. *Transnational Law and Policy Review,* 1(1), 1–17. Online: https://doi.org/10.59626/TLPR/V1/I1/2023/1

Keles, O. F. (2023): Telecommunications and Space Debris: Adaptive Regulation Beyond Earth. *Telecommunications Policy,* 47(3). Online: https://doi.org/10.1016/j.telpol.2023.102517

Kodheli, O. – Querol, J. – Astro, A. – Coloma, S. – Rana, L. – Bokal Sumit Kumar, Z. – Martinez Luna, C. – Thoemel, J. – Merlano Duncan, J. C. – Olivares Mendez, M. A. – Chatzinotas, S. – Ottersten, B. (2022): *5G Space Communications Lab: Reaching New Heights.* 2022 18th International Conference on Distributed Computing in Sensor Systems (DCOSS), Los Angeles, California, 349–356.

Lee, A. Y. (2023): The Future of the Law on the Moon. *Journal of Air Law and Commerce,* 88(1). Online: https://doi.org/10.25172/jalc.88.1.2

Louca, J. – Vrublevskis, J. – Eder, K. – Tzemanaki, A. (2023): Elicitation of Trustworthiness Requirements for Highly Dexterous Teleoperation Systems with Signal Latency. *Frontiers in Neurorobotics,* 17. Online: https://doi.org/10.3389/fnbot.2023.1187264

Malinowska, K. – Szwajewski, M. – Malinowski, B. R. (2023): *Lunar Entrepreneurship, Future Challenges and Risks to be Managed. A Comprehensive Study of Future Lunar Economy Issues, Which Shall Be Solved Today.* 74th International Astronautical Congress (IAC), Baku, Azerbaijan, 2–6 October 2023, 1–12.

Marsili, D. – Boschetti, N. – Gordon, N. – Nikas, Y. – Leger, W. – Joyce, M. – Falco, G. (2023): *Slipping Through Attackers' Fingers: Fast Neutron Communications for Space Cybersecurity.* 2023 IEEE Aerospace Conference, Big Sky, MT, USA, 1–12. Online: https://doi.org/10.1109/AERO55745.2023.10115666

Molli, S. – Tartaglia, P. – Audet, Y. – Sesta, A. – Plumaris, M. – Melman, F. – Swinden, R. – Giordano, P. – Ventura-Traveset, J. (2023): *Navigation Performance of Low Lunar Orbit Satellites Using a Lunar Radio Navigation Satellite System.* Proceedings of the 36th International Technical Meeting of the Satellite Division of the Institute of Navigation (ION GNSS+ 2023), Denver, Colorado, 4051–4083. Online: https://doi.org/10.33012/2023.19370

Mortensen, D. R. – Withee, S. (2023): *Identifying the Technical and Economic Challenges of Position, Navigation, and Timing (PNT) in a Lunar Environment.* Proceedings of the 36th International Technical Meeting of the Satellite Division of the Institute of Navigation (ION GNSS+ 2023), Denver, Colorado, 3664–3676. Online: https://doi.org/10.33012/2023.19283

Muff, R. – Marcer, A. – Matter, D. – Kokkinogenis, D. – Cossu, G. – Spirito, V. – Ciaramella, E. (2023): Optical Communication Requirements for Scientific

Missions and the Deep Space Gateway. In Minoglou, K. – Karafolas, N. – Cugny, B. (eds.): *International Conference on Space Optics – ICSO 2022,* 12777, 189–209. Online: https://doi.org/10.1117/12.2688820

Murata, M. – Koga, M. – Nakajima, Y. – Yasumitsu, R. – Araki, T. – Makino, K. – Akiyama, K.. – Yamamoto, T. – Tanabe, K. – Kogure, S. – Sato, N. – Toyama, D. – Kitamura, K. – Miyasaka, K. – Kawaguchi, T. – Sato, Y. – Kakihara, K. – Shibukawa, T. – Iiyama, K. – Tanaka, T. (2022): *Lunar Navigation Satellite System: Mission, System Overview, and Demonstration.* 39th International Communications Satellite Systems Conference (ICSSC 2022), 12–15. Online: https://doi.org/10.1049/icp.2023.1355

Nakamura, R. – Kikuchi, J. – Sasaki, T. – Matsumoto, Y. – Hidaka, M. – Murakami, N. – Ueda, S. – Satoh, N. (2023): Rendezvous Trajectory Design of Logistics Resupply Missions to the Lunar Gateway in Near-Rectilinear Halo Orbit. *Journal of Space Safety Engineering,* 10(2), 144–154. Online: https://doi.org/10.1016/j.jsse.2023.03.001

NASA (2019): *New Companies Join Growing Ranks of NASA Partners for Artemis Program.* Online: www.nasa.gov/news-release/new-companies-join-growing-ranks-of-nasa-partners-for-artemis-program/

NASA (2022): *NASA Provides Update to Astronaut Moon Lander Plans Under Artemis.* Online: www.nasa.gov/news-release/nasa-provides-update-to-astronaut-moon-lander-plans-under-artemis/

Pasquale, A. – Zanotti, G. – Prinetto, J. – Ceresoli, M. – Lavagna, M. (2022): Cislunar Distributed Architectures for Communication and Navigation Services of Lunar Assets. *Acta Astronautica,* 199(2), 345–354. Online: https://doi.org/10.1016/j.actaastro.2022.06.004

Prest, M. V. – Bonifazi, A. (2023): *The Road Towards the First European Union Space Strategy for Security and Defence Cooperation between ESA, NATO and the EU to Enhance Europe's Geopolitical Role.* Online: http://dx.doi.org/10.2139/ssrn.4424719

Raza, W. – Abele, E. – O'Hara, J. – Sadr, B. – LoPresti, P. – Imran, A. – Choi, W. – Song, I. – Altunc, S. – Kegege, O. – Ekin, S. (2022): Toward a Hybrid RF/Optical Lunar Communication System (LunarComm). *IEEE Network,* 36(6), 76–83. Online: https://doi.org/10.48550/arXiv.2203.15899

Renshaw, S. J. (2023): The Artemis Accords: Interpretation and Assessment in Light of Existing Law. *Creighton International and Comparative Law Journal,* 13(1).

Salmieri, A. – Carlo, A. (2021): Security-by-Design Approaches for Critical Infrastructure: Mapping the Landscape of Cyber and Space Law. *NATO Legal Gazette,* 42(1), 97–113.

Sawik, B. (2023): Space Mission Risk, Sustainability and Supply Chain: Review, Multi-Objective Optimization Model and Practical Approach. *Sustainability,* 15(14). Online: https://doi.org/10.3390/su151411002

Silva-Martinez, J. – Etchells, M. – Bradshaw, T. (2023): Implementation of Human Systems Integration Technical and Management Process for the Lunar Gateway Program. *Acta Astronautica,* 207, 200–205. Online: https://doi.org/10.1016/j.actaastro.2023.03.018

Scatteia, L. – Perrot, Y. (2021): *Lunar Market Assessment: Market Trends and Challenges in the Development of a Lunar Economy.* Online: www.pwc.com.au/industry/space-industry/lunar-market-assessment-2021.pdf

Smart, A. G. (2018): Google Lunar X Prize Hopefuls Struggle to Lift Off. *Physics Today,* 71(2), 31–32. Online: https://doi.org/10.1063/PT.3.3843

Smith, M. – Craig, D. – Hermann, N. – Mahoney, E. – Krezel, J. – McIntyre, N. – Goodliff, K. (2020): *The Artemis Program: An Overview of NASA's Activities to Return Humans to the Moon.* 2020 IEEE Aerospace Conference, Big Sky, MT, USA. 1–10. Online: https://doi.org/10.1109/AERO47225.2020.9172323

U.S. Department of State (2023): Artemis Accords. Remarks and Release. Online: www.state.gov/artemis-accords-remarks-and-releases/

Zuo, W. – Li, C. – Zhang, Z. – Zeng, X. – Liu, Y. – Xiong, Y. (2021): China's Lunar and Planetary Data System: Preserve and Present Reliable Chang'e Project and Tianwen-1 Scientific Data Sets. *Space Science Reviews,* 217, 1–38. Online: https://doi.org/10.1007/s11214-021-00862-3

András Edl[1]

Security and Space Colonies Theoretical Frameworks in the Age of New Space

Introduction

There is an intense debate about space travel among space professionals and some sections of the public. What would be the best approach, the most sensible goal, how should it be funded and which programs should be cut. While this debate may refine some things, the fact remains that the major space powers in 2024 appear to be very committed to establishing permanent outposts or even colonies on other planets and to utilising all the opportunities that space can offer. When talking about space colonies today, the discussion revolves around the Moon, Mars, the mining of space resources and orbital space stations. Occasionally, Venus or the moons of the gas giants are also mentioned, but they usually only exist as concepts and ideas. At the same time, due to geopolitical tensions and the multiplier effect of dual-use space technology, security concerns are becoming more prominent, which is also reflected in the space budget for 2023. According to Euroconsult (2023), government spending on defence-related space projects was higher than for civilian programs, representing a significant shift compared to previous years. This chapter will present some ideas and trends from the fields of security studies and policy to explore how these two disciplines are or could be approaching the expansion into space.

[1] Researcher, Ludovika University of Public Service, Eötvös József Research Centre, Institute of Space Law and Policy; ORCID: https://orcid.org/0000-0002-4250-7112; e-mail: edlandras@gmail.com

DOI: https://doi.org/10.36250/01209_09

SECURITY STUDIES AND SPACE COLONISATION

In the fields of security studies, the conflicts that could arise in connection with the colonies can be interpreted based on three different approaches. The realist–neorealist approach assumes that the international field is chaotic, that there is no supreme regulating force and that actors will pursue their own interests and goals, if necessary, ruthlessly and not based on morality. To assume otherwise would be naive and downright dangerous for a state or any actor. Everett C. Dolman's *Astropolitik* applies the realist theory to space activities (Dolman 2001). For a realist, a colony on another celestial body or in outer space would be a logical extension of state power and a new territory to control. Chaotic, rivalry-based relationships would persist in space and could add a new layer to already complex relationships. Establishing colonies is simply an extension of a state's (or corporation's) power, and as long as it does not reach a barrier, it will continue to expand. Realists would probably emphasise the scarcity of resources, securing strategic locations and the importance of preparation for armed conflict.

The liberalist approach to space, as presented for example in Michael Sheehan's book, recognises the existence of rivalry, conflict and the chaotic nature of international relations, but at the same time argues that there are more levels of relations, not just conflict (Sheehan 2007). There are also economic relations, alliances and space law is an important factor in the relations of space powers. Liberalists might argue that the colonisation of space is the result of internal political interactions and that democratic political systems are important for colonies. Conflict between space powers could be avoided, but only if there is trade between them, and the likelihood of conflict decreases if all actors are liberal democracies. Joint projects such as the International Space Station, mining projects carried out by all actors on a celestial body, conflict resolution and mutual aid agreements will be important.

The constructivists would agree with the liberalist thinkers in this regard and might emphasise the importance of the links between actors and that the interaction itself will shape their space activities. As Moltz and some other experts point out, space, much like the seas and oceans, is seen as celestial pathways connecting different actors, while space settlements would be expressions of national vitality and power (Moltz 2014). The narratives and myths surrounding the activities in space are important in this context because they influence the interaction between the actors.

All three approaches have the merit of pointing out important elements concerning colonies. There are significant risks, opportunities for cooperation and connections that could hold the whole structure together. Various scholars attempt to combine the ideas of these three different approaches and find a middle ground without disregarding any of the components they have identified. An example of such an attempt would be Brad Townsend's book from 2021 (Townsend 2021). A second theoretical approach could be the widely known and used framework developed by Barry Buzan and the Copenhagen School. Instead of focusing only on military issues when it comes to security, a system of interconnected sectors was created to allow for a broader interpretation of security. The original five sectors were: military, political, economic, social and environmental (Buzan et al. 1998). Later, the areas of cyber and human security were added as additional sectors.

The actors concerned with these different aspects of security were originally states. According to Buzan, there are three prerequisites for the existence of a state: 1. an ideological basis, which is usually nationalism; 2. a physical basis (resources, infrastructure, land, people, etc.); 3. an institutional basis (political system and administration) (Stone 2009). Buzan also answers the question of when something becomes a security issue. The concept of securitisation basically states that an issue can become a security issue whenever it is labelled as such. If this act convinces decision-makers, the issue in question is shifted from a purely political area to a security policy framework. Accordingly, the establishment of colonies is already a security problem. Space scientists, politicians, military planners, etc. discuss the possible security aspects of space colonies and initiate projects to counter perceived threats or devise different plans to deal with future problems.

As a comment on the sector-based security framework, the proposal to include space as a new sector in the list could be justified. Space capabilities are so closely intertwined with our way of life today and most of our defence, industrial and economic systems that they have become part of the critical infrastructure, just like the cyber domain. Due to their unique characteristics and requirements, highly specialised knowledge is required to understand what is happening in space. This knowledge and expertise are also essential to guide any kind of space policy, including space security policy.

A THOUGHT EXPERIMENT

Another possibility would be to focus on the different spatial areas where the security of the colonies may be important, or on the benefits that one entity receives from the other. This is already embedded in the interpretation of space security, which could mean three different things at once. Outer space for security:

1. outer space for security: the use of space systems for security and defence purposes
2. security in outer space: the protection of space assets and systems against all types of threats while maintaining sustainable development of space activities
3. security from outer space: protecting human life and the environment of our home planet from natural threats from space (e.g. space weather events, asteroids, etc.)

These different interpretations make the topic of space security a very broad subject (Mayence 2010). But experiments like this not only highlight the different approaches and overlapping areas of space security but can also be used to develop a system that draws attention to parts of a complex system that might otherwise be neglected. Looking at a complex system in a compartmentalised way is a widely used method. The advantage might be the certainty of getting attention, the disadvantage might be that the tools become a rigid doctrine, that other systems are rejected, or that the links between different areas are disregarded, especially if the responsibility for a particular area is given to one part of an organisation without an effective unifying department. To conduct a thought experiment: In case of establishing a permanent colony, the interpretation and assessment areas of space security could be the following:

1. Outer space for Earth's security: how to use space systems to enhance security and defence on Earth.
2. Outer space for the colony's security: how to use space systems to enhance security and defence for the colony.
3. Security in Earth's outer space: the protection of space assets and systems against all kinds of threats while maintaining sustainable development of space activities close to Earth.
4. Security in the colony's outer space: the protection of space assets and systems against all kinds of threats while maintaining sustainable development of space activities close to the colony.
5. Earth protection: protecting human life and our home planet's environment from natural threats originating from outer space (i.e. space weather events, asteroids, etc.).
6. Colony protection: protection of human life and the colony's environment from natural threats originating from outer space (i.e. space weather events, asteroids, etc.).

The fact that there is no point No. 7 is not a coincidence or an editing error. The system is not complete, several elements are missing. One addition could be the safety of the vast areas between Earth and the celestial body where the colony is located. Also, some of these areas already have known and accepted names, such as No. 5 – planetary protection. This term does not have Earth as a distinguishing adjective in the name because it is not yet necessary. The above system, which focuses primarily on the endpoints, could lead to the area in between being ignored.

Furthermore, there are axioms and assumptions built into this system that can lead to problems later on. A crucial and easily neglected component is the point of view. In this particular experiment, the reference point was the Earth, considered as a whole, while the colony was a single extended entity and not all possible colonies on the planet, so the reference scale could be skewed. The entity conducting the analysis can be a country, an alliance of countries, a corporation, or any mixture of these elements. All of these actors will view the benefits and obstacles in space from their own perspective, and divergent interests can lead to problems. The above framework could be supplemented by a layer of security in the actors' relationships.

Moreover, if Earth is chosen as a point of reference, the underlying ideological assumption could be that the planet can be seen as a unified entity or that the system is an encouragement to unification or a by-product of a desire leading towards that goal. Proponents of space colonisation often assume that colonisation might unite humanity, or that it is only possible if we leave the disputes of the past behind. Viewing the Earth as a single entity has another axiom at its core, namely that it views humanity and the Earth as one. In 2024, this is a valid axiom, but as it is often part of the arguments for space colonisation, the survival of humanity is at stake, so an even higher level of abstraction could be added: the safety of humanity, which may not be the same as Earth. This is of course a very theoretical question, but the idea itself may have some impact.

An unintended consequence of the example in our thought experiment is that the system that treats the Earth or sovereign entity and the colony separately can lead to patterns of thought and assumptions where members of one group begin to think of their own group as more important and view their partner as selfish and oppressive, creating an "us versus them" mentality that leads to conflict. This can happen, even though the oft-cited incident with the Skylab 4 crew, who deliberately turned off their radios and disregarded ground control, apparently did not take place (Uri 2020). Unresolved grievances, especially after a long period, might give potential rivals the opportunity to influence relations between the two parties and therefore pose a security risk that not only affects the efficiency of the mission.

HISTORICAL AND MILITARY ANALOGIES

After such considerations, we can discuss the use of historical analogies in approaching the complexity of space. As with any as yet unknown terrain, people tend to examine the past and try to draw conclusions and lessons that might be applicable. In case of a permanent human colonisation of space, numerous eras and examples can be used to shed light on one aspect or another of current or likely future events. The Age of Discovery is one of them. The desire for spices drove Europeans to look for alternative routes to India and they landed on a continent previously unknown to them. In the centuries that followed, America changed in a rapid and drastic way that still evokes emotions and triggers debates between different groups in society. The era of colonisation is another example, in which great empires were founded that stretched across the globe, again causing drastic changes.

There are also localised historical events that manifest themselves in the space policies of certain powers. The Wild West and the frontier spirit can be seen in the documents of American space policy. According to the Weinersmiths, recent scientific research shows that the accuracy of this idea is very low and is considered a poor model, not just to explain the way, but also for the future. However, this does not stop many proponents of space colonisation from repeating the narrative that is closely tied to prevailing narratives about U.S. history (Weinersmith–Weinersmith 2024).

In connection with the Age of Discovery and the era of colonialism, it is logical to draw parallels with naval power. Naval strategists such as Alfred Thayer Mahan have often been used as a starting point and even among space lawyers the regulation of sailing rights, fishing rights, etc. serves as inspiration. Metaphors related to the navy are also available, and not just because of the similar terminology (e.g. ship vs. spaceship, etc.). Bowen uses the analogy of sailing in shallow coastal waters to describe our current space activities (Bowen 2020: 113–115). The comparison does indeed have some merit, with the addition that it was highly dependent on maritime technology. With the development of shipbuilding, navigation and sufficient incentives, seafarers left the coastal waters. This is the same reason why new propulsion technologies are so important, as they can make journeys shorter, easier to supply, safer and cheaper, which are all important factors for space activities. That is why NASA aspires to have thermal and electric nuclear propulsion systems. One such program is the Demonstration Rocket for Agile Cislunar Operations (DRACO) research project. The project will start in 2021 and DARPA has selected General Atomics, Blue Origin and Lockheed Martin. The Department of Defense hopes to be able to perform rapid manoeuvres in cislunar space while taking advantage of the high confidence ratio of chemical propulsion and the high propulsion efficiency of electric systems. The program originally planned to demonstrate the technology in 2025 (DARPA 2021).

There are other expressions coming from the military sphere that are modified but try to emphasise the importance of the colonies. Space and the Moon are sometimes referred to as the ultimate high ground. However, not everyone agrees with the use of this term and might call it simplistic as it only emphasises some general benefits, or it might be misleading and lead to bad practices (Bowen 2022: 25–33). The use of the phrase is perhaps not the most accurate, but could also serve to raise awareness, and when that is achieved, an explanation of the different orbits and other specifications of space can follow. Between the Earth and the Moon, for example, there are Lagrange points (which are rather areas) where a spacecraft can maintain a stable position within the Earth–Moon system with low fuel consumption due to the near balance of gravitational forces. These are natural points to station space stations or observation devices because they are the peaks of the gravitational "landscape", while the Earth and to a much lesser extent the Moon are in a "well" or, to use the geographical metaphor, a valley. Parapet orbits surrounding the entire Earth–Moon system could also offer some advantages for observing the entire system (Wilmer–Bettinger 2022).

A striking difference is that Earth and Mars have no Lagrange points, they do not revolve around a common point of gravity. On the other hand, the Earth–Sun L2 point lies between the orbits of Earth and Mars, just like the Mars–Sun L1 point is. However, due to the different orbital periods, they are of less use. So-called cyclers, orbits that do not keep an object in a relatively static position between Earth and Mars, but allow a close flyby of the two planets at low energy cost, do exist, but their use can only produce limited results. As a result, strategists need to think about the security of a Mars colony very differently from that of a colony on the Moon. The term 'ultimate superiority' will not suffice here.

All of these examples can, to some extent, serve as a warning to do better this time. It is not our aim to make a thorough analysis of all examples, but we can add that they are not just blueprints or warnings, but at the same time tools used in the current political internal or geopolitical debates, revealing a clash of ideologies. Not only do they tell us what the future should look like and thus guide our politics in the present, but the images also reflect on our interpretation of the past and support certain narratives.

THE RIGHT PLACE FOR A COLONY

It goes without saying that the colony's environment is of crucial importance when it comes to any kind of security arrangements and their policies. The main ideas for colonisation focus on the Moon, Mars and sometimes space around the Earth. Space stations are a unique approach because they must be built entirely from materials transported from Earth or perhaps a future mining facility. Planets and moons are a different category, so it is worth exploring the different parameters that could influence a decision process, whether from a technical or political perspective. For comparison, the chart also includes Venus, the planet whose surface is considered particularly hostile to life.

Table 1
Characteristics of the Moon, Mars and Venus

	Moon	Mars	Venus
Distance min.–max. (in million km)	0.363–0.405	55.65–399.58	39.79–259.71
Distance in light seconds and communication delay[1]	1.3	182–1,342	133–869
Frequency of ideal launch window	could be more per day	780 days	584 days
Travel time	3–3.5 days	128–333 days	109–198 days
Orbit period (Earth years)	0.07	1.880	0.615
Length of days (Earth days)	27.3	1.026	–243.018[2]
Size compared to Earth in %	27%	53%	95%
Surface gravity Earth 9.80	16.6%	38%	91%
Atmosphere	n/a	Carbon Dioxide, Nitrogen, Argon	Carbon Dioxide, Nitrogen
Atmosphere effect	n/a	very thin, but dust storms can have an effect	highly corrosive, high pressure
Surface temperature Celsius[3]	–183 to +121	–153 to +20	+464
Surface air pressure (ratio to Earth)	0	0.01	92
Priority ranking	1st	2nd	3rd
First successful soft landing	1966	1971	1970
Human landing	1969	–	–

1. Equal to light seconds depending on the planets' positions. For example, a message sent to Mars could even take 21 minutes to reach the red planet. A reply would take the same time to arrive back to Earth. Mission controls often have one-way light time, two-way light time and distance from Earth displayed on their screens.
2. The –243 refers to Venus rotating clockwise, compared to all the other planets which rotate counter clockwise. And one day on Venus takes appr. 243 Earth days, the slowest rotation speed in the solar system. Interestingly a day on Venus is longer than its year (225 Earth days).
3. The average range of temperature on the equator or mid-latitudes. In certain places temperature could reach –253 degrees Celsius, at other locations, like craters they could be temperate and more stable.

Sources: Compiled by the author based on NASA, ESA and Planetary Society databases.

The table shows average data, but does not take into account minute quantities and is therefore not detailed enough to make precise astronomical predictions. But it shows why, despite its drawbacks, the Moon is a much more tempting and practical target. It is much closer than Venus or Mars and would be an ideal stepping stone and training ground for Mars. Observing the data also makes it clear why Venus is not a viable option for colonisation. Even though it is closer and comparable in size and gravity to Earth, the surface air pressure and corrosive atmosphere make it the least suitable for a permanent human presence.

EARLY MILITARY PLANS FOR THE MOON

The use of other planets, especially the Moon, for defence and military purposes was not unthinkable in the early years of the Cold War. Project A119, also known as the Study on Lunar Research Flights (SECRET), was a U.S. Air Force initiative. The idea was born in 1957 and a team of researchers led by Leonard Reiffel was commissioned to carry out the calculations for the project. Carl Sagan, who participated in the project, revealed its existence in an application for a Miller Fellowship. Reiffel believes that this was a breach of security on Sagan's part because the most important aspect of any such project is their existence (Reiffel 2000). The aim was to demonstrate to the world and the Soviets that the Americans could reach the moon and detonate a nuclear warhead near it and on its surface, creating a clearly visible mushroom cloud. It turned out that there would be no mushroom cloud due to the lack of atmosphere, but the explosion might still have been visible (Armor Research Foundation 1959). The exact reasons which led to the cancellation of the project are still unclear. There might have been worries about the rocket not reaching its destination and falling back on Earth.

Project E4 was the Soviet parallel to A119. E-1 had the mission to hit the moon, which was only achieved with Luna 2 in September 1959. E-2 and E-3 had a similar plan, both were to go around the moon. E-2, like Luna 3, managed to fly around and send back the first images of the far side of the moon, but

E-3 failed to reach orbit. The aim of E-4 was to detonate a nuclear warhead on the surface of our celestial companion. The Soviets even built a mock-up of the spacecraft, but fearing that the payload would fall back onto Soviet territory or impact on foreign soil in the event of an imperfect launch, they scrapped the idea (Zheleznyakov 2009).

Project Horizon was the first plan to use the moon for security purposes. In 1959, the U.S. Army conducted a feasibility study for the establishment of a Lunar Outpost. The original goal was to observe the Soviets, act as a communications relay and perhaps establish a small military outpost. By 1966, there would have been about 12 soldiers at the base, all for USD 6 billion (approximately USD 63.6 billion in 2024) (U.S. Army 1959). The total U.S. budget in 1959 was USD 93.5 billion, therefore it is not surprising that President Eisenhower cancelled the plan. All similar plans got merged with the lunar landing projects or cancelled, especially after the 1967 Outer Space Treaty.

CURRENT PROGRAMS

Today, the main goal is not to build a military observation post on the Moon. The participants in the new projects to other planets intend to establish a permanent presence on the Moon, make the whole endeavour financially and strategically viable, and use the Moon as a base camp for further exploration.

The United States has the most advanced exploration program, a robust space industry with private companies and the largest space budget on Earth. According to Euroconsult, the U.S. space budget was USD 73.2 billion in 2023 (Euroconsult 2023). The U.S. has a lot of experience, plays a major role in the operation of the ISS, has launched numerous successful missions to the Moon and Mars and has the ambitious Artemis program. The Artemis I mission was launched on the 16th of November 2022, and successfully tested the Space Launch System and the Orion spacecraft (U.S. Department of State

2024). At the time of writing this chapter, 36 countries were among the signatories.[2] However, the Artemis Accords ignited debates. Washington received criticism that they turned away from true multilateralism which can lead to fragmentation while at the same time encouraging space resource exploitation without the guarantees of the Moon Agreement (Bartóki-Gönczy – Nagy 2023). Another interesting point is the possible establishment of safety zones, as provided for in Section 11 of the agreement. These zones could be extended and would serve as an instrument to avoid any kind of interference with ongoing operations. It is feared that the safety zones could be the first step towards establishing a military presence on the Moon. In 2022, the U.S. published its National Cislunar Science and Technology Strategy and the Space Force is also paying increased attention to cislunar space and intends to launch ORACLE, a satellite designed to observe and patrol cislunar space, in 2026.

Many European countries have also signed the Artemis Accords while ESA and the EU also make an important contribution to the program, in particular through the European Service Module. Europe is a major player in global space exploration. The national budgets of the EU member states together amount to around USD 10.3 billion. The EU itself has allocated USD 2.8 billion for this purpose. According to the report, the government contribution to ESA, ESO and Eumetsat amounted to USD 6.3 billion, which comes from national sources (Euroconsult 2024). The report does not take into account the entire ESA budget for 2023, which amounts to around USD 7.7 billion. The reason for this is that the ESA budget is made up of ESA member states (66.2%), EU funds (24.2%), Eumetsat (1.8%) and other sources (7.8%) (ESA 2023). There are very high quality and important missions to the Moon and Mars launched by one or the other European organisation, but there is no separate lunar program designed to mimic the objectives of Artemis. The exact role of Europe is not

[2] Angola, Argentina, Australia, Bahrain, Belgium, Brazil, Bulgaria, Canada, Columbia, the Czech Republic, Ecuador, France, Germany, Greece, Iceland, India, Israel, Italy, Japan, Luxemburg, Mexico, the Netherlands, New Zealand, Nigeria, Poland, the Republic of Korea, Romania, Rwanda, Saudi Arabia, Singapore, Spain, Ukraine, the United Arab Emirates, the United Kingdom, the United States of America, Uruguay (15 February 2024).

entirely clear, regarding the costs and the benefits. There were opinions about Europe being treated as a subordinate or a contractor. One of the arguments was that for the money and effort invested, it was not clear when and if Europe could send an astronaut to the Moon (Parsonson 2023). Later in 2023, this issue seemed to have been solved and Europe was promised a place both on Artemis IV and Artemis V (Howell 2023).

The Indian budget amounts to around USD 1.7 billion, while Japan has a budget of USD 4.6 billion. Both countries have a range of valuable expertise and good track records when it comes to missions to the Moon and Mars. Japan's contribution is also very important for the Artemis project or the Lunar Gateway Station. India is rather reserved in this respect but has very successful missions such as the Chandrayaan series. South Korea with its USD 0.7 billion and the United Arab Emirates with its USD 0.3 billion budget are relatively latecomers, but they are ambitious and committed. The list is far from being exhaustive and this brief note does not sufficiently recognise these spacefaring nations. However, they are all more or less aligned, subscribe to the U.S.-led project and there are no significant tensions between these countries to compare with those between China and the U.S.

The People's Republic of China has a space program that is a potential competitor to the American program. Its budget amounted to USD 14.1 billion in 2023 (Euroconsult 2024). However, this is only an estimate due to a lack of sources and transparency. Chinese space activity is characterised by the intertwining of industry, the military and the communist party, making clear data difficult to obtain. Although the budget is not fully accessible, the results speak for themselves. The successful Chang'e missions, especially the Chang'e 4, which landed on the far side of the Moon, brought China international recognition and served as an incentive for Washington to accelerate its own space program. Geopolitical and geographic analogies are used in China as well. A newspaper reported in 2017 that Ye Peijian,[3] the head of the lunar program, compared the Moon to the Diaoyu–Senkaku Islands, which cause tensions

[3] Yè Péijiàn 叶培建.

with Japan as Beijing disputes the islands (Hong 2018). But this is not his first statement along this line, in 2015 he voiced similar opinions.

Strongly connected to their own Chinese Lunar Exploration Program[4] is the International Lunar Research Station[5] partnership launched in 2021. It aims to establish a permanent multi-purpose base on the Moon's surface and after a robotic phase, humans should join to aid the operation of the base as well by 2035. The main partner and founding member of the project was Russia. At the time of writing this paper, 6 other countries joined raising the total number of participants to 8.[6]

Russia, as a partner of the ILRS and a former member of the Lunar Gateway project, is now in a difficult situation. The space budget is USD 3.4 billion in 2023 (Euroconsult 2023), but the state of the space sector is not good. The Luna missions were supposed to be part of the ILRS project, but with the failure of Luna 25, the benefit of Russian participation for China is less than expected and there are serious doubts about the actual Russian capabilities. Russian space expert Asif Siddiqi believes that Russia wants to piggyback on China to get to the Moon because Russia could not do it alone (Times Radio 2023).

To summarise the current trends from a security perspective, all actors interested in colonisation seem to focus on two centres and projects, Artemis and ILRS, led by the U.S. and China. These two groups are not fixed blocs or alliances, but they reflect geopolitical trends to a large extent. The concern that the other side will arrive first and secure the best geographic locations on other planets or establish such a presence that others cannot even enter the area is present in the discussion. However, to describe these efforts as a race is inappropriate. As space policy expert Aaron Bateman put it: "Space race is a misleading characterization because the US and China, for example, are in a sustained competition to develop space capabilities that can enhance their national security aims" (Bateman 2024). The term space implies that it is

4 Zhōngguó Tànyuè中国探月.

5 Guójí Yuèqiú Kēyánzhàn国际月球科研站.

6 China, Russia, Venezuela, South Africa, Azerbaijan, Pakistan, Belarus, Egypt (15 February 2024).

a more short-term challenge with a clear starting point and finish line, which could not be further from the truth if the players want to establish a permanent presence on the Moon and continue expansion into outer space.

SUPPLY AND DESIGN FOR THE COLONIES

Establishing any kind of foothold in space or on planets, a crucial safety issue arises: the question of supplies. The most important goal is that the mission achieves its objectives. If humans are involved in the mission design, they have physiological and psychological needs to stay alive and function well for the mission. At the same time, they should avoid any kind of permanent damage to their quality of life. As we know, people are sometimes willing to perform dangerous or even potentially lethal activities in exchange for a higher salary, but ideally, such risks should be reduced to the minimum. In case of a robotic mission, the need for supplies is different, but still present. Energy sources, building materials, spare parts and the possibility of repairs are just some of the items on the list. A sophisticated system is required to supply the colony with the right quantity and quality at the right time. This serves as a link to the supplier, which can be the colony's sovereign or a third party, e.g. a private company. The supply has an origin point, must have a production location (on Earth or theoretically on a space station, another planet, etc.), a means of transportation, an endpoint where the supplies can be stored or used immediately, and in the background, financing, a political will to supply and a production capacity. However, such connections are also vulnerabilities. In the future, the best method for an opponent might be to set up a blockade to cut off supplies. The more the colony is dependent on this, the greater the risk. Stockpiling key resources, spare parts, etc. could be a short-term solution, but a more effective method would be to produce locally. This would make the colony less vulnerable and more resilient to supply problems, but this in turn also increases the ability to become independent, which may not be in the interests of the colony's ruler.

Ensuring that the colony is well-supplied and self-sustaining to a desired degree begins in the planning phase. For the sake of argument, we will use another naval analogy and consider the first colony as a nuclear submarine in combat. Both operate with a highly skilled crew in environments where humans could not survive. The colony, with its confined spaces, must be tightly sealed off from the outside world and ensure that nothing from the outside can penetrate the habitat or affect the inhabitants, be it radiation, gasses or the vacuum of space. Oxygen is a limited resource in both places, just like food, drinking water and other goods. Supplies can only be replenished at infrequent intervals. They might be too far away for any rescue team to reach them in time, so they must be able to operate independently. The energy source for the colonies may be a nuclear reactor, therefore the design must also consider the rules of nuclear safety. Of course, there are differences here too. The colony cannot travel, it would be much further away and in more inhospitable environments than any submarine ever was, but could expand its facilities over time. But a key principle for submarine design also applies to the security of space colonies: security by design.

For complex systems that include life support, mission-specific equipment, energy resources, etc., security should be a goal at the outset, even if not all relevant parts have been added or fully built. The answer to the question of whether or not a newly established space colony should have defence from the start is no. The reasons for this are numerous: cost efficiency, a matter of priorities, the absence of a threat, etc. Installing any kind of weapons on a lunar base would violate the Outer Space Treaty, trigger diplomatic conflicts and lead to an arms race on other planets. However, security requirements could be added at the design stage so that if a base needs to be expanded, the designated space, additional energy generation capacity, etc. is already in place. This could be a signal to other space powers that in the event of a conflict these elements can be added without there being an actual threat. It can be argued that the potential rival would respond in the same way on a different basis, and assumptions about differing levels of readiness in the perception of the other side may still lead to a downward spiral arising from an unfolding security dilemma for the participants.

One solution to this dilemma could be the seemingly opposite approach to preparedness, namely the absence of any security and defence considerations. This could be the initial phase for all colony projects, as the establishment of a functioning life support system, living quarters, laboratories, etc. is necessary to even begin operations. If this lack is the result of disregarding possible future problems, then it is not a sign of peaceful intentions, but rather of negligence or wilful blindness. However, if this is done as a strategy to keep the threat perception of potential rivals low, coupled with an agreement made in advance and a reliable verification system to ensure they hold up their end of the bargain, this could be a viable strategy.

PAYING THE BILL

Part of the discussion is a familiar line of argument for any kind of space activity. Why spend money on it, we should rather spend it here on Earth. Space activities for the sake of exploration are only undertaken by adventurers, but all the great explorers of the past were funded by governments hoping for trade, but there is no trading partner in space, so the benefits seem rather subjective (Schiller 2009). One justification often cited by proponents of space colonisation is that every dollar spent on space is actually spent here on Earth, funding companies, securing jobs, etc., while having a multiplier effect and encouraging innovation. There are additional benefits from the extraction of resources. It will not solve any problems on Earth, but the minerals mined on the Moon or from asteroids would be used to expand space infrastructure rather than using rockets to put material into orbit. According to Carlson, the Chinese space program was able to integrate such plans and ideas into its space program earlier than the U.S. (Carlson 2020: 68–86). Certain trace elements such as helium-3 on the Moon could represent an enormous new source of energy.

But even a mission to the Moon is expensive. There are different calculations as to how much it would cost to keep a small team of astronauts on the Moon. Older estimates vary between USD 10 and 36 billion (Anderson 2019). By comparison, the Biden Administration's proposed NASA budget for 2024 is USD 27.2 billion. Congress could only approve about USD 25 billion for 2024 and 2025, but the Artemis project is a priority (NASA 2024). The final amount will depend on launch costs and the technologies that enable the production of oxygen, food, water, fuel and construction materials on site, but it will not be cheap. Regardless of the amount, there are opinions even among space experts that overemphasising the Moon from a security perspective is misguided. To quote Aaron Bateman: "From a military standpoint, the moon is not a strategic piece of territory. In the near future, the moon will likely be a place of limited scientific research. I think that the heavy focus on the moon and cis-lunar space are misguided and that the focus should be on the way in which space systems are linked to terrestrial political, economic, etc. goals" (Bateman 2024).

The logical response to space dollars being spent on Earth is that if they spent those amounts on anything else, they would be reflected here on Earth in salaries for other professions, etc. This debate has to do with moral values, worldviews, threat perceptions, economic interests and many other factors. Perhaps it is not too far-fetched to say that at this stage we do not know what results the attempt to colonise space could bring, and we can consider it a ground-breaking new research project. It requires large investments, the outcome is uncertain, but there is hope for potential benefits on a large scale.

DISCUSSION IN SOCIETY

Space policy makers and defence experts are not the only ones debating space expansion and the best approaches to it. Governments communicate in one way or another about space programs. There are specific methods and goals for each country. In the U.S., there is a lot of talk about the space race, which is an imprecise term, but it can serve to generate enthusiasm for the space program, create a sense of urgency and perseverance, and at the same time create the impression of another historical era in which the Americans triumphed and won the space race against the Soviet Union. In China, the communication is different, it is more to strengthen the legitimacy of the communist government, to boost national pride and to show the world that China is no longer a backward nation. In general, Chinese space-related communication methods are linked to communist propaganda techniques while utilising the most sophisticated IT tools and relying on the higher receptivity and willingness of the population for political action (Edl 2022).

In parallel to government communications, academics, public figures, celebrities, various ideological groups and the general public also participate in the discussion. The use of words and phrases is a highly observable aspect of the conversation. The term colony itself can spark political debates. It needs to be the subject of another paper to fully explore the ramifications of the various terms and their use in current political debates. As a brief introduction to the topic, the main ideas seem to revolve around the historical phenomenon of colonisation, when Western, mostly European powers occupied territories and used their resources to strengthen their own economies, warfare capabilities, etc. The establishment of space colonies is often referred to as a possible return of colonisation, as it could be that spacefaring nations use the acquired resources to further strengthen their power and dominate world politics even more, instead of sharing everything (Giri 2022).

The word exploitation is also a peculiar word in many respects. It often has negative connotations, especially when it describes the relationship between people. Yet, in terms of resource extraction, however, the word describes the phase in which the discovered mineral deposits can be extracted and used. In his book, Carlson describes the phases of space colonisation as: Exploration, Expansion, Exploitation and Exclusion. In his opinion, the key to the whole endeavour lies in the third phase of exploitation, which will make the whole endeavour financially worthwhile. Any space power that makes this transition will have a far superior space program and will have great advantages in space and therefore on Earth as well (Carlson 2020: 174–213). The mutual observation of the space powers will further boost their activities in space because they do not want to be left behind. At present, the government bears most of the expenses in the exploration phase, which could create a commercial market after a while. This would be a reason for manned bases on other planets, because it might be more expensive to supply bases with human inhabitants, but at the same time the constant high revenues can attract private companies, which make services cheaper, which in turn attracts more people to the colonies, and so on and so forth. This hope is shared by most proponents of space colonies. More cautious opinions warn against getting too excited because they do not see a possible transition from exploration to exploitation and we should rather focus on sustainable mining on Earth (Segura-Salazar – Moore 2023). Others suggest we should not even try and the whole capitalistic approach is wrong because it will damage the space environment.

There is no room in this paper for a thorough analysis of the discussion on "colonies" or "exploitation". As an aside, avoiding the word colony because of historical connotations may prove insufficient to ensure that a similar event does not occur in the future. Any word can be used to describe, justify or cover up malicious intentions and actions. A painfully obvious memento of this is the word freedom. Even if the extraction of resources were not accompanied by territorial claims, there is no guarantee that the resources will not be used to feed a military-industrial complex. Refraining from asserting property rights may also mean that one does not take responsibility for damage or pollution at the site. Conversely, one could argue that precisely because of the risk of aggression and domination, the word colony should be retained as a reminder and warning that the whole process could once again become a pawn in great power politics.

INDEPENDENCE FROM THE VIEWPOINT OF SECURITY

Debates about the future of humanity and space colonies often touch on the question of the ideal political system. The relationship between the established player and the colony is a key component of this. A colony declaring independence is a possibility far in the future. It is not only an ideological question, but also a question of security and defence. There are proposals for independent, self-governing societies from the beginning. The idea sounds nice, but even if the founder and investor do not exercise control, the supply dependencies mentioned earlier can make the new colony highly dependent on other actors. For colonies with an owner or heavy dependency, the tantalising historical parallel would be the American War of Independence or any colony becoming independent. For such an event to occur, a number of conditions must be met. To revisit Buzan's idea of a state and the conditions for its existence, we could build on this idea, modifying and extending it to encompass the case of colonies gaining and maintaining their independence.

– The ideological basis: In case of the colonies, they must have the idea that they are a distinctive community, different from any kind of nation or the Earth itself. How the process of establishing this idea plays out and what the unifying idea would be, depends on many factors, could take the form of a smaller community, similar to a city (creating an independent space polis to use the analogy to the Greek city states), a country, or it could expand to all colonies on the given planet, so the unifying idea would not be nationalism, but rather "planetism". Even a dichotomy with Earth and all colonies outside Earth is a theoretical possibility.
– The drive: When we talk about gaining independence, we must add another element to the ideological foundation. A strong identity is not enough to start any kind of movement for self-government, because the prevailing idea could be to remain under the rule of the current sovereign, because of external threats, good relations, etc. The conviction that independence is achievable and more beneficial than the status quo is

paramount to all such aspirations. This conviction does not have to be fully accepted by the population, it is sufficient if the people who can control the colony share this idea. As a complementary requirement, there must be a conviction in the existing controlling faction that it is better to grant this independence than to try to prevent it in any way. This is not necessarily the result of an armed struggle. It is possible to achieve this through political action.
- The physical basis: A colony must have a sufficient number of qualified people, various types of facilities, economic capacity and the necessary physical infrastructure to sustain life. Depending on the celestial body hosting the colony, this may mean things that are not an issue on Earth, such as oxygen, radiation protection, etc. In this category we also need to include tools and capabilities to gain and maintain independence against internal or external threats.
- The institutional basis: In order to be able to govern itself, the new institution must establish and maintain its administration and institutions. In most cases, this would not mean the destruction of the previous systems; at least some elements would be preserved.

A special case of independence would be unintentional, de facto independence, when the original sovereign is unable or unwilling to exercise control over the colony. This must be the case until the colony has reached a point where it wishes to, and is able to, maintain its independence. One argument often made by space travel advocates who want to establish settlements on other planets is that this could very well happen if something were to happen to our home planet. An asteroid could hit Earth, there could be a catastrophic nuclear war, or in case of a solar activity, there could be a global collapse of the technosphere. Pelton even mentions the weakening of Earth's magnetosphere due to a magnetic polar reversal; this could mean that global civilisation is more vulnerable than previously thought (Pelton 2021: 138). The main idea is that a sufficiently developed and self-sustaining society on another celestial body would increase the chances of survival of the entire human race, it could be a seed for restoration, so that we must become a multi-planet species (Cuthbertson 2021). This alone would not be a sufficient argument to justify all expenditure on such efforts, but it can influence general opinion, have an emotional impact on individuals and strengthen the motivation of people trying to achieve this goal.

CONCLUSIONS

This chapter has presented frameworks and analogies for discussing security issues adapted to activities in space, more specifically to the establishment of colonies on other planets. Focusing on the Moon and using it as a step towards Mars projects has a good rationale and the space powers seem to be pursuing this direction while avoiding falling into a disadvantageous position vis-à-vis their geopolitical rivals. There is disagreement over priorities, approaches or even the use of certain words, on the assumption that avoiding certain words could help prevent the recurrence of similar events in the past. Geographical, historical or military concepts are often used to prepare for the unknown future, and they have their merits and limitations. Theoretical research and the creation of new frameworks will continue in order to avoid possible obstacles and problems. The expansion of widely used systems could also prove useful. This includes the inclusion of space as a new sector in the security sector framework created by Barry Buzan and the Copenhagen School. Aside from strictly security-oriented assessments, a discourse analysis of the connections between the use of terminology, various historical narratives, political ideology and psychological factors could further enhance understanding in this area and provide some viable alternatives as the construction of other celestial bodies begins.

REFERENCES

Anderson, J. (2019): Here's How Much It Would Really Cost to Build a Moon Colony. *Yahoo Finance,* 13 September 2019. Online: https://finance.yahoo.com/news/much-really-cost-build-moon-184949330.html

Armor Research Foundation (1959): *A Study on Lunar Research Flights.* Online: https://documents.theblackvault.com/documents/space/AD0425380.pdf

Bartóki-Gönczy, B. – Nagy, B. (2023): The Artemis Accords. *International Legal Materials,* 62(5), 888–898. Online: https://doi.org/10.1017/ilm.2023.17

Bateman, A. (2024): Written interview with Dr. Aaron Bateman done by András Edl on the 6th of February 2024.

Bowen, B. E. (2020): *War in Space. Strategy, Spacepower, Geopolitics.* Edinburgh: Edinburgh University Press.

Bowen, B. E. (2022): *Original Sin. Power, Technology and War in Outer Space.* London: Hurst.

Buzan, B. – Wæver, O. – de Wilde, J. (1998): *Security. A New Framework for Analysis.* London: Lynne Rienner Publishers.

Carlson, J. P. (2020): *Spacepower Ascendant. Space Development Theory and a New Space Strategy.* [s. l.]: Independently Published.

Cuthbertson, A. (2021): Elon Musk Says Mars Colony Sets Humanity Up to 'Become Interstellar'. *Independent,* 26 November 2021. Online: www.independent.co.uk/space/elon-musk-mars-colony-spacex-interstellar-b1964122.html

DARPA (2021): *DARPA Selects Performers for Phase 1 of Demonstration Rocket for Agile Cislunar Operations (DRACO) Program.* Defense Advanced Research Project Agency. Online: www.darpa.mil/news-events/2021-04-12

Dolman, E. C. (2001): *Astropolitik. Classical Geopolitics in the Space Age.* London–Portland: Frank Cass.

Edl, A. (2022): Space Program and Propaganda in the People's Republic of China. In Doma, P. – Takó, F. (eds.): *"Near and Far" 10/1. Proceedings of the Annual Conference of ELTE Eötvös Collegium Oriental and East Asian Studies Workshop.* Budapest: Eötvös Collegium, 131–144. Online: https://eotvos.elte.hu/media/fa/e8/5823639a75240a258593bb18e-75d44405149a287c5b8323bbf48d760e4c7/ec_Kozel_s_Tavol_X_06_06.pdf

ESA (2023): *ESA Budget 2023.* European Space Agency. Online: www.esa.int/ESA_Multimedia/Images/2023/01/ESA_budget_2023

Euroconsult (2023): *Space Economy Report.* Online: https://digital-platform.euroconsult-ec.com/product/space-economy-report/

Euroconsult (2024): *New Historic High for Government Space Spending Mostly Driven by Defense Expenditures.* Online: www.euroconsult-ec.com/press-release/new-historic-high-for-government-space-spending-mostly-driven-by-defense-expenditures/

Giri, C. (2022): As Geopolitical Blocs Vie for Primacy in Space, the History of Colonization Looms Large. *Centre for International Governance Innovation,* 7 February 2022. Online: www.cigionline.org/articles/as-geopolitical-blocs-vie-for-primacy-in-space-the-history-of-colonization-looms-large/

Hong, B. (2018): China's Looming Land Grab in Outer Space. *The Daily Beast,* 22 June 2018. Online: www.thedailybeast.com/chinas-looming-land-grab-in-outer-space

Howell, E. (2023): Artemis 4 and Artemis 5 Moon Missions Will Include European Astronauts. *Space,* 11 July 2023. Online: www.space.com/artemis-4-5-moon-missions-european-astronauts

Mayence, J.-F. (2010): Space Security: Transatlantic Approach to Space Governance. In Robinson, J. – Schaefer, M. P. – Schrogl, K.-U. – von der Dunk, F. (eds.): *Prospects for Transparency and Confidence-Building Measures in Space. ESPI Report 27.* Vienna: European Space Policy Institute. 35–36. Online: www.espi.or.at/wp-content/uploads/espidocs/Public%20ESPI%20Reports/ESPI_Report_27.pdf

Moltz, J. C. (2014): *Crowded Orbits. Conflict and Cooperation in Space.* New York: Columbia University Press.

NASA (2024): *NASA's FY 2024 Budget.* Online: www.planetary.org/space-policy/nasas-fy-2024-budget

Parsonson, A. (2023): *Is ESA Getting Screwed on Artemis Deal?* Online: https://europeanspaceflight.substack.com/p/is-esa-getting-screwed-on-artemis

Pelton, J. N. (2021): *Space Systems and Sustainability.* Cham: Springer.

Reiffel, L. (2000): Sagan Breached Security by Revealing US Work on a Lunar Bomb Project. *Nature,* 4 May 2000. Online: www.nature.com/articles/35011148.pdf

SCHILLER, M. (2009): *Efforts, Motivation and Benefits of Spaceflight – A Brief Guide for Space Advocates and Decision-Makers.* Online: www.files.ethz.ch/isn/124678/espi%20perspectives%2026.pdf

SEGURA-SALAZAR, J. – MOORE, K. (2023): The Hype Is Out of This World, but Mining in Space Won't Save the Earth. *The Conversation,* 30 January 2023. Online: https://theconversation.com/the-hype-is-out-of-this-world-but-mining-in-space-wont-save-the-earth-191855

SHEEHAN, M. (2007): *The International Politics of Space.* Abingdon – New York: Routledge.

STONE, M. (2009): *Security According to Buzan: A Comprehensive Security Analysis.* Online: www.researchgate.net/publication/239548228_Security_According_to_Buzan_A_Comprehensive_Security_Analysis

Times Radio [@Times Radio] (2023): The New Space Race: Russia Doesn't Have the Power to Do It Alone. Asif Siddiqi. *YouTube,* 22 August 2023. Online: www.youtube.com/watch?v=AGY88fN9V6c

TOWNSEND, B. (2021): *Security and Stability in the New Space Age.* New York: Routledge.

U.S. Army (1959): *Project Horizon.* Online: https://history.army.mil/faq/horizon/Horizon_V1.pdf

U.S. Department of State (2024): *Artemis Accords.* Online: www.state.gov/artemis-accords/

URI, J. (2020): *The Real Story of the Skylab 4 "Strike" in Space.* Online: www.nasa.gov/history/the-real-story-of-the-skylab-4-strike-in-space/

WEINERSMITH, Z. – WEINERSMITH, K. (2024): Space Isn't the Final Frontier. *Foreign Policy,* 21 January 2024. Online: https://foreignpolicy.com/2024/01/21/space-isnt-the-final-frontier/

WILMER, A. P. – BETTINGER, R. A. (2022): Holding the High Ground. Operational Considerations for the Earth–Moon System. *Aether. A Journal of Strategic Airpower and Spacepower,* 1(2), 63–78. Online: www.airuniversity.af.edu/Portals/10/AEtherJournal/Journals/Volume-1_Number-4/Wilmer_Holding_The_High_Ground__.pdf

ZHELEZNYAKOV, A. (2009): *The E-4 Project – Exploding a Nuclear Bomb on the Moon.* Online: www.svengrahn.pp.se/histind/E3/E3orig.htm

Federico Bonarota[1] – Lucia Adele Savatteri[2]

The Role of Private Sector in Space Settlements

INTRODUCTION

In 1969, with the Apollo 11 mission, the first humans took the first step on the Moon. Starting perhaps with Méliès and his film "Le Voyage dans la Lune" and continuing through Kubrick's "2001: A Space Odyssey" and all the episodes of "Star Trek" and beyond, cinematography has captured one of humanity's greatest dreams in images: the exploration of the universe.

In today's landscape, the new goal is not only to return to the Moon but also to establish settlements and explore various other potentially habitable places. However, humanity is undergoing a paradigm shift where, in a sector that was overly expensive and reliant on seemingly unattainable technologies in the past, not only public institutions but also private companies are now emerging as major players. This shift is due to the fact that government projects have to contend with cyclical budget fluctuations, changes in political leadership and, consequently, shifts in priorities within a country. In contrast, private companies are in many ways more efficient and, paradoxically, more forward-looking in their objectives.

While the private sector has been involved in the space industry in the past, albeit in a more technical and less prominent capacity, the perspective has changed significantly over the last decade. It is important to remember that this paradigm shift has not yet reached a global level. It is a heterogeneous movement that is witnessing the emergence of private companies, especially

[1] Luiss Business School; ORCID: https://orcid.org/0009-0006-5929-0761; e-mail: federico.bonarota93@gmail.com

[2] Link Campus University; ORCID: https://orcid.org/0009-0009-9138-257X; e-mail: lucia.savatteri12@gmail.com

DOI: https://doi.org/10.36250/01209_10

in the United States and, to a certain extent, in some European countries. In other politically divergent countries, the public sector remains the only way to pursue space programs.

> "...transfer of certain roles in space from the government to industry. In some cases, this was intentional and proactive on the part of governments to facilitate formation of a commercial space economy. Intentional because this is the only means to continue the growth of value creation in space in a way that is proportional to the needs of society and does not involve ballooning government budgets" (McElroy 2023: 1–12).

As McElroy points out, these private companies, with their disruptive technologies, are not only aligning themselves with space agencies but are also displacing them in the new areas they are approaching. From security to tourism, from the revenue sectors to sustainable management, this chapter aims to provide an overview of the importance that private companies have in the global mission to establish space settlements.

A "new generation of space programs is currently being observed" (Paravano et al. 2023), in which not only has there been a shift in socio-political and economic dynamics but also a new wave of regulations and public funding to support the development of the space sector, including in the private domain.

It is indeed true that private entities are highly incentivised to invest in the space settlements market, due to the possibility of a high profit gain in the long term. The immense potential and importance that a settlement could provide are significant motivating factors. These settlements would represent vast resources under the control of private enterprises, which could then leverage them to support and establish their own outposts, forging entirely novel business domains that are currently beyond our imagination. Additionally, there is concern about utilising settlement resources to support and create a parallel market that could potentially contribute to sustaining the world in various ways. Although this might appear somewhat utopian from certain perspectives, it is the present and the future that are embracing us, and to which we must adapt.

Regarding the settlement of celestial bodies, there are private companies that are showing more significant interest in the subject and are pragmatically taking steps in this direction. Among these, SpaceX, Blue Origin and ispace are the ones we will delve into. With the Starship project, SpaceX is developing the most powerful launch system ever designed, capable of carrying payloads to much greater distances and at a lower marginal cost per launch. Due to its payload compartment size, the vehicle will enable the transportation of substantial payloads as well as a large number of individuals. While there were issues with the initial launch, progress is now being made for subsequent ones. Such technology has the potential to revolutionise the way we perceive space travel, enabling longer and more enduring expeditions to celestial bodies.

Staying within the United States, another significant player in the field is Blue Origin, the space company led by Jeff Bezos, which has been actively pursuing the possibility of finding and establishing a presence on other celestial bodies for several years. Bezos envisions the future of humanity residing in extraterrestrial settlements, with Earth becoming a vacation destination. An interesting recent project in this regard is undoubtedly Blue Moon, which NASA has selected for crewed missions shuttling between the orbital station and the lunar surface. It will debut with the Artemis V mission in 2029, with an investment exceeding 7 billion dollars.

Another noteworthy player making strides in this field is undoubtedly ispace, a Japanese lunar exploration company. Their self-defined company vision is to become the bridge between Earth and the Moon, advancing missions aimed at mapping the lunar surface to locate essential water resources for human sustenance. By splitting water molecules, it will be possible to produce hydrogen-based fuel, addressing the challenge of energy production. Unfortunately, their Mission 1, Hakuto-R, launched in December 2022, ended in failure. However, this setback will certainly not deter the company from continuing its pursuit. Certainly, numerous other entities, including Virgin Galactic, Boeing, Axiom and Voyager will soon be engaging in the emerging paradigm of the settlement economy.

However, providing a private entity with the opportunity to establish itself on the Moon or other celestial bodies could have significant implications, both politically and economically. Certainly, a regime solely dictated by capital, which these actors would likely bring, might lead to the creation of the parallel market we mentioned earlier, with "virtually unlimited resources" (Pearson 2019) primarily for affluent individuals, exponentially exacerbating the existing inequalities on Earth. It may seem like a scenario from science fiction, but in some way, it is not, and it is essential to pay attention to this point before it becomes irreversible. While outer space, in many respects, could be our salvation, it is crucial to take precautions from now on to prevent excessive competition between the public and private sectors, or as it will be more appropriate to say in the coming years, between the public and the new public, leading to self-destruction.

THE ROLE OF THE PRIVATE SECTOR IN SPACE DIPLOMACY

Space Diplomacy lacks a single and univocal definition, as each school of international relations contributes its own theory to the discourse. To simplify this complex subject, we can characterise Space Diplomacy as a subset of International Relations (IR) where soft power, particularly economic and scientific influence (Davis Cross – Pekkanen 2023) is predominantly wielded to manipulate counterparts and advance specific agendas or secure agreements. Within this framework, the State is just one among several actors, including International Organisations, the global environmental movement, the corporate sector and expert groups (O'Neill 2022).

Historically, countries employed Space Diplomacy as a tool either to mitigate threats in space or to foster cooperation towards shared objectives. However, the landscape is shifting with the remarkable growth of private entities, exemplified by SpaceX and Blue Origin. These private entities are increasingly engaging in political actions, irrespective of the consent of the countries in which they operate. A notable turning point occurred in February

2022 with the intervention of Elon Musk, the owner of SpaceX, and the pivotal role played by his Starlink internet service during the Russia–Ukraine conflict.

To illustrate this transformative shift, an examination of events in Ukraine and the role played by private entities is crucial. Ukraine, anticipating Russia's impending attack (Graham-Yooll 2022), had initiated discussions with SpaceX regarding the utilisation of Starlink even before the outbreak of the war.

Post-invasion, a tweet from Vice Prime Minister Mykhailo Fedorov conveyed an unconventional request for the prompt deployment of Starlink in Ukraine (Mykhaylo Fedorovov 2022). Thanks to a prior agreement, the system was nearly ready for deployment. In just 48 hours, Starlink provided its signal antennas to Ukraine (Howell 2022), enabling internet connectivity and military communication. The turning point was the utilisation of the private service on the battlefield through the use of remotely controlled drones and missiles (Davenport–Menn 2023).

In 2022, Ukraine further requested Elon Musk to extend signal coverage, including the Crimean Peninsula, where the main fleet of Russia's Black Sea force was based, to lead a sortie. Musk declined, citing concerns about a potential Russian nuclear counterattack (Copp 2023). This refusal prompted, in September 2023, the U.S. Secretary of the Air Force, Frank Kendall, to suggest that future contracts explicitly address the potential military applications of procured services or products (Kendall 2023).

Consequently, it is plausible to expect the direct involvement of the private sector in conflicts between countries in the near future. This speculation extends to a more remote future: space settlements. From this point, we can envisage new scenarios that would significantly impact space diplomacy and redefine our understanding of it. The role of private entities is anticipated to evolve, ushering in a new era in current international relations. Certainly, it is essential to assume that, in the future, when settlements are established, Outer Space Law will undergo modifications to accommodate and ensure successful development moving from a paradigm where the Celestial Bodies, and so the resources, are a common good for all mankind to a paradigm where the resources can be extracted and used. Based on this premise, we can delineate three distinct scenarios in which the private sector plays a role.

The first scenario, with limited feasibility, envisions private entities under the control or contractual obligations of the government, reminiscent of the old space era. Abundant resources and raw materials drive settlements to thrive under strict state supervision. The state regulates and oversees costs and profits derived from extraction through rigorous contracts with severe penalties. Despite being regulated instruments, private entities ensure gains, addressing research and development costs incurred by the state. In this outline, international relations remain relatively unchanged, with actors retaining similar power dynamics. However, the private sector has lost autonomy and capacity, impeding rapid development observed in recent years. The primary risk is the potential emergence of a State-planned Space Economy, akin to historical instances in the Soviet Union (Hanson 2003: 13–48).

The second scenario, with moderate plausibility, depicts a hypothesis where private entities attain significant autonomy, no longer tethered to any specific country. They establish independent settlements, reminiscent of the concept of Merchant Republics (Lindemann 2014), engaging in trade with Earth and others for mutual benefit. These settlements thrive through innovation, financial prosperity and resource abundance. Each private actor establishes their own settlement, fostering state-like entities or leagues for collaborative efforts, such as defence, and creating free trade areas for goods and services exchange. In this hypothesis, private entities wield comparable or even greater power than major space powers, capable of initiating wars for resources or forming new organisations. They operate freely, bypassing the consent of other international actors. This disrupts international relations, as states struggle to uphold the Rule of Law. The principal risk is the potential emergence of a *Far West* scenario, where the strongest entities dominate.

The third scenario, with the highest likelihood under current conditions, envisions a collaboration between the public and private sectors, manifesting as an enhanced form of Public–Private Partnership (OECD 2012).[3] This partnership fosters private ideas and productivity to meet client needs, managing settlements through joint cooperation. The collaborative approach ensures prosperity and peaceful space utilisation, with settlements under the control of both parties, yielding benefits and drawbacks. In this outline, public and private entities maintain distinct competencies, avoiding attempts to control one another. Human needs are met, and international relations evolve, granting a preeminent role to private entities. These entities operate independently or under a country's "umbrella". However, the primary risk is Extreme Capitalism[4] (Rahman 2021) where private entities and politicians intertwine their interests in wealth and money, leading to societal division between the affluent and the impoverished.

Upon a brief analysis of these scenarios, a notable emergence is the transformed role of Space Diplomacy within International Relations. Once a peripheral concern, it becomes a central or one of the central elements due to space exploration and settling, marking a shift from Geo-politics to Space-politics with the ascent of new players and novel ideas.

PRIVATE ENTITIES AND SPACE SETTLEMENTS

Considering that "the value chain of the space economy refers to the various activities and processes involved in the creation and provision of products and services related to space" (OECD 2022), the question to be asked is whether, in a space settlement, one can still speak of the space economy in a narrow sense or whether there will be a new lunar economy, Mars economy, and so on. It is

[3] The OECD defines public–private partnerships (PPPs) as "long term agreements between the government and a private partner whereby the private partner delivers and funds public services using a capital asset, sharing the associated risks".

[4] Extreme capitalism is a condition in which large companies and rich people raise too much money and leave too little for the rest of society. As a result, the public does not have enough money to increase consumption. Demand is not increasing and the market is not growing.

certainly premature to discuss at least the Mars Economy. As long as the stakeholders, the normative framework and the perspective remain Earth-centric, speaking of the Martian economy and in some way of a Lunar Economy seems to be distant from the public opinion ideas. Certainly, there is already discussion of the lunar economy, as the Moon is a source of helium-3 reserves and rare earth elements, both essential for potential nuclear fusion and, consequently, energy sustenance, and for the technological industry.

As can be well understood, in the space settlement, there will be needs for the production of services and products related not only to space in a strict sense but also to the territory at hand, which will prove to be extremely valuable in many aspects. Thus, along with a new concept of upstream and downstream, where data collected by satellites orbiting directly around the Moon and other relevant celestial bodies will be transmitted directly to the settlement without passing through Earth, a parallel market will be created, stemming from extractions and the utilisation of all available materials. Subsequently, a range of products and services related to the subsistence of the people working on these celestial bodies will also emerge. For a private entity, therefore, investing in the new economies that are emerging and will continue to develop represents a unique opportunity.

According to the Euroconsult report for 2023, it is anticipated that market expansion will continue to stimulate global investments. Over the next decade, lunar exploration is forecasted to achieve a significant 10-year compound annual growth rate (CAGR) of 5%, ultimately reaching an estimated value of nearly $17 billion by the year 2032 (Euroconsult 2023a).

As can be observed, there are numerous economic opportunities. However, when it comes to Mars, there is much more at stake. Elon Musk himself, referring to the red planet, characterises it not just as a source of resources to extract, but as the ultimate hope for humanity, thereby rejecting the famous phrase by Branson: “There is no planet B.”

Ensuring the design of the space settlement’s economy aligns with users’ actual needs is crucial, offering an improved balance between costs, benefits and trade-offs compared to alternative approaches. Only through this approach can a private company attract the essential investments in financial, technical, policy, organisational and human resources to overcome the diverse engineering, legal and other challenges hindering its progress.

Considering this perspective, let us delineate some of the potential revenue sectors for a private entity in a settlement.

Mining: Partially addressed earlier, mining appears to be the primary revenue source that settlements could offer. In the future, there might be settlements solely dedicated to this purpose, as the phenomenon demonstrates immense potential. Depending on the celestial body, extractable resources and the actual profit potential would vary.

One of the most lucrative celestial bodies, for instance, is asteroids, rich in nickel silicates, iron, magnesium, carbon and more. There is ongoing discussion not only about using them as extraction sources but also about the possibility of establishing new settlements on these celestial bodies (Allison 2018). Astrophysicist Neil deGrasse Tyson even states: "The first trillionaire there will ever be is the person who exploits the natural resources on asteroids" (Kramer 2015).

In general, mining is not limited to precious minerals but also includes the extraction of icy water, as envisioned by companies like ispace, for nuclear energy production, and sustenance. It is also crucial to consider the significance of water in the production of hydrogen and oxygen used as propellants for launchers. Additionally, an Italian initiative involving OHB Italia and Politecnico di Milano aims to utilise the lunar regolith to extract water. It would be a great opportunity for new privates that want to approach the sector.

Shriya Yarlagadda, the Editor-in-Chief of the Harvard International Review, posits that space mining could provide a solution to challenges associated with terrestrial mining, such as child labour and other unjust practices by private companies (Yarlagadda 2022). However, unconditional possession of a vast quantity of space resources by a few private entities could potentially lead to the collapse of entire economies, posing negative repercussions. The key lies in balancing these two sides of the same coin, ensuring that this phenomenon has predominantly positive effects.

Energy: Moreover, settlements will undoubtedly require robust energy sustenance, presenting ample opportunities for private enterprises to contribute through innovative and sustainable ideas. In this context, the recent presentation of the Solaris project is noteworthy, a venture developed by ESA and led by Arthur D. Little and Thales Alenia Space Italy. This initiative involves Space-Based Solar Power, capable of consistently providing power on a 24/7 basis. This reliability addresses the need for stability in the electricity grid, particularly as the proportion of intermittent renewables grows, thereby decreasing reliance on extensive storage solutions. Undoubtedly, a project of this nature has the potential to catalyse a plethora of new initiatives and ideas, paving the way for significant private sector involvement.

Another significant project is MAPLE (Microwave Array for Power-transfer Low-orbit Experiment), a project being developed by the California Institute of Technology (Caltech) to address the challenges of space-based solar power generation. Recently, MAPLE achieved a significant milestone by successfully conducting its inaugural test of wireless microwave power transfer in space, thereby paving the way for innovative solutions in orbital solar energy production. This initiative, which is part of Caltech's Space Solar Power Project, aims to confront global energy challenges by harnessing solar power in space. The successful demonstration of MAPLE represents a promising advancement toward sustainable and efficient space-based energy solutions.

Another project, Alba, is dedicated to studying 32 different types of solar cells to identify those best suited for operation in space. This constitutes a crucial step in ensuring the efficiency and longevity of solar panels utilised in future space solar energy projects. Meanwhile, the Dolce project, which stands for Deployable on-Orbit ultraLight Composite Experiment, will test the technologies developed for packaging and deploying future solar power production and transmission stations.

Cloud services and data centre: These sectors could be of significant interest to private entities seeking investment opportunities.

In this regard, it is noteworthy that the company Lonestar has looked far ahead, considering the Moon a potential data storage location. Their motto:

"Saving Earth's data one byte at a time" reflects their vision, and with this, they have raised $5 million for lunar data centres.

Cybersecurity: Space settlements will introduce a "new approach to cybersecurity in space" (Vasquez 2023). The development of critical infrastructure in celestial bodies distant from Earth is inevitable, necessitating secure connections between these new celestial entities and the Homeland. In this regard, the private sector could have significant opportunities by providing crucial services. Simultaneously, in many aspects, these private companies are subject to the necessity of availing themselves of new cybersecurity services, therefore, both from the demand and supply perspectives, it will be a rapidly expanding sector. Given the vast scope of this topic, we will confine our examination to its foundational aspects in this context.

Space Traffic Management: Space Traffic Management (STM) refers to the coordination and regulation of space activities to ensure the safe and sustainable use of outer space. It involves monitoring and controlling spacecraft, satellites and other objects in orbit to prevent collisions and minimise space debris. STM initiatives aim to develop international guidelines and regulations to address the growing congestion and potential hazards in space, fostering cooperation among spacefaring nations and commercial entities for the peaceful and responsible exploration and use of space.

SPACE TOURISM

Among the diverse lucrative activities that the private sector could undertake in space settlements, one that is transitioning from aspiration to reality today and capturing the imagination of the public is space tourism. Envision exploring the liquid methane sea of Titan, one of Saturn's Moons, where temperatures hover around a warm minus 179 degrees Celsius. Alternatively, consider submerging into the sea beneath the frozen surface of Europa, Jupiter's icy moon, with temperatures slightly colder at minus 225 degrees Celsius. For those seeking relaxation and a touch of history, there is the option to stay at the new Moon

Grand Hotel and visit the historic site of Apollo 11 in the Sea of Tranquillity, where the first humans set foot on the Moon (NASA 2024a; NASA 2024b).

While these possibilities might appear as mere commercial suggestions from sci-fi films or novels, they are transforming into reality through the commercialisation of human space flight, allowing individuals to become passengers on space journeys and return to Earth. Thanks to the efforts of the private sector, particularly companies like SpaceX, Blue Origin, Virgin Galactic and Boeing, experiencing space travel and microgravity is now achievable through payment. It has to be said that currently going into space is like climbing Mt. Everest, launching yourself with a parachute or diving deep in the ocean: an extreme sport with a lot of side effects for the body. So, the body and mind have to be trained to get to space.

However, this is merely the initial stage, as more ambitious projects are in the planning and development stages. Projects such as the Axiom Space Station, set to be the first-ever commercial station replacing the International Space Station (ISS), and Voyager Station are on the horizon. Additionally, companies like Bigelow, that went bankrupt in 2020 (Wattles 2022) and is known for bringing the first bingo machine to space, had or are contemplating the creation of space or lunar resorts to cater to clients. Of course, each of those companies risks a lot of money and not always is their bet a winning one. Major players in the tourism sector are already in the process of developing the initial projects for their space resorts in collaboration with other space companies. For instance, the renowned hotel chain Hilton is partnering with NanoRacks (Waldek 2022), a company owned by Voyager Space – the same company behind the future Voyager space station – to explore the development of shared spaces, rooms and restaurants for prospective clients.

The project envisions constructing a circular structure of 200 metres in length to replicate the gravity of Mars. This structure is designed to accommodate up to 280 guests and 112 crew members, featuring various facilities such as a restaurant, gymnasium, bar, entertainment centre and relaxation spots (Chiedu 2023). Those involved in the construction of these space resorts are aiming for an inauguration in 2027, aligning with financial projections from

UBS estimating that the space tourism industry will be valued at 3 billion dollars by 2030 (Kamin 2022).

Regarding settlements on celestial bodies, the first proposal is the concept of a Moon village, situated on our satellite, which is the nearest celestial body to Earth. According to the European Space Agency (ESA), a distinctive aspect of this proposal is its inclusivity: "The Moon Village is open to any and all interested parties and nations. There are no stipulations as to the form their participation might take: robotic and astronaut activities are equally sought after. You might see not only scientific and technological activities but also activities based on exploiting resources or even tourism" (Woerner 2016).

Therefore, the trajectory for future settlements is expected to align with this pattern, progressively evolving to include new and expanded facilities or activities similar to those already present on Earth.

SECURITY AND SAFETY POLICIES OF FUTURE SPACE SETTLEMENTS

In the realm of space activities, security and safety entail distinct definitions: the first one defines the risk that can be referred to technical issues not directly linked to human activities such as flight safety, security, on the other hand, refers to ill or malevolent human behaviour or activities. This discussion refrains from delving into military aspects and national threats but centres on the private sector's role in ensuring the security of colonies.

As settlements and space settlements expand to the scale of cities in terms of infrastructure and population, a new imperative surfaces: public security that, in this case, overlaps with public safety. In the face of potential emergencies, companies, citizens and workers necessitate a dependable system. It is paramount to acknowledge that human lives are at stake, underscoring the indispensability of establishing a form of policing. Once again, the private sector assumes a crucial role by offering the prospect of furnishing a private police force as a measure to control and counter criminal behaviours (Elkins 2022).

Private entities are already able to ensure and will be able to ensure physical and infrastructural security through prevention and response plans, ranging from workplace violence to natural disasters. Concerning the last ones, they can support only with the State's permission. A similar collaborative trend is anticipated for settlements, where private entities may independently investigate minor crimes. There is also the prospect that in settlements, this type of "service" could serve as a substitute for national police. In such a scenario, it would fall under their jurisdiction, potentially encompassing personal injuries. The maintenance of jurisdiction by states could be facilitated through international agreements and the establishment of local courts or extradition mechanisms to Earth (Stanton Hardenstein 2016).

Continuing in the same vein of consideration regarding the presence of human settlers, another significant concern that surfaces is safety. Presently, safety in outer space is delineated as the "result of measures precluding inherent malfunction and mitigating the risks of accidental damage that would be caused by or undergone by a space object, including its component parts" (Cesari 2023).

Consequently, workers in space settlements will necessitate novel models and policies to ensure their safety throughout both working hours and leisure time. As of today, in the United States, where the private sector takes the lead, there is no overarching policy applicable to both the public and private sectors, as the Federal Aviation Administration (FAA 2022) and Congress have yet to formulate such a policy. The U.S. Congress implemented a regulatory moratorium on commercial human spaceflight in 2004. This has been subsequently extended multiple times, now persisting through 2023 (Marge 2023). What underscores the urgency is that, presently, commercial spaceflight crew and participants engage in spaceflight operations under the principle of informed consent. Hence, it is imperative for the private sector to actively collaborate with authorities in delineating policies to safeguard not only the ongoing human spaceflight endeavours but also the prospective development of the entire industry.

RISKS AND OPPORTUNITIES: SPACE SUSTAINABILITY AND THE PRIVATE SECTOR

Concluding the exposition, it is fitting to emphasise the principle that should underpin all activities within the emerging space economy, whether conducted by private entities or public institutions: sustainability.

> "Space sustainability is the ability to sustain space activities indefinitely into the future in a manner that achieves the objectives of equitable access to the benefits of the exploration and use of outer space for peaceful purposes, in order to meet the needs of the present generations while preserving the outer space environment for future generations" (UN COPUOS 2019).

This is the definition of space sustainability provided by UN COPUOS in 2019 and will serve as our foundation in the future. Recognising the potential significance of settlements on celestial bodies for all of humanity, and acknowledging that space resources, such as raw materials, are inherently limited due to the restricted availability of habitable celestial bodies, a necessity arises for a concentrated effort on resource preservation. In response to this requirement, specific attention must be devoted to the conservation of these finite resources. This can be accomplished through the establishment of sustainable cycles for resource extraction and utilisation in space.

At the intergovernmental level, it is imperative to establish guidelines, not only for public entities but even more so for private organisations engaging in space activities. This is necessary to prevent excessive liberalism, in that specific context. Specifically, this could manifest as an unrestricted and disproportionate utilisation of space resources and a lack of measures concerning debris disposal, which could lead to greater harm than benefit.

In terms of space environmental sustainability, planet Earth is confronting the issue of inactive satellites. Indeed, there are over 36,500 space debris objects larger than 10 cm, 1,000,000 space debris objects between 1 and 10 cm and 130,000,000 smaller ones in low Earth orbit (LEO). Both public initiatives and private companies are already taking measures to address the problem. Private companies, such as European entities like D-Orbit and Clear Space, as well as the Japanese company Astroscale, are launching missions aimed at "clearing the path for the future of space exploration" (Clearspace [s. a.]) and establishing a new sustainable approach to space travel.

The key point in this discussion is that instead of addressing this issue *ex post,* as in this case, it would be more beneficial in future endeavours, including the settling of new celestial bodies, to proactively prevent the problem from arising in the first place. However, being sustainable will not merely be an obligation for private entities; it will also yield substantial benefits. This pertains not only to "minimising the costs of resupplying resources" (Santomartino et al. 2023), but also to the image and longevity of planned missions. When considering the establishment of a presence on the Moon, Mars, or any other celestial body, the ultimate objective is to remain indefinitely and achieve self-sufficiency. A sustainable approach is the sole means of accomplishing this goal, and it is important to always remember that.

CONCLUSIONS

Currently, the private sector is rapidly gaining prominence, emerging as a major player in the space industry. The generated revenue amounted to 460 billion dollars in 2022, with an estimated growth projection to reach a trillion dollars by 2040 (Euroconsult 2022). This economic expansion is poised to instigate a transformative shift in various facets of our lives, influencing not only current politics and international relations, but also necessitating a re-evaluation of international regulations.

A parallel transformation will be observed in safety and security, with private companies assuming a new role. These entities are set to leverage space resources, utilising not only the raw materials from celestial bodies, but also technological advancements to position servers and systems in outer space. This burgeoning space sector will offer private citizens the opportunity to access space at an affordable price, providing a firsthand experience of life beyond planet Earth. Innovative investment mechanisms will be devised to facilitate services analogous to those available on Earth. In all likelihood, within the next decade, human presence on the Moon will be a reality, marking just the inception of an extraordinary journey.

REFERENCES

Allied Universal [s. a.]: *Public–Private Security Partnerships Are Essential to Public Safety.* Online: www.aus.com/security-resources/manufacturing-security-best-practices-5-critical-considerations

Allison, P. R. (2018): How We Could Survive on an Asteroid. *BBC,* 13 June 2018. Online: www.bbc.com/future/article/20180612-will-we-ever-colonise-an-asteroid

Cesari, L. (2023): What's in a Word? Notions of 'Security' and 'Safety' in the Space Context. *UNIDIR,* 12 May 2023 Online: https://unidir.org/whats-in-a-word-notions-of-security-and-safety-in-the-space-context/

Chiedu, J. (2023): The World's First Space Hotel Is Opening Soon & Here's What to Know About It. *The Travel,* 2 January 2023. Online: www.thetravel.com/what-to-know-about-the-first-space-hotel-in-the-world/

Clearspace [s. a.]: *Clearing the Way for the Future of Space Exploration.* Online: https://clearspace.today/

Copp, T. (2023): Elon Musk's Refusal to Have Starlink Support Ukraine Attack in Crimea Raises Questions for Pentagon. *AP News,* 12 September 2023. Online: https://apnews.com/article/spacex-ukraine-starlink-russia-air-force-fde93d9a69d7dbd1326022 ecfdbc53c2

Elkins, F. C. (2022): Police and Private Security Partnerships: Collaborating to Meet Growing Challenges. *Dispatch,* 15(2). Online: https://cops.usdoj.gov/html/dispatch/02-2022/police_private_partnerships.html

Davis Cross, M. K. – Pekkanen, S. M. (2023): Introduction. Space Diplomacy: The Final Frontier of Theory and Practice. *The Hague Journal of Diplomacy,* 18(2–3), 193–217. Online: https://doi.org/10.1163/1871191x-bja10152

Davenport, C. – Menn, J. (2023): Musk Refused to Allow Ukraine's Military to Use Starlink to Attack Russian Fleet. *The Washington Post,* 11 September 2023. Online: www.washingtonpost.com/technology/2023/09/07/ukraine-starlink-musk-biography/

Durante, F. (2021): Un'idea tutta italiana per la produzione d'acqua dalla regolite lunare. *Astrospace,* 7 May 2021. Online: www.astrospace.it/2021/05/07/unidea-tutta-italiana-per-la-produzione-dacqua-dalla-regolite-lunare/

ESA (2001): *Green Propellant for Space Propulsion.* European Space Agency. Online: www.esa.int/Applications/Observing_the_Earth/Green_Propellant_for_Space_Propulsion

ESA (2023): *ESA Developing Space-Based Solar Power Plant Plans.* European Space Agency. Online: www.esa.int/Enabling_Support/Space_Engineering_Technology/SOLARIS/ESA_developing_Space-Based_Solar_Power_plant_plans

ESA (2023): *Space Debris by the Numbers.* European Space Agency. Online: www.esa.int/Space_Safety/Space_Debris/Space_debris_by_the_numbers

Euroconsult (2022): *Value of Space Economy Reaches $464 Billion in 2022 Despite New Unforeseen Investment Concerns.* Online: www.euroconsult-ec.com/press-release/value-of-space-economy-reaches-424-billion-in-2022-despite-new-unforeseen-investment-concerns-2/

Euroconsult (2023a): *Space Economy Report.* Online: https://digital-platform.euroconsult-ec.com/product/space-economy-report/

Euroconsult (2023b): *Lunar Ambitions Boost Space Exploration Funding as Investment Set to Reach $33 Billion by 2032.* Online: www.euroconsult-ec.com/press-release/lunar-ambitions-boost-space-exploration-funding-as-investment-set-to-reach-33-billion-by-2032/

European Commission [s. a.]: *Space Traffic Management, Safeguarding Space Operations.* Online: https://defence-industry-space.ec.europa.eu/eu-space-policy/space-traffic-management_en

FAA (2022): *Providing the Safest, Most Efficient Aerospace System in the World.* Federal Aviation Administration. Online: www.faa.gov/space/additional_information/faq#commercial6

Graham-Yooll, A. (2022): Ukraine's Foreign Minister Calls for the Inclusion of Kyiv and Other Allies in Possible Talks with Russia. *CNN,* 21 February 2022. Online: https://edition.cnn.com/europe/live-news/ukraine-russia-news-02-21-22/index.html

Hanson, P. (2003): *An Economic History of the USSR 1945–1991.* London: Routledge.

Herridge, L. (2019): *50 Years Ago: Apollo Astronauts Land, Take First Steps on Moon.* Online: www.nasa.gov/centers-and-facilities/kennedy/50-years-ago-apollo-astronauts-land-take-first-steps-on-moon/

Howell, E. (2022): How SpaceX Got Starlink Up and Running in Ukraine: Report. *Space,* 10 March 2022. Online: www.space.com/how-spacex-got-starlink-running-ukraine

Kamin, D. (2022): The Future of Space Tourism Is Now. Well, Not Quite. *The New York Times,* 7 May 2022. Online: www.nytimes.com/2022/05/07/travel/space-travel-tourism.html

Kendall, F. (2023): *Speech Tour, Space and Cyber Conference Sessions.* Online: www.airandspaceforces.com/watch-read-secretary-kendall-great-power-competition/#:~:text=Department%20of%20the%20Air%20Force,11%2C%202023

Kramer, K. (2015): Neil deGrasse Tyson Says Space Ventures Will Spawn First Trillionaire. *NBC News,* 3 May 2015. Online: www.nbcnews.com/science/space/neil-degrasse-tyson-says-space-ventures-will-spawn-first-trillionaire-n352271

Lindemann, M. (2014): Introduction. A Tale of Three Cities. In *The Merchant Republics. Amsterdam, Antwerp, and Hamburg, 1648–1790.* Cambridge: Cambridge University Press. 1–17. Online: https://doi.org/10.1017/CBO9781139696852.001

McElroy, M. W. Jr. (2023): *The Space Industry of the Future.* London: Routledge.

Marge, M. (2023): Health Research Is Needed Now before Sending Civilians to Space. *Scientific American,* 22 March 2023. Online: www.scientificamerican.com/article/health-research-is-needed-now-before-sending-civilians-to-space/#:~:text=NASA%27s%20reports%20on%20astronauts%20before,muscle%20atrophy%20and%20bone%20loss

Mykhaylo Fedorov [@MykhailoFedorov] (2022):@elonmusk, while you try to colonize Mars. *Twitter,* 26 February 2022. Online: https://x.com/FedorovMykhailo/status/1497543633293266944

Nalla, M. K. – Gurinskaya, A. (2020): Private Police and Security Governance: Mapping Emerging Trends and Future Directions. *Journal of Contemporary Criminal Justice,* 36(1), 101–109. Online: https://doi.org/10.1177/1043986219890208

NASA (2024a): *Europa Overview.* National Aeronautics and Space Administration. Online: https://science.nasa.gov/jupiter/moons/europa/

NASA (2024b): *Titan Overview.* National Aeronautics and Space Administration. Online: https://science.nasa.gov/saturn/moons/titan/

OECD (2012): *OECD Principles for Public Governance of Public–Private Partnerships.* Organisation for Economic Co-operation and Development. Online: www.oecd.org/gov/budgeting/oecd-principles-for-public-governance-of-public-privatepartnerships.htm

OECD (2022): *OECD Handbook on Measuring the Space Economy.* Paris: OECD Publishing. Online: www.oecd.org/publications/oecd-handbook-on-measuring-the-space-economy-2nd-edition-8bfef437-en.htm

O'Neill, K. (2012): *The Environment and International Relations.* Cambridge: Cambridge University Press. Online: https://doi.org/10.1017/CBO9780511805974

Paravano, A. – Locatelli, G. – Trucco, P. (2023): Evolution of Space Programs Governance. In Müller, R. – Sankaran, S. – Drouin, N. (eds.): *Research Handbook on the Governance of Projects.* Cheltenham: Edgar Elgar Publishing. 411–428. Online: https://doi.org/10.4337/9781802208078.00043

Pearson, J. (2019): American Capitalism Is Suffocating the Endless Possibilities of Space. *Vice,* 10 May 2019. Online: www.vice.com/en/article/59qmva/jeff-bezos-space-capitalism-outer-space-treaty

Rahman, A. A. (2021): *Extreme Capitalism and the Diminishing Growth.* Online: http://dx.doi.org/10.2139/ssrn.3901652

Santomartino, R. – Averesch, N. J. H. – Bhuiyan, M. – Cockell, C. S. – Colangelo, J. – Gumulya, Y. – Lehner, B. – Lopez-Ayala, I. – McMahon, S. – Mohanty, A. – Santa Maria, S. R. – Urbaniak, C. – Volger, R. – Yang, J. – Zea, L. (2023): Toward Sustainable Space Exploration: A Roadmap for Harnessing the Power of Microorganisms. *Nature Communications,* 14. Online: https://doi.org/10.1038/s41467-023-37070-2

Stanton Hardenstein, T. (2016): In Space, No One Can Hear You Contest Jurisdiction: Establishing Criminal Jurisdiction of the Outer Space Colonies Tomorrow. *Journal of Air Law and Commerce,* 81(2), 251–288. Online: https://scholar.smu.edu/jalc/vol81/iss2/4

UN COPUOS (2019): *Guidelines for the Long-term Sustainability of Space Activities.* UN Committee on the Peaceful Uses of Outer Space. Online: www.unoosa.org/res/oosadoc/data/documents/2018/aac_1052018crp/aac_1052018crp_20_0_html/AC105_2018_CRP20E.pdf

Vasquez, C. (2023): *Growing Reliance on Satellites Requires New Approach to Cybersecurity in Space, Expert Says.* Online: https://cyberscoop.com/space-cybersecurity-critical-infrastructure/

WALDEK, S. (2022): Hilton Is Building Astronaut Hotel Rooms in Space. *Travel and Leisure,* 20 September 2022. Online: www.travelandleisure.com/hilton-voyager-space-starlab-hotel-rooms-6741170

WATTLES, J. (2022): The International Space Station Could Fall from the Sky in 2031. What Happens Next? *CNN,* 4 February 2024. Online: https://edition.cnn.com/2022/02/04/tech/international-space-station-commercial-business-scn/index.html

WOERNER, J. (2016): *Moon Village.* ESA, European Space Agency. Online: www.esa.int/About_Us/Ministerial_Council_2016/Moon_Village

YARLAGADDA, S. (2022): Economics of the Stars: The Future of Asteroid Mining and the Global Economy. *Harvard International Review,* 8 April 2022. Online: https://hir.harvard.edu/economics-of-the-stars/

Zsolt Csepregi[1]

Challenges of the Legal Protection of Peace, Passage and Profit on Space Colonies

Since life has emerged on Earth it has aspired to extend its reach to ever new territories. There was only one frontier that Earth-based biology could not brave in all the hundreds of millions of years, the space between planets. A paradigm shift was required in the adaptation of lifeforms, one not based on biological evolution but on the emergence of culture and technology. While humankind has used its technology to inhabit, or at least utilise almost all corners of the Earth, space remained a domain of myth, legend and religion for millennia. Only in the early 20th century did humans manage to invent planes to traverse the skies rapidly and rocket engines to escape Earth's gravity. Over the past decades, we have made the initial steps of conquering this new domain, stepped on the Moon and inhabited Earth's orbit, if not with life, at least with technology. The next step in the evolution of human civilisation and thereby the spread of life, the establishment of space colonies on the Moon, Mars and possibly beyond, has become a realistic mid-term goal for the leading space nations and their partners.

However, physically reaching these locations and building infrastructure is not enough in itself. As humanity's spread is not enabled by biology but mainly by culture and technology, as with all previous conquests, rules, customs and in the end, law must be set. Effective social life consists not only of physical presence but of lawful order to guide our activities and avoid descending into chaos through armed conflict. Once these new space enterprises are launched and operated, they will consume a significant amount of national and private resources, meanwhile, they are also posed to generate profit and

[1] Doctoral student, Ludovika University of Public Service, Doctoral School of Military Sciences; ORCID: https://orcid.org/0000-0003-3543-8961; e-mail: zsolt.jpca@gmail.com

DOI: https://doi.org/10.36250/01209_11

thereby multiply the invested capital. This additional consideration means that further legal protection is needed to guarantee the strengthening of civilian and profit-oriented aspects of the new space activities alongside the pressing security considerations.

This chapter discusses the applicability of the existing international legal framework on future space colonies focusing on three main issues: what is permitted to defend a space facility on or around an astronomical body other than Earth; the business environment and economic activity considerations and the right of safe transport. The chapter concludes by highlighting the need to mitigate existing legal gaps before the establishment of space colonies.

OVERVIEW OF THE APPLICABLE LEGAL FRAMEWORK

As with all new territories reached by humans, issues of war and peace were the primary factors in shaping the legal environment of space activities. It is beyond symbolic, that the first human made object reaching outer space was the V2 rocket, the "vengeance weapon" built by Nazi Germany to bring devastation to Allied cities. The political context of the initial emergence of space law was the Cold War. While the superpowers were deeply antagonistic towards each other, the Cold War was more focused on deterrence, building and maintaining alliance networks and spheres of influence, instead of active warfare between the U.S. and the USSR. Beyond the complex political environment, the particular security consideration regarding space activities was first and foremost its role in nuclear warfare and deterrence. The tools for reaching space were the same tools which enabled mutual destruction by intercontinental missiles armed with nuclear warheads. Satellites, vital for modern communications, navigation and analysing natural and human processes on Earth were also responsible for detecting a nuclear first strike from the enemy. Therefore, space has this dual nature from a human perspective, of being capable of enabling warfare and conflict while also providing great benefit through peaceful activities and international cooperation.

The urgent need to develop the legal framework of space activities emerged once the USSR successfully put the Sputnik satellite in orbit in 1957, with the U.S. in close pursuit. The new achievements in space could have upset previous meticulous calculations regarding nuclear warfare, therefore the rules had to be settled, to keep the Cold War from heating up. In terms of international politics, the establishment of the United Nations Committee on the Peaceful Uses of Outer Space (UN COPUOS) as a permanent body in 1959 has been a rapid development. The next two decades have seen a dynamic development of the elements of space law; however, it is important to note that there was no and there cannot be any *ex lex* state in space, as the UN Charter applies to all human issues even without any specific legal framework for a particular issue (Sulyok 2022: 79). In 1962, the United Nations General Assembly Resolution 1802 (XVII) has requested that the UN COPUOS establish a comprehensive legal framework for the "peaceful use" of space. It was however not defined what "peaceful use" meant, and this points to a further important point, the lack of exact definitions in space law. As all nations have different capabilities and interests, consequently they have differing visions for the utilisation of space, or if they cannot reap certain benefits, they are motivated to block their adversaries or competitors from gaining advantages from space activities. This means that the development of space law has been hindered by the lack of an all-encompassing vision for space, and the method to resolve the disputes was employing often loose terms when legislating new space law treaties. While the nations have many different interests, they all want to avoid a nuclear Armageddon, therefore it was logical to adopt two non-binding General Assembly resolutions to swiftly limit the potential for the Cold War to "heat up" in outer space. The General Assembly Resolution 1962 (XVIII) entitled Declaration of Legal Principles Governing the Activities of States in the Exploration and Use of Outer Space has set the main framework for the subsequent Outer Space Treaty and thereby set the guidelines for the use of outer space for peaceful purposes. Furthermore, in 1963 the Treaty Banning Nuclear Weapon Tests in the Atmosphere, in Outer Space and Under Water and the United Nations General Assembly Resolution 1884 (XVIII) banned the deployment of nuclear weapons in outer space which was a highly alarming prospect during the Cold War and even to this day. These were urgent needs to avoid a rapid escalation in terms of the (potentially nuclear) weaponisation of space, while the more nuanced negotiations were ongoing regarding the adoption of a comprehensive and hard legal framework for space law.

More than five years after the "urgent" need emerged to create a legal instrument guiding peaceful space activities, in 1967 the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies (Outer Space Treaty, or OST) has been adopted. The OST affirms that the UN Charter is the basis for guaranteeing international peace and security, thereby it also confirms that international humanitarian law applies to space warfare (Ramey 2000: 127). This repeated reassurance of the role of the UN Charter is vital to enshrine core legal rules in space law. Even though there is no strict hierarchy between international treaties, the UN Charter takes precedence in case any other treaties counteract it (Sulyok 2022: 80). A major remaining issue regarding peace and conflict in space is the issue of what exactly does the "peaceful use" mean, which all the legal framework intends to assure (Vlasic 1991: 37). The two possible interpretations lead to significantly different outcomes and future for space activities. One maximalist understanding called non-military use favoured by the Soviet bloc would interpret this as a ban on any kind of utilisation, direct or indirect, of space for military purposes, therefore banning the *militarisation of space.* The other, in hindsight more realistic ambition calling for non-aggressive use is preventing to the farthest extent possible the *weaponisation of space,* meaning the deployment and stationing of weapons in space (Harrison et al. 2021: 3). International practice firmly supports the latter understanding originally promoted by the U.S. and its allies that peaceful use of space means a varying degree of bans on the weaponisation of outer space. Space is militarised, meaning that it can indirectly support countries in achieving their military goals, including communication, intelligence, navigation and potentially serve as the route where intercontinental ballistic missiles would travel if they would be used in an armed conflict.

Apart from the direct relevance for potential conflict in space, the most important element of the OST and the basis of later space law is that under Article II, outer space, including the Moon and other celestial bodies can be explored freely, but cannot be subjected to national appropriation. This notion has created the basic framework of space activities, one that is ever more constraining as the technological possibilities soon extend our reach to other celestial bodies. The ban on exercising sovereignty in outer space, including on celestial bodies, including exclusive usage, or restricting access of other parties. The permitted activities are the freedom of exploration, use and scientific investigation (OST, Article I). As I will demonstrate later, these rules stand in opposition to the vision of the major space powers, most importantly the U.S. which is the farthest ahead to launch space activities involving a degree of exercising sovereignty beyond the norms established in the OST permitting sovereign rights over registered space objects, including objects landed or (most relevant for this chapter) constructed on a celestial body, anyone on board and the country's nationals in space (OST, Article VIII).

The OST was followed up by four other treaties, setting the finer details of space activities. The Agreement on the Rescue of Astronauts, the Return of Astronauts and the Return of Objects Launched into Outer Space (1968) expands on the responsibilities of other nations vis-à-vis the astronauts who, considering the extreme danger of their activities in a most hostile natural environment, require the maximum extent of protection and aid in case of an emergency. The Convention on the International Liability for Damage Caused by Space Objects (1972) has settled the responsibility for causing damage through space activities and enshrined the state bearing the cost of any damage by a space object or astronaut operating under their flag. Thirdly, the Convention on Registration of Objects Launched into Outer Space (1975) has established the practice of registering objects launched into space at the relevant UN bodies, a practice which needs an urgent update to make space activities transparent instead of creating insecurity through vague descriptions.

The last international treaty of this generation of space law is the Agreement Governing the Activities of States on the Moon and Other Celestial Bodies

(Moon Agreement) adopted in 1979 which has qualified the resources of the Moon and other celestial bodies of our Solar System as a "common heritage of mankind" thereby severely limiting the potential for outer space resource extraction (Moon Agreement, Article 11). It has proposed an international regime to coordinate any future space mining is implausible due to the persistent conflicts and clashes of interests among the nations. The Moon Agreement also reinforced the earlier ban on deploying weapons of mass destruction (WMD) in outer space set in the OST, a key pillar of the legal limits on the weaponisation of space [Moon Agreement, Article 3(2)]. Unlike the OST and the three follow-up treaties, which have widespread international acceptance and more than 100 countries ratifying them, the Moon Treaty has been largely a failed legal enterprise as only 17 countries ratifying it, with only France and India among the leading space nations even signing, but not ratifying the treaty.

After the failure of the Moon Agreement and the slowing pace of the space race as other considerations emerged during the end of the Cold War, legislation of hard space law under UN auspices has gone off track, notwithstanding the achievements in terms of non-binding General Assembly resolutions adopted in the 1980s and 1990s, which belong to soft law instruments. There was no need, nor interest in resuming the legislative process during the 1990s. In the first decade of the post-Cold War order, international cooperation seemed to reign with unchallengeable U.S. leadership, Russia lost its means to act as a peer competitor and China was not yet a major space power. In this context, an overarching legislation gave way to different soft law instruments, including memoranda of understanding and agreements governing particular projects. Soft law offered a flexible way of guiding the cooperation of willing countries based on mutual interests in joint space activities. While soft law has its advantages, it cannot substitute international treaties regulating the most crucial aspects of space law, especially peace and security and resource extraction (Froehlich–Pecujlic 2016: 37). As the OST and the following three basic treaties were legislated until 1975, the technological environment for which these legal tools were developed are currently almost fifty years old. By the 2020s humanity is within reach of deploying infrastructure and conducting economic activity on the Moon, Mars and possibly several asteroids, which creates a potential for security threats stemming from the increasing competition (Defense Intelligence Agency 2022: 35). In the centre of these concerns are the required ownership over land, resources and access in outer space, interests will clash which can result in armed conflict. Therefore, comprehensive adaptation of space law to current and future challenges has never been more urgent.

LEGAL LIMITS ON WAGING ARMED CONFLICT ON SPACE COLONIES

Existing space legislation primarily aims at preventing a nuclear war on two levels. Firstly, it aims to prevent any attack against the adversaries' satellites in case an armed conflict erupts, as such an attack could be most likely interpreted as a prelude to a nuclear strike by the attacker (Edl 2023: 52). Secondly, it consists of strong bans on deploying weapons of mass destruction in Earth orbit and outer space (Yoo 2020: 96). Current efforts at adapting the legal tools to ban weaponisation and at least limit the further militarisation of space still mostly focus on the danger presented by anti-satellite weapon (ASAT) weapons, their testing and the resulting environmental damage (Borgen 2020). These considerations are rational, due to the limited possibilities of other celestial bodies to become part of an armed conflict in comparison to Earth orbit which has been a possible warfighting domain for decades, even if countries and alliances only adopted this formally in recent years. While the OST bans the stationing of weapons of mass destruction in Earth orbit, it does permit other types of weapons (Schmitt 2006: 104). The legal framework guiding peace and security in Earth orbit intends to limit the use of these weapons, by banning the use of force, unless it is a case of self-defence or under a prior and express authorisation by the UN Security Council (UN Charter, Chapter VII). However, due to the outdated nature of the OST, most of the possible space weapons were not imaginable during the legislating process half a century ago, therefore they are not regulated (Eagleson 2023).

Nonetheless, even during the Cold War space law intended to counter any possibilities of weaponising other celestial bodies. This previous, mostly hypothetical plausibility is gaining additional relevance as the projects aiming at returning to the Moon and reaching Mars are advancing. The OST, which is the main source of what is legally permissible when preparing for an armed conflict in space (and refers to the UN Charter), in its Article IV, bans deploying any kind of weapons on celestial bodies, may they be conventional weapons or weapons of mass destruction. Even though it is still unlawful to initiate an armed conflict, even the preventive deployment of weapons on or in orbit of the celestial bodies is banned. This creates a significant problem when thinking about the issues of protection of space colonies and other assets spacefaring nations would build on other celestial bodies. The first question is defence, how can someone justify deploying, for example, missile defence systems on their space colonies, as the rockets or energy beams utilised for destroying incoming missiles, could be used for offensive aims as well, which has already been proven in Earth orbit (Harrison 2020: 7).

It is hard to imagine any nation investing hundreds of billions of dollars' worth of capital in space colonies, only to have them destroyed by a few missiles from an adversary and become very expensive sitting targets. It can be imagined that the most vital parts of any space colony, factory or other facility would burrow underground for protection (this would also make sense to protect the space colonists from harmful radiation); however, this would only mean that the transportation and communication systems of the colony would be vulnerable to an attack. An intermediate step in advancing the relevant legal framework has emerged in the Artemis Accords, signed by 36 nations, which, under U.S. leadership sets out to create a common ground for the return to the Moon and eventually to Mars. In the Accords the signatories agree to establish "safety zones" guarding their facilities and activities in outer space against harmful interference (NASA 2020: 5–6). However, the exact nature of these zones is not defined, only that the detailed regulations of the particular safety zone will be communicated to the other parties. What is permissible in a safety zone and what will be the negative consequences to any party committing a transgression in these zones? Without kinetic or cyberweapons installed to protect these zones, the new concept lacks a significant element of hard power to support the security aspect of the zone. Therefore, currently it should be understood as an initial concept to be updated with practical details when the space programmes of the Artemis Accords' signatories are in a more advanced state.

The second issue apart from protection against kinetic attacks is that a country does not only want to protect its assets after an attack was launched but present a credible threat to any potential adversary so that even the attempt of an armed aggression by a hostile party could invite a response against their space facilities. Mutual deterrence has been a cornerstone of the balance of threat systems on Earth, of which the mutually assured destruction by nuclear weapons between the U.S. and the USSR during the Cold War is the most famous example. An offensive action must bear a certain risk for the attacker, otherwise predating on other nations would be a cost-free strategy and peaceful international relations would be unimaginable. This prospect is similarly threatening the future of space colonisation and international relations in outer space. One practical solution might be deploying defensive systems and deterring weaponry (non-WMD) on spacecraft patrolling in space between celestial objects, but not on orbital trajectories. These military assets, however, would need to use energy sources to manoeuvre in space, and this is not a sustainable solution at our current technological level.

A similar problem emerges when considering the legality of establishing military bases on the Moon and other celestial bodies which are strictly banned under Article IV of the OST. Is it plausible that nations will not establish military bases after a certain developmental stage of their space assets? It is, again, hard to imagine that in the tense international environment, the expansion of human presence in space can advance without an accompanying hard power security umbrella, or simply put, without deploying military assets in space. One could imagine nations circumventing the current, binding international regulations and secretly and illegally arming their space colonies, aiming to deploy dual-use equipment, for example, defensive lasers covered as mining lasers or a similar scheme. Also, defensive weaponry is not only important against human aggression but also as planetary defence, would these get a pass under the ban on weaponisation of celestial objects? Until now I have only discussed kinetic weapons, which were the focus of existing space law, however, electronic and cyberweapons can also hinder space colonisation efforts. Under the non-binding Tallinn Manual 2.0 on the International Law Applicable to Cyber Warfare, Rule 68 states:

> "Any cyber operation that originates in, transits, or terminates in outer space and rises to the level of an unlawful threat or use of force is barred" (Schmitt 2017).

However, the Tallinn Manual is not a binding legal document, and these cyberattacks are even more easily deniable than kinetic attacks.

The final issue, when it comes to the defence and security of the space colonisation effort, is the difficulty of monitoring the exact situation on other celestial bodies and their orbits. Even on Earth, during contemporary conflicts, it is challenging to have real-time intelligence on the whole of the battlefield, and to give advanced warning. Also, there are ample opportunities for deniability. The difficulty is exponentially greater as the distance grows between the object of monitoring and the monitoring agent. Firstly, developing surveillance equipment which gives accurate information on what is happening on the surface of the Moon or Mars or beyond is a technological feat and expensive. This also applies to equipment installed on space facilities and their maintenance. Secondly, there are the physical constraints for example the speed of light, which limits the availability of real-time intelligence and therefore coordination between the home base and the colony or facility in space. These all provide windows of opportunity for any potential aggressor to commit an attack in outer space, create facts on the ground (or orbit) and even later deny any responsibility. While investing in more advanced equipment can ease some of the difficulties, physical constraints result in the need to make space colonies autonomous in their defence to a degree, a requirement which is not permitted under current international space law.

BUSINESS CONSIDERATIONS

Space colonisation has definite scientific and research value, not to speak about the sense of advancement and high morale it would result in if humans stepped on Mars and could successfully establish permanent colonies. However, discovery and pride only last as long as security and business considerations come into the picture. After discussing security constraints, I will turn to the similarly debilitating limits on any potential economic ventures in space. The value of the space economy is projected to reach one trillion dollars a year in a decade (Brukardt et al. 2022: 12.) with virtually unlimited growth potential in the future. This means that any nation which gets a head start on capturing market share will also alter the balance of power on Earth; therefore, this is not only a business consideration but also a national security concern. Currently, in 2024, the major obstacle to rapidly expanding economic activities in space is still technological and financial and not predominantly legal in nature. However, the legal constraint will emerge once the first space colony is established, and economic activity starts which would involve some kind of ownership in outer space.

The four main types of sovereignty claims can be grouped into land or position; bases or facilities; resources; and the generated profits. Under the current space law framework, a nation can establish stations and colonies on celestial bodies or in their orbits, given that they serve solely peaceful purposes, and the owner provides access to other nations to them (Outer Space Treaty, Article VIII). Notwithstanding, we must note that once the first space colony or other permanent facility is built, it will mean that other nations cannot build their colony at that same location. Therefore, the process of space colonisation will in practice create a new challenge for the legal environment, namely how to move forward once space exploration becomes an (at least partly) zero-sum game, with nations exclusively settling particular areas on celestial objects. Secondly, providing access to other nations for monitoring reasons, such as assuring that no weapons of mass destruction are stored inside space colonies or orbiting stations is reasonable. However, this "access" could be abused and in effect obstruct the work and indeed the life of the space colonists. What would happen, for example, if one hundred astronauts of another nation would appear at a space colony only suitable for sustaining one hundred colonists already at the facility? While there are certain safeguards against the potential abuse of this method in the legal body [Outer Space Treaty, Article XII; Moon Agreement Article 15(1)] mainly by requiring "reasonable advance notice" of the visit to provide an opportunity for "appropriate consultation", there are no rules regarding what "reasonable" or "appropriate" means in practice. I would argue that when there are such doubts about the outcomes, security considerations will naturally prevail in the calculations of each nation. However, to uphold security, one needs sovereign decision-making powers and the ability to enforce security measures. Without sovereign rights in space, rules of human interaction break down, for which neither our legal, social, or international norms are ready.

Considering the issue of resources, space facilities cannot be sustainable in the long term without utilising materials present on the celestial bodies. Apart from sunlight, which is basically unlimited, all other resources come in restricted quantity and with limited access. One could argue that, for example, harvesting water out of the icecaps of Mars for sustaining a research colony is only done in support of keeping the astronauts alive and thereby it falls under legally permitted activity to sustain scientific space operation [Moon Agreement, Article 6(2)]. However, once a country or company starts resource extraction in outer space, this will create a constant debate about to what degree and exact usage is permissible, and the strict rule of the current international legal environment is challenged, which, I argue, opens the way to eventual mining of resources for business ventures. An interesting case of dual-use applications can be also envisioned in outer space by blurring the lines not only between military and peaceful use but between scientific and commercial–industrial usage of the extracted resources. Before turning to the main issue, space mining, we should consider the few economic activities which are imaginable under the current space law. Naturally, the first are research activities, all nations and their companies are free to establish research colonies to conduct tests and to develop new technologies and materials. The second is space manufacturing if it only uses materials from Earth and utilises the micro-gravity and clean environment in space to create instruments of unprecedented quality. It is plausible that even when supplied from Earth with materials, such space factories can be profitable if placed in Earth's orbit, but it would not be reasonable to place such a factory on another celestial body if it cannot use the resources present there. Thirdly, non-material services provided by other celestial bodies are legal. Tourism, entertainment and communication services can be imagined in this category, but what company would want to take oxygen from Earth to their hotel on the Moon if it can be extracted from the available resources there?

The main issue is, however, resource extraction from celestial bodies for commercial goals, which includes the mining of the materials or even utilising them to sustain the colonisation effort. These practices are strictly forbidden under the current space law. They would be in breach of legal norms in three ways, firstly, occupy certain parts of celestial bodies, secondly, gain exclusive ownership over the extracted materials, and thirdly, gain most probably an extra value from the enterprise. Even though most nations did not ratify or even sign the Moon Treaty, which further constrained commercial resource extraction possibilities, as the OST also bans bringing any locations or resources in outer space under national sovereignty, all the above activities are illegal. To demonstrate the surreal nature of the current legal situation, it is worthwhile to imagine a few hypothetical scenarios of how space mining would occur under a current legal framework. Even if one nation would establish a space mine, they would not own the site and would need to provide open access to other nations, who could in theory enter freely into the facility. Also, the mined materials would be not owned by the mining nations and other nations could, again, in theory, freely take the materials for scientific exploration. Finally, any profit generated by the space venture would have to be shared internationally and not owned by the owner nation or company.

There are important first steps to alter the legal framework regulating the space economy, do away with the constraints inherent in the OST and ignore the Moon Treaty. There are two avenues of these efforts, the first one is different kinds of national space legislation permitting a limited, economy-focused sovereignty over space assets. The second is international agreements between like-minded nations. Considering the first, national space legislation of the United States, Japan, the United Arab Emirates and Luxemburg all create an environment for companies and the nations they belong to be able to benefit from the space economy and permit resource extraction for business purposes (Ünüvar 2022). These more permitting national legislations are currently in conflict with the prevailing international space regulations, which creates the potential for legal conflict in the future if these outstanding differences are not settled. Secondly, agreements like the Artemis Accords attempt not only to spearhead the space colonisation effort but also to create legal facts on the ground. As with the reinterpreting of what is permissible to guarantee security in space, the Artemis Accords is even more bold in rewriting the rules of utilising space resources. Under Section 10 of the Accords, it is stated that "the extraction of space resources does not inherently constitute national appropriation under Article II of the Outer Space Treaty". While this section concerns primarily sustaining the operation of the particular space mission it still means that the signatories with the leadership of the U.S. will start resource extraction on celestial bodies once the program arrives at the stage where this becomes relevant. After the initial, operation-focused resource extraction practices are well underway it is difficult to foresee a future in which eventually the lucrative prospects in the space economy would not be utilised. The question is whether we will have a follow-up treaty to the OST setting guidelines to business connected sovereignty or have a fractured and deeply conflicted legal framework of an outdated OST existing in parallel with more advanced and practical national and soft law instruments.

TRANSPORTATION AND THE RIGHT OF PASSAGE

As mentioned, the OST enshrines free access to all points in space (Outer Space Treaty, Article I), and therefore it is illegal for any country to block access to another nation's space objects, including vehicles, stations and other facilities. Several additional rules, however, must be applied to enjoy this freedom of access and movement.

Firstly, as nations are liable for the damage their space objects or their astronauts cause, the free movement must not result in damage to another object, which would be basically space-ramming (Outer Space Treaty, Article VII).

Secondly, the protection of transportation not only stems from the right to free access but also the overarching principle of protecting the life of the astronauts as envoys of humankind (Outer Space Treaty, Article V). Endangering them is strictly forbidden and every effort must be made to aid them by other nations in an emergency which develops in space.

Thirdly, nations must register their space objects with the UN Secretary General (where the Register is in practice managed by the United Nations Office for Outer Space Affairs) and inform and regularly update the UN regarding their ongoing mission on celestial bodies. This has the purpose of guaranteeing that these missions are serving only peaceful purposes and do not, for example, carry weapons to other celestial bodies. There is no established verification method however, no inspectors to make sure these registrations are exact. There are usually also quite vague descriptions hiding the true purpose of the space objects launched.

Fourthly, the employed transportation methods must be safe for the environment. This means, for example, that nuclear fission engines, while not completely ruled out (UN COPUOS – IAEA 2009), are much debated, as there is no established method of what to do with the radiating materials. Also, one could argue that a nuclear-powered spacecraft can be of dual nature and used not only as a science probe but as a crude weapon of mass destruction as well.

It is also worthwhile to note that safe transportation in space is impossible without advancements in space observation and navigation technologies. Space traffic management encompasses the means and the rules to access, conduct activities in, and return from outer space safely, sustainably and securely (European Commission [s. a.]). Even understanding real-time the position, speed and trajectory of all space objects orbiting Earth is still in its infancy and the task becomes exponentially greater as the distance grows from Earth (Defense Intelligence Agency 2022: 36). As I have discussed in the subchapter about security, the lack of verification creates opportunities for damage and potentially armed conflict in space, both by providing opportunity and motivation due to a miscalculation and misunderstanding of the facts. Safe transportation is an element of this conundrum, which not only has technological elements but also legal and regulatory requirements. Significant investment will be needed in space traffic management with all its aspects. A particular issue is the building of spaceports around Earth orbit and orbiting other celestial bodies. Would these be also free to access to other nations? A wholly new system of regulation will need to emerge once some nations start building these facilities as the resources to sustain port calls by spacecraft are much more demanding than on the oceans of Earth, and even there, port calls have their own political, security and diplomatic system in international relations.

A particular issue emerges with space blockades, which are forbidden under existing international law, however, we must be ready for the instance one nation starts applying them. In realistic terms, a blockade is an attempt by a country to obstruct another nation's effort at accessing a particular location on a celestial body or in space or accessing outer space from Earth itself. A blockade may be physical or conducted through electronic interference. This notion is already present in Chinese strategic thinking about interstate competition in space; therefore, it is plausible that it will become a feature of space colonisation efforts (Edl 2022: 265). A space blockade is naturally illegal under international law, as it precludes free access, however, a blockading nation could refer to its stated rights to an aforementioned "safety zone" around its space facilities or objects. A space environment where nations erect blockades without the fear of other countries breaking the blockade by employing weapons is not sustainable. A similar problem emerges regarding the safety of space transportation lanes, when they are developed, meaning some of the most economical routes to access certain locations on celestial bodies or in space. These lanes will need to be protected against natural and human threats, which is difficult to imagine without defensive weaponry. These can be installed at the endpoints, space milestones or spaceports and on hypothetical patrolling spacecraft. However, currently, this would be illegal (apart from armed spaceships not in orbit), and as with mutual deterrence and defensive reasons, a new legal equilibrium must follow as the practice of space colonisation will move ahead in the coming decades.

FUTURE CHALLENGES AND CONCLUSIONS

The conclusion from the above overview of some of the legal aspects of security, business considerations and transportation connected to outer space activities and space colonisation is that there are multiple debilitating contradictions and legal obstacles. The legal framework under UN auspices was developed for the main issues of the first two decades of the space race starting in 1957 and since the relative failure of the Moon Treaty, this process has been frozen. The existing hard space law has many positive aspects, but it lagged behind in the 1980s and became obsolete as the new space race emerged with complex business considerations, new technologies and a transition to a tense and increasingly multipolar world order. Current legal efforts are understandably focused on banning or at least regulating ASAT weapons; however, it does address the issue that rapidly unfolding space colonisation efforts will need protection, which can be only provided by hard power, meaning deploying military assets into space. Unmitigated weaponisation of space is not in the interest of any party, but neither is a situation in which the first country introducing weapons could endanger the investment of all other powers. This would be akin to building colonies on another continent, without sending any soldiers to protect them, it is unimaginable. Therefore, as the first colonies and facilities are built and the "safety zones" are established, a constructive discussion must emerge regarding the defensive systems permissible on and around space facilities.

This international legal effort is vital, as national law and soft law are not substitutes for the further development of space law under UN auspices and the family of treaties following the OST. The main issue will be how each space power will adjust to the practices of the other major powers, codified in international treaties, and not how countries self-regulate or settle joint conduct with their partners and like-minded nations. Peaceful and profitable exploration and colonisation of space will depend on the mutual understanding between the U.S., the European states and Japan, and the three other major space powers, Russia, China and India. Anything less than an international treaty on security, ownership and transportation will bear a significant risk to continued peaceful activity in outer space. National law and soft law are worthwhile for self-regulation, presenting stability and a regulatory framework to the business community and signalling intent underpinning the major legal negotiations in the future. This will be required for the transitional period we are embarking upon when each space block is aiming at charting its next major space programmes and coalesce around a common vision. Naturally, the most advanced of these initiatives is the Artemis Accords, which means that as presented above, this has the most comprehensive evolutionary vision for the adaptation of the legal framework, upsetting the status quo, while also keeping the cornerstones of the security-focused achievements and the overarching value of the peaceful nature of space exploration of the OST treaty family.

In the end, no country, not even the U.S. can go alone in space and not let serious risks mount from other major space powers. Asymmetric threats are just as prevalent in space warfare in the future as on Earth, but the dangers are amplified by the remote and inhospitable nature of the environment. This means that not only a supporting network of partners and allies will be needed but also a degree of understanding reached with competitors and even adversaries. As all nations perfectly understand that an ASAT warfare would be a race to the bottom, warfare erupting in outer space would just negate the possibility for all nations to benefit from the resources of other celestial bodies. International practice accompanied by national law and soft law will chart the way in setting the first milestones of space colonisation. However, international treaties will be needed to make these trailblazer practices sustainable for the coming decades. With the end of U.S. hegemony in space, the growing number of countries interested in stable space colonisation and resource extraction will create tensions, while on the other hand raising the number of interested parties in setting a stable legal environment for all of them to benefit from space. Space can be safe and profitable even in a multipolar world order, but to achieve that, certain outdated concepts pointed out in the chapter will need to be rewritten or reinterpreted. Therefore, we should expect a conflicted decade ahead of us, as nations break with the status quo.

REFERENCES

Agreement Governing the Activities of States on the Moon and Other Celestial Bodies adopted by the General Assembly in its resolution 34/68, opened for signature on 18 December 1979, entered into force on 11 July 1984.

Borgen, C. J. (2020): *Space Power, Space Force, and Space Law.* Lieber Institute. Online: https://lieber.westpoint.edu/space-power-space-force-space-law/

Brukardt, R. – Klempner, J. – Pacthod, D. – Stokes, B. (2022): The Role of Space in Driving Sustainability, Security, and Development on Earth. *McKinsey & Company,* 19 May 2022. Online: www.mckinsey.com/industries/aerospace-and-defense/our-insights/the-role-of-space-in-driving-sustainability-security-and-development-on-earth

Defense Intelligence Agency (2022): *Challenges to Security in Space. Space Reliance in an Era of Competition and Expansion.* Online: www.dia.mil/Portals/110/Documents/News/Military_Power_Publications/Challenges_Security_Space_2022.pdf

Eagleson, D. (2023): Protecting Our Critical Satellite Infrastructure: The Importance of Space-Based Infrastructure to Humanity and Its Status within NATO. *NATO Review,* 24 October 2023. Online: www.nato.int/docu/review/articles/2023/10/24/protecting-our-critical-satellite-infrastructure-the-importance-of-space-based-infrastructure-to-humanity-and-its-status-within-nato/index.html

Edl, A. (2022): Deterrence in Space. *Hadtudomány,* 32(1), 256–267. Online: https://doi.org/10.17047/Hadtud.2022.32.E.256

Edl, A. (2023): A világűr-tevékenység és a biztonság. *Századvég,* 3(1), 47–67. Online: https://szazadvegfolyoirat.hu/wp-content/uploads/2023/09/SZAZADVEG_2023_01_teljes.pdf

European Commission [s. a.]: *Space Traffic Management.* Online: https://defence-industry-space.ec.europa.eu/eu-space-policy/space-traffic-management_en

Froehlich, A. – Pecujlic, A. N. (2016): *Mechanisms for the Development of International Norms Regarding Space Activities.* European Space Policy Institute. Online: www.espi.or.at/wp-content/uploads/espidocs/Public%20ESPI%20Reports/Rep57_ABA_160522-1906.pdf

Harrison, T. (2020): *International Perspectives on Space Weapons.* Center for Strategic and International Studies. Online: www.csis.org/analysis/international-perspectives-space-weapons

Harrison, T. – Johnson, K. – Young, M. (2021): *Defense Against the Dark Arts in Space: Protecting Space Systems from Counterspace Weapons.* Center for International and Strategic Studies. Online: www.csis.org/analysis/defense-against-dark-arts-space-protecting-space-systems-counterspace-weapons

NASA (2020): *The Artemis Accords. Principles for Cooperation in the Civil Exploration and Use of the Moon, Mars, Comets, and Asteroids for Peaceful Purposes.* Online: www.nasa.gov/wp-content/uploads/2022/11/Artemis-Accords-signed-13Oct2020.pdf

Ünüvar, G. (2022): Can National Laws on Space Resources Serve as Evidence of Customary International Law? *Opinio Juris,* 8 Nov 2022. Online: https://opiniojuris.org/2022/11/08/can-national-laws-on-space-resources-serve-as-evidence-of-customary-international-law

Ramey, R. A. (2000): Armed Conflict on the Final Frontier: The Law of War in Space. *The Air Force Law Review,* 48, 1–158.

Schmitt, M. N. (2006): International Law and Military Operations in Space. *Max Planck Yearbook of United Nations Law,* 10, 89–125. Online: www.mpil.de/files/pdf3/04_schmittii1.pdf

Schmitt, M. N. (2017): *Tallinn Manual 2.0 on the International Law Applicable to Cyber Warfare.* Cambridge: Cambridge University Press. Online: https://doi.org/10.1017/9781316822524.016

Sulyok, G. (2022): Nemzetközi jogi szabályozás. In Bartóki-Gönczy, B. – Sulyok, G. (eds.): *Világűrjog.* Budapest: Ludovika Egyetemi Kiadó. 79–115.

Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies adopted by the General Assembly in its resolution 2222 (XXI), opened for signature on 27 January 1967, entered into force on 10 October 1967.

UN COPUOS – IAEA (2009): *Safety Framework for Nuclear Power Source Applications in Outer Space.* United Nations Committee on the Peaceful Uses of Outer Space – International Atomic Energy Agency. Online: www.unoosa.org/pdf/publications/iaea-nps-sfrmwrkE.pdf

Vlasic, I. A. (1991): The Legal Aspects of Peaceful and Non-Peaceful Uses of Outer Space. In Jasani, B. (ed.): *Peaceful and Non-Peaceful Uses of Space. Problems of Definition for the Prevention of an Arms Race.* London: Routledge.

Yoo, J. (2020): Rules for the Heavens: The Coming Revolution in Space and the Laws of War. *University of Illinois Law Review,* (1), 123–194.

Boudour Mefteh[1]

Examining the Concept of Space Mining Colonies: Expected Benefits and Legal Matters

INTRODUCTION

As population expansion and resource availability are inversely linked with rising energy demand worldwide, tensions will probably get worse. In the end, we would be forced to look to other planets and extraterrestrial resources to complement or replace those found on Earth (Hannon 2022). This is where the idea of colonies focusing on space resource extraction comes from.

As we delve further into this topic, it should be considered that we are mostly talking about the theoretical features of space-mining colonies. No operational mining colonies exist outside of Earth currently. In the future, there might be colonies involved in mining or colonies primarily focusing on mining activities. In this chapter, we examine the legal background for both, with a focus on the possibility of establishing highly specialised colonies with the purpose of resource extraction. By engaging in this conceptual research, we may look into potential results and implications for future space exploration and resource utilisation.

These colonies are currently only a speculative concept, but as technology advances and interest in space exploration grows, it is important to start discussing their economic benefits and the legal difficulties that may hinder their lawfulness.

1 PhD candidate, Géza Marton Doctoral School of Legal Studies, University of Debrecen; ORCID: https://orcid.org/0009-0001-5255-6874; e-mail: boudour.mefteh111@mailbox.unideb.hu

DOI: https://doi.org/10.36250/01209_12

We can say that space-mining colonies might offer a promising solution to our resource scarcity problem by tapping into the vast resources available in space. Numerous experts have supported this theory, such as John S. Lewis, author of *Mining the Sky. Untold Riches from the Asteroids, Comets, and Planets,* in 1997 strongly arguing for the potential benefits of space mining to both science and the economy. Another notable example is Chris Lewicki, the CEO of Planetary Resources and a former NASA engineer, who has been a loyal supporter of space mining, emphasising how the technology may help future space exploration missions and enable sustainable resource utilisation beyond Earth.

But to be fair to the topic, we cannot deny that some think that this might not bring too much to our lives. As an example, NASA's researcher and planetary scientist Phil Metzger has questioned whether space mining is economically viable considering the high cost and challenging technology requirements of extracting and transmitting resources from space. Moreover, Martin Elvis has a similar opinion. He is an astrophysicist at the Harvard Smithsonian Center for Astrophysics, and he questioned the feasibility of space mining initiatives since he believes that the costs involved in extraction and transportation may be more expensive than any potential rewards. Whether these colonies will ever be established and if they might be economically viable remains to be seen. In this paper, we intend to examine certain aspects that might be relevant in case different spacefaring actors intend to start space resource extraction through permanent human settlements.

According to Bidshahri, these colonies should be self-sustaining habitats (Bidshahri 2019) equipped with advanced technology and infrastructure, enabling humans to extract valuable minerals and rare elements from asteroids, moons and other celestial bodies (Le Meur – Levacher 2022: 74–92). With the potential to revolutionise resource sustainability, space-mining colonies could pave the way for a new era of exploration and ensure the long-term survival of humanity. NASA thought that humans could effectively occupy space in the 1970s (Johnson–Holbrow 1977). Now that it is becoming a near reality; Moon Express and ispace are planning to mine the Moon. Along with this, Space Development Nexus has a plan to mine near-Earth asteroids (Nanalyze 2021). Many nations, including Australia, Canada, China, France, Germany, India, Japan, Russia, the United States and the United Kingdom (Pelton 2016: 105–120) have expressed interest in space mining (Hannon 2022).

According to the Harvard International Review, "mining just the top 10 most cost-effective asteroids is, those that are both closest to Earth and greatest in value would produce a profit of around US $1.5 trillion". The main-belt asteroid Psyche, according to the article, "has been reported to contain USD 700 quintillion worth of gold, enough to give each person on Earth about USD 93 billion" (Yarlagadda 2022). Helium-3, which is present in rock and soil on the Moon, may one day prove to be a lucrative resource if nuclear fusion is made possible; It makes sense that businesses would seek to benefit from mining space resources (Yarlagadda 2022).

But before continuing, it might be necessary to ask: Would not the world gold market be impacted if these enormous quantities became available? This is a legitimate worry since a sudden flow of resources from space mining may cause the dynamics of the market to change. Therefore, even if the finding of such a massive mineral deposit in space is fascinating, care must be taken to properly evaluate its practical consequences for market dynamics and financial distribution.

Mining colonies may be essential for future power generation in outer space, necessitating exploration and maintenance of base stations and stopover sites (Madhavan Nair et al. 2008: 1337–1342). However, as space colonies live their own lives, they may evolve independently and lose their relationship with Earth confronting a variety of obstacles, including technical failures and the psychological effects of isolation, which could ultimately cause them to fall apart or be abandoned (Powell et al. 2001: 737–765).

Space-mining colonies might be the next big human endeavour. Yet, there is a gap between corporate entities' ambitions and international and domestic space legislation that is still unfilled. The Outer Space Treaty might present the simplest framework for colony establishment, yet it raises more concerns than solutions. In this article, we will attempt to address the following question:

What are the economic benefits and the legal concerns associated with the creation of mining colonies in space?

To answer this question, this article will adopt a normative methodology with an economic approach that integrates a normative legal framework supported by quantitative statistics to address this subject. By examining the potential benefits and challenges, this approach aims to provide a comprehensive analysis of the feasibility and sustainability of such mining colonies. Additionally, it will consider the implications of international law and regulations on such ventures, ensuring a well-rounded evaluation of the topic.

TERMINOLOGICAL CLARIFICATIONS

Before diving into the analysis of the topic, we must first identify the main terms that will be frequently used in this chapter.

Space mining

Space mining can be defined as "the exploration, exploitation, and utilization of natural resources to be found on the Moon, other planets, and near-Earth asteroids (NEAs)" (Gres 2022). Yet, when it comes to the expression "space resource extraction", according to some experts, this is far more appropriate than "space mining" because it refers to the process of mining resources rather than space itself. Unlike traditional mining on soil, by using this term, we can both characterise the operation and emphasise how it differs from mining on Earth. We may further refine our definition by distinguishing between "space resources" and "asteroid resources". Any natural resource or substance that exists in space, especially on planets, and may be mined or used for a variety of purposes is referred to as a "space resource". These resources consist of water, minerals, solar energy, helium 3, and so on (McKay et al. 1992).

On the other hand, "asteroid resources", specifically refer to resources found on asteroids that can be mined and utilised. Due to the size difference between meteoroids and planets, asteroids are frequently referred to as "minor planets" (New Space Economy 2023).

In light of this, we may question if space mining is justified legally and whether current laws allow such actions, given that space mining is not a novel idea but rather an ongoing mission that mankind is continuously attempting to achieve. This matter will be tackled in the coming paragraph after identifying our second main term, colony.

Colony: Space colonisation or space settlement, any differences?

The term colony can be tricky to define and use without being in the realm of criticism. According to the Cambridge Dictionary, the word colony refers to "a country or area controlled politically by a more powerful country that is often far away". Furthermore, "a colony is also a group of people with a shared interest or job who live together".

Within the space sector, space colonisation is a literal translation of "human habitation in space, other than Earth, it could be anywhere. It might exist in orbit, on Mars, or another planet" (Mane 2022). A possible form of space colonisation would be an orbiting space station. Right now, there is just one fully functional low Earth orbit space station, which is the International Space Station (ISS) (Mane 2022).

This definition can be simple and accurate, but the word colony does hold other concepts that cover the meaning. Especially with colonialism, the term "colony" may carry unfavourable historical connotations of exploitation, oppression and lack of autonomy. Thus, many experts on the subject prefer to use other names, such as "settlement" or "station", when referring to habitations or installations in space. Despite this, we can see that most different futuristic space projects are still using mainly the word "colony" or "space colonisation".

In the context of space exploration, the term "colony" has evolved to refer to the establishment of a human settlement on a celestial body, like the Moon or Mars, mainly not for controlling purposes. This change is revealing a more positive and broad vision for space exploration in the future. It also demonstrates the possibility of international cooperation in building viable communities outside of Earth. Likewise, the usage of the term in numerous space projects might be an effort to get the attention of the audience, raising appreciation for the excitement of these missions and greater hopes for the future. In this case, the second meaning of the term "colony" cited in the Cambridge Dictionary above "a colony is also a group of people with a shared interest or job who live together" may be applicable in the space sector.

REASONS: WHY SPACE MINING COLONIES?

The construction of space colonies in the future could be motivated by the possibility of finding water, fuel sources, and rare minerals on distant planets or asteroids, so we can gain financially from them. Furthermore, space colonisation may serve as a foundation for upcoming interplanetary travel and other technological breakthroughs.

Natural and geopolitical reasons

The first reason are rare earth elements (REE) (Zampa 2021). These kinds of elements can be found on the Moon and other celestial bodies (Staedter 2020). Additionally, and most intriguingly, platinum, palladium and rhodium have been discovered on our Moon (Gocha 2020), along with water ice (Kerr 2009). As a result, exploring and utilising these resources could reduce our dependence on Earth's limited minerals and open up new possibilities for space exploration and the colonisation of other mining planets.

The second reason is geopolitical; control and access to REE and other materials have become a strategic concern for countries worldwide, leading to intense competition and conflicts over their acquisition and trade. For example, China has been the dominant producer of REE for many years. This has given China significant influence in international trade negotiations and has caused other countries to seek alternative sources and develop their domestic production capabilities (Seaman 2019). For example, the United States is now investing in REE projects to reduce its reliance on Chinese supply and safeguard its technological advancements and national security interests (Hannon 2022). This makes us wonder if the success of such projects could potentially reduce the motivation for space mining in the future.

Economic reasons

Going back to one of the main focuses of this article, if there are minerals worth mining in space, it means that we can benefit economically from them. Using these elements can lead to job creation and financial growth. Furthermore, the development of space mining technologies and infrastructure can boost innovation and drive advancements in other industries, ultimately benefiting the global economy.

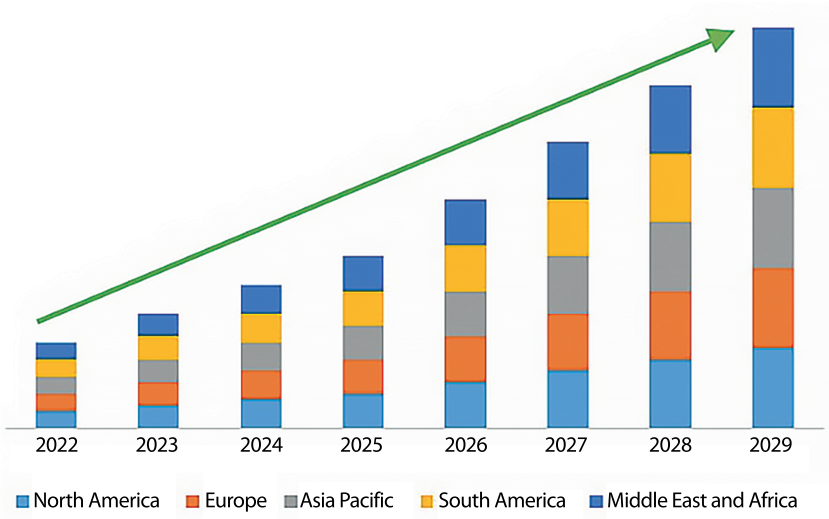

Figure 1
Global space mining market by regions, 2022 to 2029
Source: Data Bridge Market Research 2023

Figure 1 demonstrates how space mining has a significant potential for financial gain. Space mining companies and states can extend their operations and generate new revenue streams by extracting precious resources from celestial bodies, such as water and rare metals. In fact, the space mining market is expected to increase at a Compound Annual Growth Rate (CAGR) of 20.48% to reach USD 5,068.06 million by 2029 from its value of USD 1,141.62 million in 2021, according to Data Bridge Market Research (Data Bridge Market Research 2023).

Also, if mining is already profitable on Earth, then colonising other planets has the enormous potential to bring far higher profits. Building space mining colonies would open new possibilities for resource discovery and utilisation, resulting in previously unheard-of technological advancements and economic growth, in addition to expanding the volume of resource extraction. Moreover, according to some experts, space mining colonies are just like "establishing markets in space" (Weinzierl 2018).

Strategies for establishing a futuristic Moon mining colony

Since this vision is so close to becoming a reality, a variety of strategies designed to promote transparency in the management structures for future lunar colonies reflect inclusive and sustainable space exploration methods. To build a comprehensive framework that addresses multiple interests while adhering to existing space treaties, SGAC's E.A.G.L.E. Project, for example, promotes collaboration among numerous stakeholders, such as governments, business entities, academics and international organisations (SGAC 2021). Comparably, to enable a variety of individuals to engage in decision-making procedures and get access to lunar resources, the Open Lunar Foundation promotes an open-access strategy that emphasises equality and transparency. As a result, these approaches seek to advance economic development and innovation in lunar operations while balancing the interests of many investors (UNOOSA 2023). In addition, there are a few other points that emphasise the need for a flexible governance structure adapted to the opportunities and challenges of space settlement. These include decentralised models powered by commercial space firms like SpaceX and Blue Origin, government-led strategies, and collaborative concepts like the Moon Village promoted by the European Space Agency.

THE LEGAL FRAMEWORK: WOULD SPACE MINING COLONIES BE LEGAL?

The legality of future space colonies involved in mining activities is mostly linked to the legality of the mining operation itself. The legality of space mining is debatable, and international negotiations are currently underway to establish a more comprehensive legal framework for space mining colonies. In this section of our paper, we will first explain why this controversy exists, which is mostly due to the ambiguity of the terms used in space law relating to this topic. Second, we will analyse both sides of the debate, focusing on the arguments of each as well as the international community's position on resolving this matter through accords or domestic legislation.

Space mining and International Law

The legal ambiguity surrounding the space mining activities

This section of our chapter will primarily focus on the Outer Space Treaty (OST), which serves as a key legal framework governing space activities and is also known as the *Magna Carta* of international Outer Space law, as well as the Moon Agreement, which addresses the exploitation of natural resources in space.

The debate about whether space mining is fully legal or not is mostly based on the vague language used in the OST. This created two opinions: the first States affirming its legality and having already started with the preparation of their space mining projects, and the second States that are still against it concerning its illegality and the consequences that can occur from mining natural resources in space in the absence of clear regulations in place.

To analyse the uncertainty about whether space mining is legal or not, we can start with the 'ordinary meaning' of the terms used in the OST. Even though space mining is not expressly covered, all space-related activities are still governed by the various obligations under that treaty. In this instance, the word "use" in Article I does not specify whether the extraction of space resources qualifies as "use", nor does its ordinary meaning indicate whether property rights over extracted space resources can be obtained (Byers–Boley 2023).

Referring now to Article II of the treaty, it is forbidden for any country to appropriate space "by claim of sovereignty, by means of use or occupation, or by any other means". As "national appropriation" is also ambiguous under this context, some scholars said that it has no ordinary meaning and it is unclear if this refers to the dominant exploitation of a resource or territory by a single nation or not (Byers–Boley 2023).

When it comes to the Moon Agreement, it contains less ambitious language compared to the OST; we must first mention that this agreement, which is ratified by 18 countries, none of whom are major spacefaring states, may be due to an implied language prohibiting lunar resource exploitation. For some, Article II(2) of the Moon Agreement mirrors the restrictions outlined in Article II of the OST (Freeland–Jakhu 2009). However, one of the primary objectives of the Moon Agreement is to promote the "exploitation" of the Moon's natural resources through the Agreement's existing provisions and the eventual establishment of an international framework. It follows that the restriction on natural appropriation in Article 11(2) of the Moon Agreement does not, by itself, restrict the use of natural resources; doing so will require removing such resources from their "place" on the Moon (Byers–Boley 2023). The uncertainty of what could be the right expression of the terms frosted the debate on the legality of space mining activity.

Analysing the lawfulness of space mining: Identifying different positions

Possible barriers to confirming the legality of space mining

The doubt and uncertainty about the legality of space mining is due to the existence of some signs that restrict this activity and, as a result, limit the existence of space mining colonies in the future. These forbidden indicators, based on international space law, can be primarily related to the expression used in the OST "appropriation" mentioned in its Article II, which can be defined based on the Cambridge Dictionary, as "the act of taking something for your use, usually without permission".

States and private entities may be restricted from mining space

These can also be referred to as the "subject" of the *non-appropriation*. Article II of the OST mainly aims to limit states' ability to engage in "national appropriation" by prohibiting it. Supporters counter that this prohibition does not apply to private entities, which means they are free to appropriate, use, or claim celestial bodies for their own financial advantage (Pop 2008). However, the Chinese translation of the treaty appears to restrict the ban on appropriation to State parties alone "state appropriation", whereas the English, French, Russian and Spanish versions of the document refer to a broad prohibition on appropriation "national appropriation". An inaccurate translation could be the cause of this disconnect (Jinyuan 2017). In this case, we can say that Article II is interpreted to allow private appropriation, which is said to go against the intent of the OST because appropriation by private entities or States interferes with unlimited access to space. The term "national appropriation" was meant to refer to both public and private appropriation, as the Outer Space Treaty's writing history attests to (Freeland–Jakhu 2009). Conforming to Article VI of the treaty, State parties are responsible for maintaining responsibility for national activities conducted in space by governmental and non-governmental entities and for making sure that such activities comply with the treaty's provisions. Therefore, private companies' appropriation of space should be viewed as non-appropriation by their States (Tronchetti 2014: 193–196). In light of this, we can mention a court case – such as the United States of America v. One Lucite Ball Containing Lunar Material (One Moon Rock) and One Ten Inch by Fourteen Inch Wooden Plaque (2003)[2] – in which the judge claimed that it was illegal to own or sell celestial bodies as a whole or in parts (Freeland–Jakhu 2009). This therefore strengthens this interpretation of the prohibition mentioned in Article II (Jinyuan 2017).

The uncertainty of the legal status of the celestial bodies and their resources is identical

This can be referred to as the "object" of the *non-appropriation,* in other words, are the resources of celestial bodies non-appropriable, just like the celestial bodies themselves? (Jinyuan 2017). If this is the case, then resource exploitation, which is essentially a "taking of possession" and an "exercise of control" over them, amounts to a partial appropriation of celestial bodies. Opinions on this matter diverge. While some contend that both space and its natural resources are covered by the non-appropriation principle of Article II (Gorove 1973), some maintain that while the concept applies to space, it does not apply to its natural resources (Williams 1987: 142–151). The Outer Space Treaty forbade states from claiming space and celestial bodies as their own territory, to prevent sovereignty claims over outer space. This treaty was ratified in the 1960s when the mining of these resources was a low-priority concern and public interest in extracting natural resources from space only developed in the 1970s, but some support the idea that this restriction was mainly for military purposes (Gabrynowicz 2004: 1041). In other words, the activities that are prohibited are expressly stated in the treaty, and space

2 For more information see www.collectspace.com/news/usvmoonrock.pdf.

mining is not expressly listed; nonetheless, the absence of an express statement of prohibition does not imply its legality (Coffey 2009: 119).

There are two main concerns to answer: first, are there any naturally occurring objects in space that are not celestial bodies because of their significant differences in size and composition, and second, are tiny asteroids considered a material resource whose appropriation is not expressly prohibited? The term "celestial bodies" is mentioned several times in the OST, yet it does not define it. This lack of definition leaves room for interpretation regarding whether asteroids fall under the category of celestial bodies and if they fall under the same possible prohibition or not. Generally, since the OST did not make any observations or differences, it all falls under the used term of a celestial body and, as a result, under the same possible restriction (Jinyuan 2017).

The claims of sovereignty

Or referred to as the "means" of *non-appropriation,* Article II of the Outer Space Treaty specifically forbids appropriation using "sovereignty" claims. This includes claims over space, which qualify as appropriations. As an explanation, even in cases where no formal claim to sovereignty is made, arguing in favour of property rights over resources mined from space may constitute a de facto declaration of sovereignty. The non-appropriation principle may be broken if a state views resources from asteroids as belonging to its territory (Tronchetti 2014: 193–196). The use or occupation of space in a way that prohibits others from profiting from that present sovereignty is known as appropriation. The U.S. Space Resource Act, for example, acknowledges property rights over "asteroid resources or space resources obtained", but it does not define the phrase "obtained" precisely. There have been several questions raised about the U.S. federal legislation governing the unextracted, *in situ* asteroid resources and whether it equates to "other means" of national appropriation (Jinyuan 2017).

The Moon Agreement prohibits the use of space, especially for things and subjects. It declares that the Moon's surface, subsoil, or natural resources should not be owned by any state, international organisation, country, or person. Unlike the Outer Space Treaty, it states that the Moon and its resources are the common heritage of mankind (Jinyuan 2017).

Principles supporting the possibility of the legality of space mining

The principle of freedom of exploration and use of outer space

Supporters of mining space are looking at it as the manifestation of the principle of the freedom of use of outer space, which is expressly guaranteed by the OST (Schmitt 2021: 21–26). In common usage, "use" means applying or employing something; yet, some understand it to mean both non-commercial and commercial use, such as using space and celestial bodies for profit (Freeland–Jakhu 2009). The IISL Board of Directors maintains that there is no global consensus over whether freedom of use encompasses the ability to obtain and use non-renewable natural resources, such as water and minerals found on celestial planets (Hobe 2016). Based on the Vienna Convention on the Law of Treaties 1969, "a treaty should be interpreted in good faith [...] and in the light of its object and purpose". Considering this, we may assert that the Outer Space Treaty aims to encourage free space exploration and utilisation rather than impose restrictions on it. The fact that state parties have acknowledged that it is in the common interest of all mankind to encourage space exploration and peaceful uses makes this statement most likely true.

We can support this freedom position with one of the latest declarations from Michelle Hanlon, director of the Center for Air and Space Law Research at the University of Mississippi in the United States. She said: "At present, everything is permitted on the Moon." Furthermore, she explained that existing laws stipulate the Moon's use exclusively for peaceful purposes and prohibit the establishment of military installations. Essentially, she emphasised that while there are regulations in place, they do not impose significant restrictions on what can be placed on the Moon, except for the prohibition of nuclear weapons (Goddard 2024).

However, ownership of mineral resources is not assumed by legal text. Under the laws of various regulations, wild animals, for example, are res nullius, or ownerless property. They can be considered private property when reduced to possession by being killed or captured (Byers–Boley 2023). By contrast, mineral resources could be generally owned by States or private entities and are not subject to the Mineral Resources Law of the People's Republic of China, Article 3, which provides that '[m]ineral resources belong to the State'.

Mineral resources, do not follow the "first come, first served" as mentioned in the Mineral Resources Law of the People's Republic of China. Similar regulations have been set by the UN Convention in some regions outside of national borders, such as the freedom of access to high seas fisheries as long as conservation measures are taken (UNCLOS Article 116). Yet, these norms cannot be extended to outer space to prohibit the exploitation of its natural resources because the preceding domestic legislation and international treaties prohibiting mineral exploitation are based on agreements between states. In addition, the natural resources in outer space, like those in the deep bottom, are not defined as the "common heritage of mankind" under the UNCLOS in Article 136. Outer space is not subject to national sovereignty, space resources are effectively in a "state of nature". The Earth's resources can no longer be used without considering the interests of others due to industrialisation and population growth. Considering how plentiful these resources are, one might conclude that mining minerals in space is legal if one considers the opportunity that others must engage in similar activities, and it is not a privilege for a few countries (Jinyuan 2017).

The principle of the collective interests of all nations and the common heritage of humanity

In Article I of the OST, outer space exploration and use, "shall be carried out for the benefit and in the interests of all countries, irrespective of their degree of economic or scientific development, and shall be the province of all mankind". This means that any activity in space should be done to benefit all nations and all humankind. It is important to ensure that the resources are utilised fairly and equitably to uphold this principle. The use of the term "shall" emphasises the necessity of such action, and as a result, it "should be treated as a binding legal obligation" (Cheng 1997). When Article 11(2) of the Moon Agreement forbids the possession of lunar resources, it does not forbid using and accessing them. Rather, it highlights the necessity of safe management and regulation to guarantee that the utilisation of these resources is carried out in a way that aligns with the values of equity, sustainability and the common interest of all countries.

The concept of common interest governs the freedom of use of space, to ensure that the interests of all nations are considered while exploring and using space. In principle, all nations would gain from the extraction of natural resources in space, as it could help with the shortage of resources on Earth and encourage advancements in science and technology. Yet, as the advantages and interests shared by all nations are not equal to those shared by each nation, what is advantageous to one state may not be to another. Although, it is sometimes challenging to achieve each state's benefits and interests (Hudgins et al. 2002).

Despite the mode of production, the exploitation of space resources should be carried out by a collective body or capable entities in a free market. And the benefits should be distributed according to distributive justice, with all states entitled to an equal share (Paxson III 1993: 487).

What about the international customary law position?

Regarding space mining operations, customary international law presents a nuanced and dynamic position. It is debatable whether new customs laws adapted specifically to space mining are necessary, even if several well-known concepts, like the prohibition on space appropriation, have been recognised as components of customary law. In actuality, the evolution of customary law on this subject is influenced by several factors, including the duration of time, consistency and generality of state practice. Space mining operations do not yet have enough developed norms. Nevertheless, customary law, which allows scientific research but forbids commercial space exploitation, makes it difficult to draw a clear distinction between the two types of activity. Moreover, although accords like the Moon Agreement forbid commercial mining until an international framework is established, their recognition and customary standing remain questionable (Jinyuan 2017). Actually, "the true test of the Moon Treaty both as treaty and customary law will not come until the exploitation of extraterritorial resources becomes technically and economically feasible" (Listner 2011).

The Artemis Accords: Consolidation or fragmentation of the space mining legal framework?

Initially, the Artemis Accords were a series of 13 guidelines meant to promote international cooperation in space exploration. They were first signed on 13 October 2020, by eight states: Australia, Canada, Italy, Japan, Luxembourg and the United States. Signing the Artemis Accords is a requirement for NASA's larger Artemis Program, which aims to put a human again on the moon and conduct further human exploration of Mars (Zielinski 2023). In alignment with the purpose of this paper, when it comes to the debate of space mining lawfulness, can the Artemis accords provide a clearer solution to the issue?

The most "controversial" aspect of the Accords is Section 10, dealing with the utilisation of space resources (Bartóki-Gönczy – Nagy 2023: 888–898). It emphasises the potential benefits of using space resources for sustainable and safe space activities. While stating that the extraction of these resources rarely corresponds to national appropriation under Article II of the Outer Space Treaty. As mentioned in the previous section of this article, the ambiguity of the OST regarding the space mining activity and the identification of the "national appropriation" can lead to confusion between different perspectives as it "leaves room for different interpretations" (Bartóki-Gönczy – Nagy 2023: 888–898).

These accords go by the USA approach to space mining, depending on the principle of freedom of exploitation established by Article I of the OST, which is also adopted by its domestic laws, the Commercial Space Launch Competitiveness Act of 2015, which we will tackle in the next section. Regardless, it may create difficulties in international cooperation and regulation of space mining activities.

Another concept emphasised in the Artemis guidelines that we have to highlight is the "safety zones" to protect ongoing mining activities and prevent interference from other entities. Thus, it may raise concerns about the right to property in outer space as a territorial claim and potential conflicts in space governance as the characteristics of these zones, such as the size and scope, are not explicitly fixed, giving them flexibility depending on the "nature of the operation", which could be a risk to interfere with the OST requirements (Bartóki-Gönczy – Nagy 2023: 888–898). As critics, China has expressed doubts about the concept of the safety zones delineated in the accords, and the head of Russia's space program has stated that the accords are now too "U.S.-centric" to be approved (Osburg–Lee 2022).

In sum, the Artemis Accords initiated discussions within the framework of the United Nations regarding the legal issues surrounding the exploitation of space resources. Yet, criticism can be seen as an act of unilateral action, negating multilateralism, which, as a result, can lead to the fragmentation of international space law. In addition, the lack of provisions regulating the liability of futuristic activities and environmental protection principles could lead to ongoing gaps in the space legal framework (Bartóki-Gönczy – Nagy 2023: 888–898).

SPACE MINING AND DOMESTIC LAWS

United States of America

After being signed into law by President Obama in 2015, the United States passed the "Commercial Space Launch Competitiveness Act" (CSLCA). The establishment of a stable and predictable legal framework aims to provide

American companies that collect and utilise space resources not only legal protection but also freedom, such as the ability to own, transport, or sell asteroid and space resources (Tronchetti 2014: 193–196). As mentioned in this paper, conceding that there is no clear indication of whether mining space is completely legal or not, this act is the subject of criticism from a lot of scholars, especially those who are against space mining depending of its illegality. Furthermore, this domestic law was reinforced later with the Artemis Accords, discussed above, which further solidified the U.S. stance on commercial space activities. But it also makes us question whether it is a sort of planned dominance or just to harmonise its legislation.

Luxemburg

To provide stability and a high degree of security for investors, explorers and miners, Luxembourg constructed an effective legal and regulatory framework in 2017 that includes specialised space regulation (Legilux 2017). By adopting this, it positions itself as the second nation in the world and the first in Europe to provide a legal framework for space resource exploration and utilisation. Following the provisions of Article II of the Outer Space Treaty, this statute is not intended to facilitate the "national appropriation" of any part of outer space, including the Moon and other celestial bodies. The objective is to elucidate Luxembourg's national stance regarding the permissible status of resources that can be retrieved from certain celestial bodies and space overall. It also lays out the guidelines for managing and approving private space exploration projects, which include both resource use and exploration (Legilux 2017).

The United Arab Emirates

The United Arab Emirates implemented Federal Law No. 12, which governs the space industry, in December 2019. This legislation addresses a wide range of space-related operations, such as resource transfer, space mining and vehicle launches. The Director General of the UAE Space Agency, Dr Mohammed

Al Ahbabi, referred to this law as a "law for tomorrow" (Warner 2021). Addedly, "space resources" are defined as "any non-living resources present in outer space, including water and minerals". It is interesting to note that the law does not expressly say that using space resources is legal; instead, it lists "space resource exploration or extraction activities" and "activities for the exploration and use of Space Resources for scientific, commercial, or other purposes" as regulated space activities.

This legislation has liability provisions, which set it apart from previous domestic laws: According to Article 14, if the international community finds that the UAE violated the OST, the operator might be held accountable (Federal law no. 12 on the regulation of the space sector 2019).

Japan

Japan is the fourth country to establish a legal framework that supports the entry of its businesses into the economic exploitation of asteroids and other planets, joining the United States, Luxembourg and the United Arab Emirates (Pons 2021). Under Japan's Space Resources Act (JSR Act), companies can acquire property rights over space resources "if the government approves their notified research methods, timing, and objectives". Water, minerals and other natural resources that exist in outer space, including the moon and other celestial bodies, are selected as space resources. The legislation is silent on the definition of "natural resources" and whether they are inanimate or abiotic. Furthermore, resources located on or within celestial bodies are treated equally by the law with the celestial body itself. The law does, however, recognise obligations to abide by international law, which may indicate restrictions on asserting ownership over a whole celestial body.

Just as in the United Arab Emirates, authorisations are transferable only with the prime minister's prior consent. Lastly, in addition to permitting space operations, the Space Resources Act specifies the property rights that the licence holder will possess. According to Article 5, a person who obtains ownership of space resources due to actions carried out under their authorisation does so when they "possess the resource intending to own it". Japan acknowledges the ownership of resources collected from space by a private entity (DePagter 2023). However, an English version is not there yet from the Japanese Government, this claim can be due to the uncoherent translation used by some scholars.

In conclusion of this section, we can say that the jurisdiction mentioned above covers mainly space mining activities and not the regulation of establishing the colonies that will probably one day serve the extraction of space resources. However, these laws could shape the legal framework applied to the space mining colonies – if they come into existence – since they have already established the basis of the activity. Yet, it contains some lacunae that may need to be addressed in the future to ensure clarity and consistency in the regulation of space mining colonies and the effectiveness of the mining activity itself.

CRIMINAL JURISDICTION OF THE SPACE MINING COLONIES: A NEAR FUTURE OR A SCIENCE FICTION?

"That's how justice works around here. We don't have jails or fines. If you commit a serious crime, we exile you to Earth" (Weir 2017). Our question here is, what if a crime occurred in these colonies if they existed, is space law able to cover this topic? The incident that occurred on the International Space Station (ISS) is an example since we can consider it as an orbital colony. Yet, investigators do not count it as the first crime in outer space since the damage and the plaintiff were on Earth. In 2019, NASA astronaut Anne McClain faced accusations that she had inappropriately accessed her divorced spouse's bank account while living on the ISS (Baker 2020). In Article 22 of the 1998 ISS Intergovernmental Agreement, nations agreed that jurisdiction over space-based personnel would be assigned according to their nationality. However, McClain was not prosecuted by the state, and the matter was settled in private between the parties.

Currently, the Space CSI investigates murder in microgravity, and this issue is also the subject of research by detectives. Michelle Hanlon predicted that "Jurisdiction will be tricky". The OST is silent when it comes to criminal jurisdiction, and these kinds of crimes can be out of reach of the liability convention. Another claim made by the CEO of For All Moonkind Inc. is that, according to the OST and the liability convention, space objects remain under the jurisdiction and control of the state that launched the object. "But what happens if the crime occurs in an object made in space? Jurisdiction will be even more complex!" (Serrie 2024).

The lack of clear regulations surrounding space crimes raises concerns about accountability and enforcement in outer space when thinking about establishing mining colonies. It is suggested by White (2021) to create an Outer Space Criminal Statute (OSCS). By creating a common norm for future activities and addressing inadequacies in current criminal law. This would contribute to ensuring that those who operate in space, including individuals and private entities, are held responsible for any illegal activity they may have committed.

CONCLUSIONS

Considering all that has been discussed, we can sum up the matter by stating that the idea of establishing space mining colonies in the future holds enormous potential, driven by our natural curiosity, global needs and economic ambitions. Nonetheless, this ambitious objective presents a variety of legal concerns that must be addressed. The legality of space mining operations is a major topic of debate, and we can say that it has a direct impact on the possibility of establishing colonies for these kinds of operations. This debate is a result of the ambiguity in the terms and provisions of the current space law and whether the current domestic laws that are trying to govern this activity are in harmony with international space law or not. This, for sure, will necessitate careful interpretation of the rules and principles that govern space activities in general. In addition, if these colonies become a reality, it raises worries about the applicable legal framework in cases of criminal acts. We cannot deny that the concept of establishing space mining colonies is promising for humankind's future exploration and resource use in outer space. Yet, a compromise between the different nations and the adoption of a clear position toward the lawfulness of space resource extraction activities that will enhance the probability of creating space mining colonies should be a priority.

REFERENCES

Baker, M. (2020): NASA Astronaut Anne McClain Accused by Spouse of Crime in Space. *The New York Times,* 27 August 2020. Online: www.nytimes.com/2019/08/23/us/astronaut-space-investigation.html

Bartóki-Gönczy, B. – Nagy, B. (2023): The Artemis Accords. *International Legal Materials,* 62(5), 888–898. Online: https://doi.org/10.1017/ilm.2023.17

Bidshahri, R. (2019): What It Will Take for Humans to Be Self-Sustaining in Space. *Singularity Hub,* 5 September 2023. Online: https://singularityhub.com/2019/02/15/what-it-will-take-for-humans-to-be-self-sustaining-in-space/

Byers, M. – Boley, A. (2023): *Who Owns Outer Space? International Law, Astrophysics, and the Sustainable Development of Space.* Cambridge: Cambridge University Press. Online: https://doi.org/10.1017/9781108597135

Cheng, B. (1997): *Studies in International Space Law.* Oxford: Oxford University Press. Online: https://doi.org/10.1093/acprof:oso/9780198257301.001.0001

Coffey, S. (2009): Establishing a Legal Framework for Property Rights to Natural Resources in Outer Space. *Case Western Reserve Journal of International Law,* 41(1), 119–137. Online: https://heinonline.org/HOL/Page?handle=hein.journals/cwrint41&div=9&g_sent=1&casa_token=&collection=journals

Data Bridge Market Research (2023): *Global Space Mining Market – Industry Trends and Forecast to 2029.* Online: www.databridgemarketresearch.com/reports/global-space-mining-market

DePagter, M. M. (2023): "Who Dares Wins": How Property Rights in Space Could Be Dictated by the Countries Willing to Make the First Move. *Chicago Journal of International Law,* 1(2), 116–133. Online: https://cjil.uchicago.edu/online-archive/who-dares-wins-how-property-rights-space-could-be-dictated-countries-willing-make

Federal Law No. 12 on the Regulation of the Space Sector, Article 4 (19 December 2019) (U.A.E.). Online: https://perma.cc/L32M-WKCT

Freeland, S. – Jakhu, R. (2009): Article II. In Hobe, S. – Schmidt-Tedd, B. – Schrogl, K.-U. (eds.): *Cologne Commentary on Space Law.* Volume 1. Cologne: Carl Heymanns Verlag. 44–64.

Gabrynowicz, J. I. (2004): Space Law: Its Cold War Origins and Challenges in the Era of Globalization. *Suffolk University Law Review,* 37(4), 1041–1073.

Gesl, P. M. (2018): *Preparing for the Next Space Race: Legislation and Policy Recommendation for Space Colonies.* Doctoral dissertation. Air University. Online: www.airuniversity.af.edu/AUPress/Display/Article/3030780/preparing-for-the-next-space-race/

Gocha, A. (2020): Lucrative Lunar? Startup Companies Raise Significant Funding to Mine the Moon for Rare Earth Elements and More. *The American Ceramic Society,* 7 January 2020. Online: https://ceramics.org/ceramic-tech-today/aeronautics-space/lucrative-lunar-startup-companies-raise-significant-funding-to-mine-the-moon-for-rare-earth-elements-and-more/

Goddard, J. (2024): Exploration spatiale: qui fait la loi sur la Lune? *Courrier International,* 9 March 2024. Online: www.courrierinternational.com/article/exploration-spatiale-qui-fait-la-loi-sur-la-lune

Gorove, S. (1973): Limitations on the Principle of Freedom of Exploration and Use of Outer Space: Benefits and Interests. *Proceedings of the 13th Colloquium on the Law of Outer Space,* 74.

Gres, T. (2022): *Space Mining.* Space Generation Advisory Council. Online: https://spacegeneration.org/sgac-ecsl-un-model/67883-2#:~:text=Space%20mining%20comprises%20the%20exploration,3)%2C%20metals%20and%20water

Hannon, T. P. (2022): *Outer Space Mining and the Future of Space Law.* Doctoral Dissertation. University of Nevada.

Hobe, S. – Schmidt-Tedd, B. – Schrogl, K.-U. – Popova, R. – Stubbe, P. (2020): *Cologne Commentary on Space Law. Volume II – Кёльнский комментарий к космическому праву (Том II).* Berlin: Berliner Wissenschafts-Verlag.

Hobe, S. (2016): The International Institute of Space Law Adopts Position Paper on Space Resource Mining. *Zeitschrift für Luft- und Weltraumrecht,* 65(2), 204–209.

Hudgins, E. L. – Boaz, D. (2002): *Space. The Free-Market Frontier.* Washington, D.C.: Cato Institute.

JINYUAN, S. (2017): Legality of Unilateral Exploitation of Space Resources Under International Law. *International and Comparative Law Quarterly,* 66(4), 991–1008. Online: https://doi.org/10.1017/S0020589317000367

JOHNSON, R. D. – HOLBROW, C. H. (1977): *Space Settlements: A Design Study.* Scientific and Technical Information Office, National Aeronautics and Space Administration.

KERR, R. (2009): Yes, There's Ice on the Moon – But How Much, and What Use Is It? *Science,* 326(5956), 1046. Online: https://doi.org/10.1126/science.326.5956.1046-a

Legilux (2017): Loi du 20 juillet 2017 sur l'exploration et l'utilisation des ressources de l'espace. *Journal officiel du Grand-Duché de Luxembourg,* 20 July 2017. Online: https://legilux.public.lu/eli/etat/leg/loi/2017/07/20/a674/jo

LE MEUR, P.-Y. – LEVACHER, C. (2022): Mining and Competing Sovereignties in New Caledonia. *Oceania,* 92(1), 74–92. Online: https://doi.org/10.1002/ocea.5330

Luxembourg Space Agency [s. a.]: *Legal Framework for Space Resources.* Online: https://space-agency.public.lu/en/agency/legal-framework.html

LISTNER, M. (2011): The Moon Treaty: Failed International Law or Waiting in the Shadows? *The Space Review,* 24 October 2011. Online: www.thespacereview.com/article/1954/1

MANE, S. (2022): Space Colonization for Human Habitation in Space Environment. *International Journal of Enhanced Research in Science, Technology & Engineering,* 11(5), 20–24.

MCKAY, M. F. – MCKAY, D. S. – DUKE, M. B. (1992): *Space Resources. Materials.* National Aeronautics and Space Administration, Scientific and Technical Information Program. Online: https://newspaceeconomy.ca/wp-content/uploads/2023/02/sp509-3-materials.pdf

MADHAVAN NAIR, G. – SRIDHARA MURTHI, K. R. – PRASAD, M. Y. S. (2008): Strategic, Technological and Ethical Aspects of Establishing Colonies on Moon and Mars. *Acta Astronautica,* 63(11–12), 1337–1342. Online: https://doi.org/10.1016/j.actaastro.2008.05.012

Nanalyze (2021): 8 Reusable Rocket Companies for Cheaper Space Travel. *Nanalyze,* 30 March 2021. Online: www.nanalyze.com/2021/03/reusable-rocket-companies/

New Space Economy (2023): *Space Resource Mining… What Is It and How Real Is It?* Online: https://newspaceeconomy.ca/2023/03/12/a-short-history-of-asteroid-mining/

OSBURG, J. – LEE, M. (2022): Governance in Space: Mining the Moon and Beyond. *RAND,* 12 September 2023. Online: www.rand.org/pubs/commentary/2022/11/governance-in-space-mining-the-moon-and-beyond.html

Paxson III, E. W. (1993): Sharing the Benefits of Outer Space Exploration: Space Law and Economic Development. *Michigan Journal of International Law,* 14(3), 487–517.

Pelton, J. N. (2016): *The New Gold Rush. The Riches of Space Beckon!* Cham: Springer.

Pons, J. (2021): US, Luxembourg, Emirates, and Now Japan Take the Lead to Exploit Space Mining. *Atalayar,* 28 July 2021. Online:www.atalayar.com/en/articulo/new-technologies-innovation/us-luxembourg-emirates-and-now-japan-take-lead-exploit-space-mining/20210728103455152275.html

Pop, V. (2008): *Who Owns the Moon? Extraterrestrial Aspects of Land and Mineral Resources Ownership.* Dordrecht: Springer. Online: https://doi.org/10.1007/978-1-4020-9135-3

Powell, J. – Maise, G. – Paniagua, J. (2001): Self-sustaining Mars Colonies Utilizing the North Polar Cap and the Martian Atmosphere. *Acta Astronautica,* 48(5–12), 737–765. Online: https://doi.org/10.1016/S0094-5765(01)00081-9

Schmitt, H. H. (2010): Return to the Moon. In Benaroya, H. (ed.): *Lunar Settlements.* Boca Raton: CRC Press. 21–26. Online: https://doi.org/10.1201/9781420083330

Seaman, J. (2019): Rare Earths and China. A Review of Changing Criticality in the New Economy. *Notes de l'IFRI,* 23 January 2019. Online: www.ifri.org/sites/default/files/atoms/files/seaman_rare_earths_china_2019.pdf

Serrie, J. (2024): Space CSI Investigates a Murder in Microgravity. *Fox News,* 19 March 2024. Online: https://www-foxnews-com.cdn.ampproject.org/c/s/www.foxnews.com/science/space-csi-investigates-murder-microgravity.amp?fbclid=IwAR1R3EEOOx2V-VrrX6lJAk9dRz4YDHemGxgi-OiaGkA1wfSRIKcNr3ad2L4I

SGAC (2021): *Effective and Adaptive Governance for a Lunar Ecosystem. Lunar Governance Report.* Online: https://spacegeneration.org/wp-content/uploads/2021/05/EAGLE-Report.pdf

Space Station Agreement 1998. Online: www.state.gov/wp-content/uploads/2019/02/12927-Multilateral-Space-Space-Station-1.29.1998.pdf

Staedter, T. (2020): Why on Earth Should We Be Mining the Moon? *Now,* 6 September 2023. Online: https://now.northropgrumman.com/why-on-earth-should-we-be-mining-the-moon

Statista (2023): *Market Value of Asteroid Mining 2017–2025.* Online: www.statista.com/statistics/1023115/market-value-asteroid-mining/

Szocik, K. – Wójtowicz, T. – Braddock, M. (2020): The Martian: Possible Scenarios for a Future Human Society on Mars. *Space Policy,* 54. Online: https://doi.org/10.1016/j.spacepol.2020.101388

Tronchetti, F. (2014): Private Property Rights on Asteroid Resources: Assessing the Legality of the Asteroids Act. *Space Policy,* 30(4), 193–196. Online: https://doi.org/10.1016/j.spacepol.2014.07.005

Tronchetti, F. (2016): Title IV – Space Resource Exploration and Utilization of the US Commercial Space Launch Competitiveness Act: A Legal and Political Assessment, *Air and Space Law,* 41(2), 143–156.

UNCLOS, Article 116 and Part VII, Section 2 in general.

UNOOSA (2023): *Open Lunar Foundation – Input to the Working Group on Legal Aspects of Space Resource Activities.* Online: www.unoosa.org/res/oosadoc/data/documents/2023/aac_105c_22023crp/aac_105c_22023crp_25_0_html/AC105_C2_2023_CRP25E.pdf

Vienna Convention on the Law of Treaties (23 May 1969) 1155 UNTS 331 [VCLT] Article 31(3)(b).

Warner, K. (2021): UAE Looks to Regulate Asteroid Mining as It Aims to Lure the Private Space Sector. *The National,* 27 November 2019. Online: www.thenationalnews.com/uae/science/uae-looks-to-regulate-asteroid-mining-as-it-aims-to-lure-private-space-sector-1.943028

Weinzierl, M. (2018): Space, the Final Economic Frontier. *Journal of Economic Perspectives,* 32(2), 173–192. Online: https://doi.org/10.1257/jep.32.2.173

Weir, A. (2017): *Artemis.* New York: Penguin Random House.

Williams, S. M. (1987): The Law of Outer Space and Natural Resources. *International & Comparative Law Quarterly,* 36(1), 142–151.

Yarlagadda, S. (2022): Economics of the Stars: The Future of Asteroid Mining and the Global Economy. *Harvard International Review,* 8 April 2022. Online: https://hir.harvard.edu/economics-of-the-stars/

Zielinski, L. Y. (2023): Disputes Over Space Mining on the Horizon? *Newsletter Officer, IBA Space Law Committee,* 10 September 2023. Online: www.ibanet.org/disputes-over-space-mining-on-the-horizon

Zampa, C. (2021): *Rare Earth Elements: Dynamics in the Global Market.* Master's dissertation. Università Ca' Foscari Venezia.

Norton O. Szabó[1]

How Do We Get to Mars? A Comprehensive Analysis of the Technologies, Challenges and Strategies for Crewed Interplanetary Travel

Introduction

For centuries, Mars has captivated humanity, its mysterious red glow a beacon in our night sky. This fascination has evolved from distant observations to direct exploration, with robots now probing its surface. Our journey from curiosity to exploration is a key chapter in understanding our celestial neighbour. As space exploration enters a new era, the focus shifts from whether we can reach Mars to how and when.

This study explores the myriad challenges and opportunities of a manned mission to Mars, delving into the complexities of space travel and life aboard a spacecraft. It is not just a technical journey but a testament to human ingenuity and our desire to explore. Beyond scientific curiosity, this mission could offer insights into life's origins and a potential refuge for humanity, underscoring the significance of Mars and the irreplaceable nature of our home planet.

[1] Konkoly Observatory, HUN-REN Research Centre for Astronomy and Earth Sciences; MTA Centre of Excellence, ELTE Eötvös Loránd University, Institute of Physics; ORCID https://orcid.org/0009-0007-1015-0327; e-mail: szabo.norton@csfk.org

DOI: https://doi.org/10.36250/01209_13

ROCKETS AND SPACECRAFT

Evolution and current state of launch vehicles

In the realm of Mars exploration, various rockets have played crucial roles in deploying rovers and probes. These include the Atlas V, which launched the Mars Reconnaissance Orbiter and the Curiosity rover, and the Delta II, responsible for sending Spirit and Opportunity to the Red Planet. Each of these missions contributed significantly to our understanding of Mars, demonstrating the capabilities and limitations of contemporary launch technology.

Currently, SpaceX's Starship Heavy represents the forefront of launch vehicle development. This spacecraft is designed not just for orbital missions but interplanetary travel, with Mars as a key target. Its development is closely watched by the space community, as it promises to revolutionise space travel (Kramer 2023) with its unprecedented payload capacity and potential for reusability. Starship Heavy's success could dramatically lower the cost of space exploration (Pappalardo 2023) and make ambitious missions like manned Mars expeditions more feasible (Heldmann et al. 2022).

This focus on reusability and efficiency marks a significant shift in launch vehicle design, reflecting the evolving needs and goals of space exploration in the 21st century. Starship Heavy is currently under development. As of the end of the beginning of 2024, it had two test flights, one in April and one in November. Despite a fiery start, both test launches provided SpaceX with essential data for the future.

The emphasis on sustainability, cost-effectiveness and reusability in Starship Heavy's design is a testament to the changing landscape of space travel, where the dream of Mars colonisation is inching closer to reality. We can already see its effect as both China (Beil 2023) and private companies (Rocket Lab 2019) try to shift their focus to reusable rockets and copy SpaceX's approach. The success of Starship Heavy and similar ventures will be pivotal in shaping the future of human space exploration, potentially making Mars not just a distant dream, but a reachable destination.

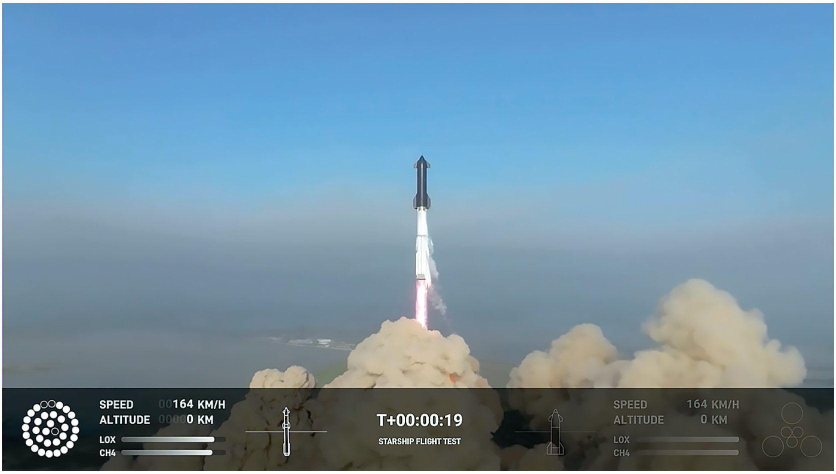

Figure 1
The 1st orbital test launch of SpaceX's Starship Heavy, Boca Chica, TX, USA, 20 April 2023
Source: SpaceX 2023

POSSIBLE ORBITAL PATHS TO AND FROM MARS

As we embark on interplanetary travel, the trajectory we chart from Earth to Mars is not merely a line drawn between two points. It is a carefully orchestrated path governed by the laws of celestial mechanics and the constraints of our technology. The journey to Mars begins with the fundamental question of trajectory. The answer lies not only in the destination but also in the journey itself, where efficiency, safety and the limitations of our spacecraft dictate the course we set.

The Hohmann Transfer Orbit

The *Hohmann Transfer Orbit* (HTO) is a concept that has become the bedrock of space travel. Named after Walter Hohmann, a German engineer who, in 1925, presented it as a fuel-efficient way to travel between two orbits, the HTO is an elliptical path that takes advantage of the orbital mechanics of celestial bodies (Hohmann 1925). Hohmann's revelation was that by timing our launch to coincide with a precise alignment of Earth and Mars, known as an opposition, we could use the least amount of energy to escape Earth's gravity and intercept Mars.

This trajectory involves two key manoeuvres: first, a launch into a parking orbit around Earth, followed by a precisely timed burn that propels the spacecraft into the elliptical transfer orbit, which is designed to be tangential to both Earth's orbit, where the journey begins, and the orbit of Mars, the intended destination. The spacecraft coasts along this path until it reaches the point in its orbit closest to Mars, where another burn adjusts its trajectory to enter an orbit around Mars or land on its surface. The Hohmann Transfer Orbit is a cornerstone in Mars missions, balancing fuel efficiency with practical challenges.

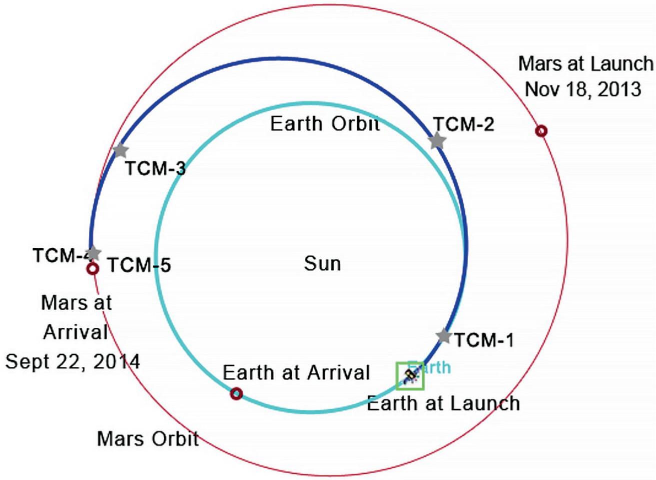

Figure 2
The Hohmann Transfer Orbit demonstrated via NASA's MAVEN Mission
Note: TCM is short for "trajectory correction manoeuvre"
Source: NASA JPL 2014

Its propellant efficiency, crucial for the heavy demands of crewed missions, stems from optimising energy use between Earth and Mars, considering their gravitational forces. This simplicity in design aids in straightforward mission planning and has a proven track record through numerous uncrewed missions, offering reliability and valuable data.

However, HTO's extended travel time, typically around nine months to Mars, raises significant concerns. This duration increases exposure to cosmic radiation and solar particle events, posing health risks to astronauts. The prolonged microgravity environment also impacts psychological and physical health, necessitating comprehensive onboard resources for mitigation. Additionally, HTO's dependence on the specific alignment of Earth and Mars, occurring every 26 months, restricts launch scheduling flexibility.

For human missions, HTO represents a trade-off between minimising fuel consumption and addressing the challenges of extended travel and infrequent launch opportunities. The pursuit of faster transfer orbits and advanced propulsion technologies is driven by the need to overcome these limitations, aiming to make Mars journeys safer and more viable. Fast Transits, as these alternatives are known, seek to significantly shorten travel time, enhancing the feasibility of manned Mars expeditions.

Alternative propulsion technologies

Fast Transits to Mars involve trajectories that are more energy-intensive than the Hohmann Transfer but can cut the travel time to Mars by several months. This reduction is crucial for crewed missions, as it minimises the time astronauts are exposed to cosmic radiation and the detrimental effects of microgravity on the human body. One of the most promising technologies for achieving Fast Transits is the development of advanced propulsion systems.

Nuclear Thermal Propulsion (NTP) (Borowski et al. 2012) can potentially double the efficiency of traditional chemical rockets, allowing for quicker travel times. By heating a propellant like hydrogen with a nuclear reactor, NTP provides a higher specific impulse, which is a measure of propulsion efficiency. As of 2023, no working prototypes were constructed, however, NASA and DARPA have already announced a partnership to create such engines (Hall 2023).

Electric Propulsion, also known as ion or plasma propulsion, is a technology that accelerates ions to create thrust. While it offers a much higher specific impulse than chemical propulsion, its lower thrust levels make it more suitable for cargo missions or as a supplement to other propulsion methods on crewed flights (Dankanich et al. 2010).

Solar Sails uses the pressure of sunlight to propel a spacecraft. Although the acceleration is gradual, over time it can reach high speeds without expending propellant. The concept is new neither to science nor to fiction. In 1865 Jules Verne possibly was the first to describe such a machine in *From the Earth to the Moon*. When talking about the motion of projectiles and planets, he writes "there will someday appear velocities far greater than these, of which light or electricity will probably be the mechanical agent" (Verne 1865). The concept was first tested in 2010 during the successful IKAROS mission after the probe deployed its 20 m-span solar sail (Tsuda et al. 2011).

Free-return trajectory

If our focus is fuel efficiency – and we do not intend to land on Mars – we can also consider free-return trajectories. A free-return trajectory is a path that takes a spacecraft to Mars and back to Earth without requiring significant propulsion manoeuvres for the return journey. This type of trajectory was famously used during the Apollo 13 mission to safely return the crew to Earth (Cass 2005) and is considered a potential safety feature for Mars missions. Although this trajectory might not be ideal for landing crewed missions, for sample returns and resupply missions it should prove to be useful. If we wish to land on Mars using a free-return trajectory, the mission duration would increase significantly as the crew would be forced to wait 550 days until the vehicle circles back to Mars (Landau–Longuski 2004).

The Hohmann Transfer Orbit with a free-return trajectory to Mars would involve launching at a time when the spacecraft can loop around Mars and use its gravity to redirect back to Earth. This "slingshot" effect would allow the spacecraft to return without additional propulsion, providing a built-in abort option should the mission encounter critical issues en route to Mars.

Free-return trajectories, while providing an added safety net for space missions, come with their own set of limitations. A notable drawback is the increased travel time; these trajectories are longer than direct transfers, resulting in a prolonged duration in outer space. Specifically, a mission on a free-return path could spend approximately 530 days continuously in interplanetary space (Donahue–Duggan 2022). Another significant constraint is the limited launch windows. The precise alignment required between Earth and Mars for a free-return trajectory severely limits the number of suitable launch opportunities, with such an opportunity arising only once every 15 years. Additionally, these trajectories offer reduced flexibility; once a mission is committed to a free-return path, there is limited scope to adjust the timeline or alter mission objectives, which can be a critical factor in mission planning and execution.

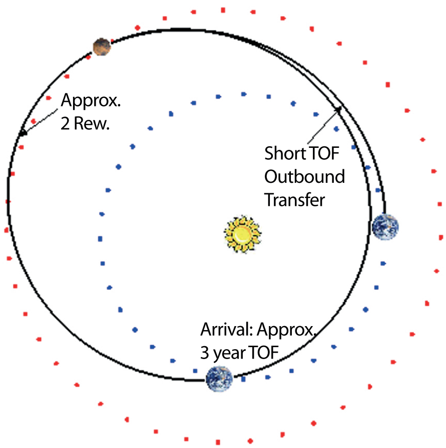

Figure 3
Mars free-return trajectory
Source: Landau – Logunski 2004

In conclusion, while the Hohmann Transfer Orbit remains a viable and efficient route to Mars, the evolution of space travel necessitates the consideration of Fast Transits. These alternatives offer the potential for faster journeys, increased safety, and the pioneering spirit required to push the boundaries of human space exploration.

OBSTACLES OF GETTING TO MARS

Embarking on a voyage to Mars transcends the bounds of human exploration, venturing into realms fraught with challenges both known and unforeseen. This section delves into the myriad obstacles and solutions intrinsic to interplanetary travel, examining the formidable barriers of cosmic radiation, micrometeoroids and the life-sustaining intricacies of advanced life support systems.

The risks and dangers of micrometeoroids

Micrometeoroids, the tiny fragments of rock and metal dispersed throughout our solar system, pose a significant threat to space missions due to their high velocity and ubiquitous presence. Originating from comets, asteroids and the debris left over from the formation of planetary systems, these particles, often no larger than a grain of sand, travel at speeds exceeding tens of kilometres per second (Friichtenicht 1964). This immense velocity endows them with formidable kinetic energy, transforming these seemingly innocuous specks into perilous projectiles in the vacuum of space.

The risk they present is not merely theoretical; numerous spacecraft have borne the brunt of micrometeoroid impacts, most notably, in its two decades, the International Space Station (ISS) has sustained over 1,400 micrometeoroid and orbital debris (MMOD) strikes (Hyde et al. 2019).

Figure 4
MMOD impact on the window of ISS Zvezda Service Module
Source: Riley 2016

Micrometeoroid impacts are inevitable. It is imperative that spacecraft designs incorporate protective measures to ensure that vital life support systems and the astronauts themselves are safeguarded by the craft's outer shell or even by the array of scientific instruments onboard. Given the potential for damage, regular spacewalks may become a routine yet crucial aspect of the mission, allowing astronauts to inspect and address any impairments caused by these cosmic assailants.

Leveraging the ISS's MMOD shielding techniques, future crewed Mars missions could adopt similar protective measures. Key among these is the "Stuffed" Whipple (SW) shield, an advanced version of the standard Whipple shield, comprising an outer aluminium bumper, a non-metallic intermediate layer and an inner rear wall. This design is particularly effective in areas prone to higher MMOD impacts, such as a spacecraft's forward and lateral sections. For

Mars missions, optimising the standoff distance between these layers, typically between 10 and 30 cm on the ISS, will be crucial in balancing protection with spacecraft design constraints and launch vehicle capacities (Christiansen et al. 2009).

Radiation in interplanetary space

Space radiation presents a formidable challenge for Mars-bound astronauts. Unlike the relative safety provided by Earth's magnetic field and atmosphere, space offers no such protection, exposing travellers to a relentless barrage of cosmic rays and solar radiation.

Cosmic rays, originating from distant supernovae and other astrophysical phenomena (Drury 2012), consist of high-energy particles that can penetrate deep into both spacecraft and human tissue. Solar radiation, emanating from our own Sun, also contains these charged particles (Parker 1965) and includes a spectrum of harmful emissions.

These radiations not only pose a risk to the physical health of astronauts, through increased cancer risk and potential damage to the central nervous system (Simonsen et al. 2020) but also threaten the integrity of spacecraft electronics and materials.

Addressing the risks posed by space radiation is a critical component of mission planning for Mars. The development of effective shielding is a primary focus, with researchers exploring materials and technologies that can absorb or deflect these high-energy particles. Innovations such as water-based shielding, where water tanks or supplies double as a protective barrier (Adamo–Logan 2016), new composite materials or even mini-magnetospheres (Bamford et al. 2014) are at the forefront of this research. Beyond physical barriers, mission planners also strategise to minimise exposure time, particularly during periods of intense solar activity (Simonsen–Nealy 1991).

Life support and sustenance

In the context of a Mars mission, life support and sustenance are critical components that ensure the survival and well-being of astronauts (Wieland 1994). The life support system on a spacecraft bound for Mars must be robust and largely self-sustaining, capable of recycling air, water and possibly even waste.

Advanced systems for air revitalisation and water recovery are essential. These systems must efficiently recycle carbon dioxide back into oxygen and purify water from various sources, including humidity from the air and astronauts' waste. The technology used on the ISS, such as the Environmental Control and Life Support System (ECLSS) (Brown–Tobias 2020), provides a foundation, but these systems will need enhancements for the longer duration and greater autonomy required for Mars missions.

Sustenance for Mars missions poses unique challenges due to the extended duration and limited cargo capacity. Traditional methods of storing food for space missions, which rely on pre-packaged meals, may not be viable for the longer Mars missions (Obrist et al. 2019). Instead, research is being directed towards more sustainable solutions, such as growing food in space (Salisbury 1999). Hydroponic and aeroponic systems are being explored for this purpose (Oluwafemi 2018). These systems must be energy-efficient, require minimal resources, and be capable of growing a variety of nutritious foods to meet the dietary needs of astronauts.

Future Mars missions may also see the implementation of more advanced life support technologies. Concepts like bioregenerative life support systems (Fu et al. 2016), which use biological processes to recycle waste and produce food and oxygen, are being studied. These systems could potentially create a more Earth-like environment, aiding not just in physical health but also in psychological well-being.

LANDING ON MARS

Entry, descent and landing

The Entry, Descent and Landing (EDL) phase of a Mars mission is fraught with challenges, due to delay in communication and the thin Martian atmosphere. This atmosphere is thick enough to generate significant heat during entry, necessitating robust heat shields, yet too thin for conventional parachutes to slow a spacecraft sufficiently for a safe landing (Huang 2020). This paradox has led to the development of innovative EDL technologies.

Aerobraking, a technique where the spacecraft uses the Martian atmosphere to slow down, plays a crucial role (Luo–Topputo 2021). The spacecraft's heat shield must withstand extreme temperatures during this high-speed entry (Edquist et al. 2014). Following aerobraking, parachute deployment is the next critical step. However, given the thin atmosphere of Mars, parachutes alone cannot decelerate the spacecraft to safe landing speeds. This limitation has spurred the development of retro propulsion techniques (Korzun et al. 2008), where rockets are fired in the opposite direction of travel to further reduce speed.

The Sky Crane manoeuvre, successfully employed by NASA's Curiosity (Way et al. 2007) and Perseverance (Maki et al. 2020) rovers, exemplifies the innovative solutions to these challenges. In this manoeuvre, a rocket-powered descent stage lowers the rover on cables to the surface, allowing for a controlled and precise landing even in rough terrain. This technique, while complex, has proven effective in safely delivering payloads to specific Martian locations.

The advent of reusable rockets, such as SpaceX's Starship, represents a significant shift in how we approach crewed missions to Mars. Unlike previous missions that relied on sky cranes for precision landing, the Starship envisions a direct, rocket-powered descent onto the Martian surface. SpaceX's participation in NASA's Artemis program, which aims to return humans to the Moon, will serve as a vital testing ground for the capabilities of Starship.

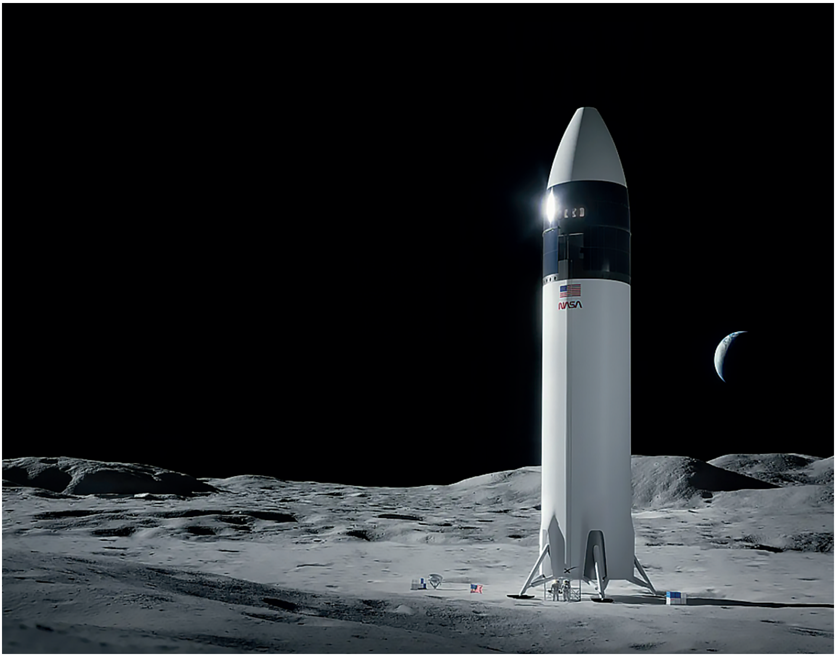

Figure 5
Artist's concept of SpaceX's Human Landing System on the surface of the Moon
Source: NASA 2022

In 2021 NASA and SpaceX signed a contract (NASA 2021) to develop and manufacture the Starship Human Landing System (HLS) and conduct a test flight and a crewed mission. The lunar missions will provide essential data on the performance of the Starship in extraterrestrial landing and launch scenarios, directly informing its adaptation for Mars missions.

The concept of precision landing by rocket propulsion was tested on 19 January 2024 by the Japan Aerospace Exploration Agency (JAXA). Their Smart Lander for Investigating Moon (SLIM) lander touched the Lunar surface 55 m East of the targeted landing site proving the capability of such technology (JAXA 2024).

Suitable landing sites

Selecting suitable landing sites on Mars is a complex process that involves balancing scientific interests with practical considerations. Key factors include terrain analysis, availability of water ice, access to solar energy, dust storm patterns and the site's overall accessibility.

Terrain analysis is crucial for ensuring a safe landing and operation of the mission. Sites must be flat and at a low altitude to facilitate a safe landing and provide a stable base for operations. The presence of water ice is a significant factor, as it not only offers potential resources for sustaining human life but also for fuel production.

One such landing area, the Vernal crater area in Arabia Terra, presents a compelling case as a landing site for future human exploration (Pajola et al. 2022). Its geological richness, evidenced by the presence of ancient hot springs, aeolian ridges and a diverse bedrock stratigraphy, offers significant exobiological interest. The site's high water equivalent hydrogen content (Wilson et al. 2018) suggests abundant in-situ resources like water ice and hydrated minerals (Stamenković 2019), crucial for sustaining human presence and potential in-situ resource utilisation. Additionally, its equatorial location ensures optimal surface temperatures and solar flux, making it not only scientifically intriguing but also practically viable for long-term human exploration.

Previous landing sites, such as those of InSight (Golombek et al. 2020) and Viking missions, offer valuable insights into Martian conditions and potential resources. These sites have been thoroughly studied, providing a wealth of data that can inform future missions.

Pre-deployment of supplies

In Mars exploration, the debate between pre-deploying assets versus carrying everything on the mission is pivotal. Pre-deploying habitats and supplies can reduce risk and cargo requirements for crewed missions, allowing for more scientific equipment or redundancy systems. This kind of mission planning will be tested in NASA's Artemis program on the lunar surface (Smith et al. 2020).

However, this approach relies heavily on successful prior missions and in-situ resource utilisation for long-term sustainability. Conversely, carrying all necessary supplies and equipment offers greater mission flexibility and immediate self-sufficiency but demands significantly higher cargo capacity and advanced logistics planning. Balancing these approaches is key to ensuring the success and safety of Mars missions.

COMMUNICATION AND CONNECTION WITH EARTH

The challenges of time delay

The communication between Earth and Mars is subject to significant time delays, varying from a few minutes to over twenty minutes one-way, depending on the relative positions of the two planets. This delay poses unique challenges, especially when compared to lunar missions where the delay is negligible. For instance, the Apollo missions to the Moon benefited from near real-time communication, allowing for immediate ground support in decision-making. In contrast, Mars missions, such as the autonomous landings of rovers, must rely heavily on pre-programmed systems and autonomy in decision-making due to the delay (Wong et al. 2002).

This time delay was most dramatically illustrated during the "seven minutes of terror" (NASA Jet Propulsion Laboratory 2012) – the time it takes for a probe to enter the Martian atmosphere and land on the surface, all occurring without real-time intervention from Earth. During this period, the spacecraft must autonomously execute a series of complex manoeuvres, as any command from Earth would arrive too late to be of use.

To address these challenges, missions to Mars employ various time delay protocols and asynchronous communication strategies (Bhasin et al. 2001). These include extensive pre-mission programming, robust autonomous systems capable of making critical decisions independently (Harris et al. 2019), and the use of 'if–then' logic to handle different scenarios that the spacecraft might encounter. This approach ensures that despite the communication lag, missions can proceed safely and effectively, albeit with a greater reliance on the spacecraft's onboard systems and less on real-time inputs from mission control.

Current communication technologies with Martian probes

Current communication with Mars probes relies on NASA's Deep Space Network (DSN) (Rogstad et al. 2005), a global array of large antennas providing the vital link for data transmission to and from distant spacecraft. Mars rovers, such as Curiosity and Perseverance, primarily communicate with Earth through orbiters, acting as relays. This system enhances the data rates achievable, compared to direct rover-to-Earth communication, which is limited by the rovers' smaller antennas and lower power.

The DSN supports high-bandwidth communication, essential for transmitting large volumes of scientific data, including high-resolution images and detailed instrument readings. However, the data rates are still relatively modest, constrained by the vast distance between Mars and Earth and the current limitations of radio-frequency technology.

The applicability of these communication technologies to crewed missions is a subject of ongoing research and development (Cesarone et al. 2007). While the existing infrastructure has served robotic missions effectively, the demands of a crewed mission, including higher data rates for more complex operations and the need for more consistent and reliable communication, will necessitate enhancements to the current system. This could involve the deployment of more powerful orbiters around Mars or the development of new communication technologies to ensure a robust and continuous link with a crewed spacecraft.

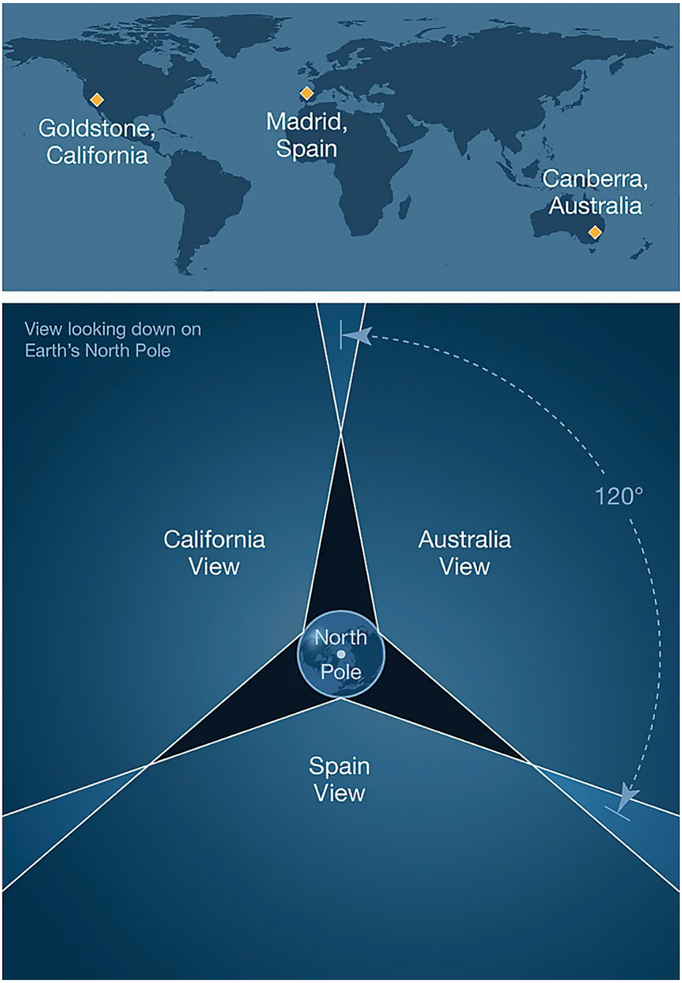

Figure 6
NASA's Deep Space Network consists of three strategically placed radio arrays to minimise blind spots
Source: NASA 2023a

Satellites and continuous communication

Continuous communication with Mars is challenged by the orbital dynamics of Earth and Mars, leading to periods when direct communication is almost impossible due to solar conjunction (Morabito–Hastrup 2002) when the Sun lies directly between the two planets. This event occurs approximately every 26 months and can last for about two to three weeks, during which communication with Mars missions is severely limited or entirely paused to avoid interference from the Sun's corona (Pätzold et al. 2012).

To address this, a network of orbiters placed into the L4 and L5 points of the Sun–Mars system equipped with advanced communication technology could provide continuous data relay and coverage (Breidenthal et al. 2018), ensuring a stable communication link even during solar conjunction. These orbiters would need to be strategically positioned to maintain a line of sight with both the Martian surface and Earth, overcoming the bandwidth limitations and logistical challenges posed by the vast distance.

For emergency communication protocols during solar conjunction, alternative strategies such as pre-programmed autonomous operations for Mars-based assets and the use of redundant communication systems are essential. These measures would ensure that missions can continue to operate safely and effectively, even when direct communication with Earth is not possible (NASA 2023b). The implementation of such a comprehensive communication infrastructure would be a significant step towards ensuring the safety and success of future crewed missions to Mars.

CONCLUSIONS

The endeavour to send humans to Mars represents a paradigm shift in our cosmic aspirations, encompassing a broad spectrum of technological, physiological and logistical challenges. This study has systematically dissected the multifarious elements that underpin such a mission, elucidating the nuanced interplay between advanced propulsion systems, life support technologies and interplanetary communication strategies.

Foremost in this venture is the evolution of launch vehicles, exemplified by SpaceX's Starship Heavy or China's Long March 9. This innovation in rocketry not only signifies a leap towards more sustainable space travel but also redefines our approach to interplanetary missions, positioning Mars as an attainable destination. The shift towards reusability and cost-effectiveness in these vehicles reflects a broader transformation in space exploration philosophy, aligning with the imperatives of long-term sustainability and accessibility.

Trajectory planning to Mars highlights a critical balance between efficiency and safety. While traditional paths like the Hohmann Transfer Orbit offer fuel efficiency, the exploration of Fast Transit trajectories – enabled by advancements in propulsion technologies such as Nuclear Thermal Propulsion and Electric Propulsion – opens avenues for reduced travel times and enhanced crew safety.

Addressing the hazards of micrometeoroids and cosmic radiation involves a confluence of engineering prowess and innovative shielding solutions. These protective measures not only safeguard spacecraft integrity but also ensure the well-being of astronauts, underlining the mission's human-centric focus. Similarly, the development of sophisticated life support systems, encompassing air revitalisation and water recovery, demonstrates a commitment to creating sustainable and habitable environments in space.

The complexity of Mars landings necessitates a fusion of aerobraking, retropropulsion and precision landing technologies, underscoring the intricate engineering required for successful extraterrestrial touchdowns. Moreover, the strategic selection of landing sites integrates scientific objectives with practical considerations, highlighting the meticulous planning inherent in these missions.

Finally, the study emphasises the imperative of robust communication systems to overcome the challenges posed by interplanetary time delays. The advancement of communication technologies and strategies is pivotal in ensuring continuous and reliable contact with Earth, an essential aspect of mission safety and success.

In conclusion, this study affirms that crewed Mars missions are not merely feats of engineering and science but are emblematic of humanity's enduring quest for knowledge and exploration. As we edge closer to realising this monumental goal, the journey to Mars stands as a testament to human ingenuity, resilience and the unyielding spirit of discovery.

Acknowledgement

N. O. Sz. thanks the financial support provided by the undergraduate research assistant program of Konkoly Observatory. He also acknowledges the support and assistance of his supervisor and scientific lector, László L. Kiss. The author acknowledges that ChatGPT was used to optimise the structuring of the article and the flow of the English text, but the content of it is solely the work of the author.

REFERENCES

Adamo, D. R. – Logan, J. (2016): Aquarius, a Reusable Water-based Interplanetary Human Spaceflight Transport. *Acta Astronautica,* 128, 160–179. Online: https://doi.org/10.1016/j.actaastro.2016.07.026

Bamford, R. A. – Kellett, B. – Bradford, J. – Todd, T. N. – Benton, M. G., Sr. – Stafford-Allen, R. – Alves, E. P. – Silva, L. – Collingwood, C. – Crawford, I. A. – Bingham, R. (2014): An Exploration of the Effectiveness of Artificial Mini-Magnetospheres as a Potential Solar Storm Shelter for Long Term Human Space Missions. *Acta Astronautica,* 105(2), 385–394. Online: https://doi.org/10.1016/j.actaastro.2014.10.012

Beil, A. (2023): How Chang Zheng 9 arrived at the "Starship-like" design. *NASA Space Flight,* 27 April 2023. Online: www.nasaspaceflight.com/2023/04/cz-9-update/

Berg, H. E. – Tesch, P. A. (1998): Force and Power Characteristics of a Resistive Exercise Device for Use in Space. *Acta Astronautica,* 42(1–8), 219–230. Online: https://doi.org/10.1016/S0094-5765(98)00119-2

Bhasin, K. – Hayden, J. – Agre, J. R. – Clare, L. P. – Yan, T.-Y. (2001): *Advanced Communication and Networking Technologies for Mars Exploration.* 19th International Communications Satellite Systems Conference and Exhibit, Toulouse, France. Online: https://ntrs.nasa.gov/citations/20010091011

Borowski, S. K. – McCurdy, D. R. – Packard, T. W. (2012): *Nuclear Thermal Propulsion (NTP): A Proven Growth Technology for Human NEO/Mars Exploration Missions.* 2012 IEEE Aerospace Conference, Big Sky, MT, USA. 1–20. Online: https://doi.org/10.1109/AERO.2012.6187301

Breidenthal, J. – Jesick, M. – Xie, H. – Lau, C.-W. (2018): *Deep Space Relay Terminals for Mars Superior Conjunction.* 2018 SpaceOps Conference, Marseille, France, 28 May – 1 June. Online: https://doi.org/10.2514/6.2018-2424

Brown, C. A. – Tobias, B. (2020): *History, Current Operations and Management of Water Systems on the International Space Station.* 16th International Conference on Space Operations, Cape Town, South Africa, 18–22 May 2020. Online: https://ntrs.nasa.gov/api/citations/20200010347/downloads/20200010347.pdf

Cass, S. (2005): Apollo 13, We Have a Solution: Part 2. *IEEE Spectrum,* 1 April 2005. Online: https://spectrum.ieee.org/apollo-13-we-have-a-solution-part-2

Cesarone, R. J. – Abraham, D. S. – Deutsch, L. J. (2007): Prospects for a Next-Generation Deep-Space Network. *Proceedings of the IEEE,* 95(10), 1902–1915. Online: https://doi.org/10.1109/JPROC.2007.905043

Chambers, P. (1999): *Life on Mars. The Complete Story.* London: Blandford.

Christiansen, E. L. – Nagy, K. – Lear, D. M. – Prior, T. G. (2009): Space Station MMOD Shielding. *Acta Astronautica,* 65(7–8), 921–929. Online: https://doi.org/10.1016/j.actaastro.2008.01.046

Dankanich, J. – Vondra, B. – Ilin, A. (2010): *Fast Transits to Mars Using Electric Propulsion.* 46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 25–28 July 2010. Online: https://doi.org/10.2514/6.2010-6771

Donahue, B. – Duggan, M. (2022): *The 2033 Crew Mars Flyby Mission.* 2022 IEEE Aerospace Conference, Big Sky, MT, USA. 1–16. Online: https://doi.org/10.1109/AERO53065.2022.9843408

Drury, L. O'C (2012): Origin of Cosmic Rays. *Astroparticle Physics,* 39–40, 52–60. Online: https://doi.org/10.1016/j.astropartphys.2012.02.006

Edquist, K. T. – Hollis, B. R. – Johnston, C. R. – Bose, D. – White, T. R. – Mahzari, M. (2014): Mars Science Laboratory Heat Shield Aerothermodynamics: Design and Reconstruction. *Journal of Spacecraft and Rockets,* 51(4), 1106–1124. Online: https://doi.org/10.2514/1.A32749

ESA (2004): *Water and Methane Maps Overlap on Mars: A New Clue?* Online: www.esa.int/Science_Exploration/Space_Science/Mars_Express/Water_and_methane_maps_overlap_on_Mars_a_new_clue

Fomina, E. V. – Lysova, N. Y. – Kukoba, T. B. – Grishin, A. P. – Kornienko, M. B. (2017): One-Year Mission on ISS Is a Step Towards Interplanetary Missions. *Aerospace Medicine and Human Performance,* 88(12), 1094–1099. Online: https://doi.org/10.3357/AMHP.4847.2017

Friichtenicht, J. F. (1964): Micrometeoroid Simulation Using Nuclear Accelerator Techniques. *Nuclear Instruments and Methods,* 28(1), 70–78. Online: https://doi.org/10.1016/0029-554X(64)90351-9

Fu, Y. – Li, L. – Xie, B. – Dong, C. – Wang, M. – Jia, B. – Shao, L. – Dong, Y. – Deng, S. – Liu, H. – Liu, G. – Liu, B. – Hu, D. – Liu, H. (2016): How to Establish a Bioregenerative Life Support System for Long-Term Crewed Missions to the Moon or Mars. *Astrobiology,* 16(12), 925–936. Online: https://doi.org/10.1089/ast.2016.1477

Golombek, M. – Warner, N. H. – Grant, J A. – Hauber, E. – Ansan, V. – Weitz, C. M. – Williams, N. – Charalambous, C. – Wilson, S. A. – DeMott, A. – Kopp, M. – Lethcoe-Wilson, H. – Berger, L. – Hausmann, R. – Marteau, E. – Vrettos, C. – Trussell, A. –Folkner, W. – Le Maistre, S. – Mueller, N. – Grott, M. – Spohn, T. – Piqueux, S. –Millour, E. – Forget, F. – Daubar, I. – Murdoch, N. – Lognonné, P. – Perrin, C. –Rodriguez, S. – Pike, W. T. – Parker, T. – Maki, J. – Abarca, H. – Deen, R. – Hall, J. –Andres, P. – Ruoff, N. – Calef, F. – Smrekar, S. – Baker, M. M. – Banks, M. – Spiga, A. – Banfield, D. – Garvin, J. – Newman, C. E. – Banerdt, W. B. (2020): Geology of the InSight Landing Site on Mars. *Nature Communications,* 11(1). Online: https://doi.org/10.1038/s41467-020-14679-1

Hall, L. (2023): NASA, DARPA Partner with Industry on Mars Rocket Engine. *NASA,* 26 July 2023. Online: www.nasa.gov/technology/nasa-darpa-partner-with-industry-on-mars-rocket-engine/

Harris, A. – Teil, T. – Schaub, H. (2019): *Spacecraft Decision-Making Autonomy Using Deep Reinforcement Learning.* 29th AAS/AIAA Space Flight Mechanics Meeting, Hawaii. Online: https://hanspeterschaub.info/Papers/Harris2019.pdf

Heldmann, J. L. – Marinova, M. M. – Lim, D. S. S. – Wilson, D. – Carrato, P. – Kennedy, K. – Esbeck, A. – Colaprete, T. A. – Elphic, R. C. – Captain, J. – Zacny, K. – Stolov, L. – Mellerowicz, B. – Palmowski, J. – Bramson, A. M. – Putzig, N. – Morgan, G. – Sizemore, H. – Coyan, J. (2022): Mission Architecture Using the SpaceX Starship Vehicle to Enable a Sustained Human Presence on Mars. *New Space,* 10(3), 259–273. Online: https://doi.org/10.1089/space.2020.0058

Hohmann, W. (1925): *Die Erreichbarkeit der Himmelskörper: Untersuchungen über das Raumfahrtproblem.* Berlin: Oldenbourg Wissenschaftsverlag. Online: https://doi.org/10.1515/9783486751406

Huang, D. Z. – Avery, P. – Farhat, C. – Rabinovitch, J. – Derkevorkian, A. – Peterson, L. D. (2020): Modeling, Simulation and Validation of Supersonic Parachute Inflation Dynamics during Mars Landing. *AIAA Scitech 2020 Forum,* 6–10 January 2020. Online: https://doi.org/10.2514/6.2020-0313

Hyde, J. L. – Christiansen, E. L. – Lear, D. M. (2019): *Observations of MMOD Impact Damage to the ISS.* International Orbital Debris Conference. Online: www.ho:u.usra.edu/meetings/orbitaldebris2019/orbital2019paper/pdf/6001.pdf

JAXA (2024): Outcome for the Smart Lander for Investigating Moon (SLIM)'s Moon Landing. *JAXA,* 25 January 2024. Online: https://global.jaxa.jp/press/2024/01/20240125-1_e.html

Kelly, S. (2017): *Endurance. My Year in Space, a Lifetime of Discovery.* New York: Vintage.

Korzun, A. M. – Cruz, J. R. – Braun, R. D. (2008): *A Survey of Supersonic Retropropulsion Technology for Mars Entry, Descent, and Landing.* 2008 IEEE Aerospace Conference, Big Sky, MT, USA. 1–15. Online: https://doi.org/10.1109/AERO.2008.4526290

Kramer, M. (2023): SpaceX's Starship could transform the space industry. *Axios,* 18 April 2023. Online: www.axios.com/2023/04/18/spacex-starship-transform-industry

Landau, D. – Longuski, J. (2004): *A Reassessment of Trajectory Options for Human Missions to Mars.* AIAA/AAS Astrodynamics Specialist Conference and Exhibit, 16–19 August 2004. Online: https://doi.org/10.2514/6.2004-5095

Letourneau, Jonathan (2021): *Every Mission to Mars in One Visualization*. Online: www.visualcapitalist.com/cp/every-mission-to-mars/

Loehr, J. A. – Lee, S. – English, K. L.– Sibonga, J. – Smith, S. M. – Spiering, B. A. – Hagan, R. D. (2011): Musculoskeletal Adaptations to Training with the Advanced Resistive Exercise Device. *Medicine and Science in Sports and Exercise,* 43(1), 146–156. Online: https://doi.org/10.1249/MSS.0b013e3181e4f161

Lowell, P. (1908): *Mars as the Abode of Life.* New York: Macmillan.

Luo, Z.-F. – Topputo, F. (2021): Mars Orbit Insertion Via Ballistic Capture and Aerobraking. *Astrodynamics,* 5, 167–181. Online: https://doi.org/10.1007/s42064-020-0095-4

Mader, T. H. – Gibson, C. R. – Pass, A. F. – Kramer, L. A. – Lee, A. G. – Fogarty, J. – Tarver, W. J. – Dervay, J. P. – Hamilton, D. R. – Sargsyan, A. – Phillips, J. L. – Tran, D. – Lipsky, W. – Choi, J. – Stern, C. – Kuyumjian, R. – Polk, J. D. (2011): Optic Disc Edema, Globe Flattening, Choroidal Folds, and Hyperopic Shifts Observed in Astronauts after Long-duration Space Flight. *Ophthalmology,* 118(10), 2058–2069. Online: https://doi.org/10.1016/j.ophtha.2011.06.021

Maki, J. – Gruel, D. – McKinney, C. – Ravine, M. A. – Morales, M. – Lee, D. – Willson, R. – Copley-Woods, D. – Valvo, M. – Goodsall, T. – McGuire, J. – Sellar, R. G. – Schaffner, J. A. – Caplinger, M. A. – Shamah, J. M. – Johnson, A. E. – Ansari, H. – Singh, K. – Litwin, T. – Deen, R. – Culver, A. – Ruoff, N. – Petrizzo, D. – Kessler, D. – Basset, C. – Estlin, T. – Alibay, F. – Nelessen, A. – Algermissen, S. (2020): The Mars 2020 Engineering Cameras and Microphone on the Perseverance Rover: A Next-Generation Imaging System for Mars Exploration. *Space Science Reviews,* 216. Online: https://doi.org/10.1007/s11214-020-00765-9

Morabito, D. – Hastrup, R. (2002): *Communicating with Mars During Periods of Solar Conjunction.* Proceedings, IEEE Aerospace Conference, Big Sky, MT, USA. Online: https://doi.org/10.1109/AERO.2002.1035260

NASA (2010): Final Minutes of Curiosity's Arrival at Mars. *NASA,* 19 July 2010. Online: www.nasa.gov/image-article/final-minutes-of-curiositys-arrival-mars/

NASA (2017): Mariner 9. *NASA,* 20 December 2017. Online: https://science.nasa.gov/mission/mariner-9/

NASA (2021): As Artemis Moves Forward, NASA Picks SpaceX to Land Next Americans on Moon. *NASA,* 16 April 2021. Online: www.nasa.gov/news-release/as-artemis-moves-forward-nasa-picks-spacex-to-land-next-americans-on-moon/

NASA (2022): *About Human Landing System.* Online: www.nasa.gov/reference/human-landing-systems/

NASA (2023a): Deep Space Network. *NASA,* 18 July 2023. Online: https://science.nasa.gov/learn/basics-of-space-flight/chapter18-1/

NASA (2023b): NASA's Mars Fleet Will Still Conduct Science While Lying Low. *NASA,* 10 November 2023. Online: https://mars.nasa.gov/news/9512/nasas-mars-fleet-will-still-conduct-science-while-lying-low/

NASA Communications (2020): NASA's Perseverance Rover Will Carry First Spacesuit Materials to Mars. *NASA,* 28 July 2020. Online: www.nasa.gov/centers-and-facilities/johnson/nasas-perseverance-rover-will-carry-first-spacesuit-materials-to-mars/

NASA Jet Propulsion Laboratory [@NASAJPL] (2012): 7 Minutes of Terror: The Challenges of Getting to Mars. *YouTube,* 22 June 2012. Online: www.youtube.com/watch?v=Ki_Af_o9Q9s

NASA JPL (2010): NASA's Odyssey Spacecraft Sets Exploration Record on Mars. *NASA,* 25 April 2011. Online: https://web.archive.org/web/20110425065346/http://mars.jpl.nasa.gov/odyssey/news/whatsnew/index.cfm?FuseAction=ShowNews&NewsID=1091

NASA JPL (2012): In-situ Exploration and Sample Return: Entry, Descent, and Landing. *NASA,* 13 April 2012. Online: https://mars.nasa.gov/mer/mission/technology/edl/

NASA JPL (2019): Mars Global Surveyor. *NASA,* 7 September 2019. Online: https://mars.nasa.gov/mars-exploration/missions/mars-global-surveyor/

NASA JPL (2021): NASA's Ingenuity Mars Helicopter Succeeds in Historic First Flight. *NASA,* 19 April 2021. Online: www.nasa.gov/news-release/nasas-ingenuity-mars-helicopter-succeeds-in-historic-first-flight/

NASA JPL (2022): InSight Top Science Results. *NASA,* 8 December 2022. Online: https://mars.nasa.gov/insight/mission/science/results/

NASA JPL – Caltech (2014): *Hohmann Transfer Orbit.* Online: https://mars.nasa.gov/maven/multimedia/images/index.cfm?ImageID=6042

Obrist, M. – Tu, Y. – Yao, L. – Velasco, C. (2019): Space Food Experiences: Designing Passenger's Eating Experiences for Future Space Travel Scenarios. *Frontiers in Computer Science,* 1(3). Online: https://doi.org/10.3389/fcomp.2019.00003

Oluwafemi, F. A. – De La Torre, A. – Afolayan, E. M. – Olalekan-Ajayi, B. M. – Dhital, B. – Mora-Almanza, J. G. – Potrivitu, G. – Creech, J. – Rivolta, A.

(2018): Space Food and Nutrition in a Long Term Manned Mission. *Advances in Astronautics Science and Technology,* 1, 1–21. Online: https://doi.org/10.1007/s42423-018-0016-2

Pajola, M. – Pozzobon, R. – Silvestro, S. – Salese, F. – Rossato, S. – Pompilio, L. – Munaretto, G. – Teodoro, L. – Kling, A. – Simioni, E. – Lucchetti, A. – Tornabene, L.L. – Marinangeli, L. – Tangari, A. C. – Wilson, J. – Cremonese, G. – Massironi, M. – Thomas, N. (2022): Geology, In-Situ Resource-Identification and Engineering Analysis of the Vernal Crater Area (Arabia Terra): A Suitable Mars Human Landing Site Candidate. *Planetary and Space Science,* 213. Online: https://doi.org/10.1016/j.pss.2022.105444

Pappalardo, J. (2023): Starship's Fiery Crash Was Still a Win for the Future of Spaceflight. Here's Why. *National Geographic,* 20 April 2023. Online: www.nationalgeographic.com/science/article/spacex-starship-rocket-launch-space-elon-musk

Parker, E. N. (1965): The Passage of Energetic Charged Particles Through Interplanetary Space. *Planetary and Space Science,* 13(1), 9–49. Online: https://doi.org/10.1016/0032-0633(65)90131-5

Patel, Z. S. – Brunstetter, T. J. – Tarver, W. J. – Whitmire, A. M. – Zwart, S. R. – Smith, S. M. – Huff, J. L. (2020): Red Risks for a Journey to the Red Planet: The Highest Priority Human Health Risks for a Mission to Mars. *Npj Microgravity,* 6. Online: https://doi.org/10.1038/s41526-020-00124-6

Pätzold, M. – Hahn, M. – Tellmann, S. – Häusler, B. – Bird, M. K. – Tyler, G. L. – Asmar, S. W. – Tsurutani, B. T. (2012): Coronal Density Structures and CMEs: Superior Solar Conjunctions of Mars Express, Venus Express, and Rosetta: 2004, 2006, and 2008. *Solar Physics,* 279, 127–152. Online: https://doi.org/10.1007/s11207-012-9991-y

Perminov, V. G. (1999): *The Difficult Road to Mars. A Brief History of Mars Exploration in the Soviet Union.* Washington, D.C.: NASA History Division Office of Policy and Plans and Office of Space Science.

Riley, H. R. (2016): Micrometeoroids and Orbital Debris (MMOD). *NASA,* 14 June 2016. Online: www.nasa.gov/centers-and-facilities/white-sands/micrometeoroids-and-orbital-debris-mmod/

Rocket Lab (2019): *The World's First Reusable Orbital Small Rocket.* Online: www.rocketlabusa.com/launch/reusable-rockets/

Rogstad, D. H. – Mileant, A. – Pham, T. T. (2005): *Antenna Arraying Techniques in the Deep Space Network*. Hoboken: John Wiley & Sons.

Salisbury, F. B. (1999): Chapter 5 Growing Crops for Space Explorers on the Moon, Mars, or in Space. *Advances in Space Biology and Medicine,* 7, 131–162. Online: https://doi.org/10.1016/S1569-2574(08)60009-X

Schiaparelli, G. V. (1878): *Osservazioni astronomiche e fisiche sull'asse di rotazione e sulla topografia del pianeta Marte fatte nella Reale Specola di Brera in Milano coll'equatoriale di Merz durante l'opposizione del 1877*. Roma: Atti della R. Accademia dei Lincei, Memorie della Classe di Scienze Fisiche, Matematiche e Naturali.

Simonsen, L. C. – Nealy, J. E. (1991): Radiation Protection for Human Missions to the Moon and Mars. *NASA Technical Paper,* (3079). Online: https://ntrs.nasa.gov/api/citations/19910008686/downloads/19910008686.pdf

Simonsen, L. C. – Slaba, T. C. – Guida, P. – Rusek, A. (2020): NASA's First Ground-based Galactic Cosmic Ray Simulator: Enabling a New Era in Space Radiobiology Research. *PLOS Biology,* 18(5). Online: https://doi.org/10.1371/journal.pbio.3000669

Slack, K. J. – Williams, T. J. – Schneiderman, J. S. – Whitmire, A. M. – Picano, J. J. (2016): *Evidence Report: Risk of Adverse Cognitive or Behavioral Conditions and Psychiatric Disorders*. Online: https://humanresearchroadmap.nasa.gov/Evidence/reports/BMED.pdf

Smith, M. – Craig, D. – Hermann, N. – Mahoney, E. – Krezel, J. – McIntyre, N. – Goodliff, K. (2020): *The Artemis Program: An Overview of NASA's Activities to Return Humans to the Moon*. 2020 IEEE Aerospace Conference, Big Sky, MT, USA. 1–10. Online: https://doi.org/10.1109/AERO47225.2020.9172323

Smith, S. M. – Zwart, S. R. – Heer, M. (2015): *Evidence Report: Risk Factor of Inadequate Nutrition*. Online: https://humanresearchroadmap.nasa.gov/Evidence/other/Nutrition-20150105.pdf

SpaceX [@SpaceX] (2023): Starship Flight Test. *YouTube,* 20 April 2023. Online: www.youtube.com/watch?v=-1wcilQ58hI

Squyres, S. W. et al. (2004): The Opportunity Rover's Athena Science Investigation at Meridiani Planum, Mars. *Science,* 306(5702), 1698–1703. Online: https://doi.org/10.1126/science.1106171

Stamenković, V. et al. (2019): The Next Frontier for Planetary and Human Exploration. *Nature Astronomy,* 3, 116–120. Online: https://doi.org/10.1038/s41550-018-0676-9

Stuster, J. (2010): *Behavioral Issues Associated with Isolation and Confinement: Review and Analysis of Astronaut Journals.* Online: https://ntrs.nasa.gov/citations/20100026549

Tsuda, Y. – Mori, O. – Funase, R. – Sawada, H. – Yamamoto, T. – Saiki, T. – Endo, T. – Kawaguchi, J. (2011): Flight Status of IKAROS Deep Space Solar Sail Demonstrator. *Acta Astronautica,* 69(9–10), 833–840. Online: https://doi.org/10.1016/j.actaastro.2011.06.005

Verne, J. (1865): *De la Terre à la Lune.* Paris: Pierre-Jules Hetzel.

Washam, E. (2010): Cosmic Errors: Martians Build Canals. *Smithsonian Magazine,* December 2010. Online: www.smithsonianmag.com/science-nature/Cosmic-Errors.html?c=y&page=2

Way, D. W. – Powell, R. W. – Chen, A. – Steltzner, A. D. – San Martin, M. A. – Burkhart, P. D. – Mendeck, G. F. (2007): *Mars Science Laboratory: Entry, Descent, and Landing System Performance.* 2007 IEEE Aerospace Conference, Big Sky, MT, USA. 1–19. Online: https://doi.org/10.1109/AERO.2007.352821

Wei, Y. – Zhang, Y. (2019). The Simulation and the Calculation of the Shortest Hohmann Transfer Orbit to Mars. *Journal of Applied Mathematics and Physics,* 7, 2384–2400. Online: https://doi.org/10.4236/jamp.2019.710162

Wieland, P. O. (1994): *Designing for Human Presence in Space: An Introduction to Environmental Control and Life Support Systems.* National Aeronautics and Space Administration, Office of Management, Scientific and Technical Information Program. Alabama, Marshall Space Flight Center.

Wilson, J. T. – Eke, V. R. – Massey, R. J. – Elphic, R. C. – Feldman, W. C. – Maurice, S. – Teodoro, L. F. A. (2018): Equatorial Locations of Water on Mars: Improved Resolution Maps Based on Mars Odyssey Neutron Spectrometer Data. *Icarus,* 299, 148–160. Online: https://doi.org/10.1016/j.icarus.2017.07.028

Wong, E. – Masciarelli, J. – Singh, G. (2002): *Autonomous Guidance and Control Design for Hazard Avoidance and Safe Landing on Mars.* AIAA Atmospheric Flight Mechanics Conference and Exhibit, 5–8 August 2012. Online: https://doi.org/10.2514/6.2002-4619

Zwart, S. R. – Launius, R. D. – Coen, G. K. – Morgan, J. L. L. – Charles, J. B. – Smith, S. M. (2014): Body Mass Changes During Long-Duration Spaceflight. *Aviation Space and Environmental Medicine,* 85(9), 897–904. Online: https://doi.org/10.3357/ASEM.3979.2014

Ákos Kereszturi[1]

The Challenges of Human Presence on the Surface of Mars

The human presence on the surface of Mars poses many challenges for the planned expeditions *(Figure 1),* the most important are: compensating for the unpleasant environmental parameters, providing conditions for life maintenance and various further needs, satisfying technical and engineering needs, and achieving scientific and other exploration objectives. In addition, the maintenance of optimal social relations and morale of the crew, in addition to maintaining communication with the Earth must also be realised. These aspects are considered below, and please note that some specific aspects might fit into several of the themes presented.

UNPLEASANT ENVIRONMENTAL PARAMETERS

The conditions on the surface of Mars are unpleasant compared to those on Earth, but still significantly better than those characteristic in space. There is no single aspect of the Martian human presence that poses such a difficulty that cannot be overcome, but there is still a wide range of needs for improvement in various methods and technologies. In addition to durable and reliable operation, small devices that can be easily repaired are preferably done on Mars, and most critical devices need back-ups that can be activated during the mission in case of failure of one of them, or they are in parallel operation.

[1] Konkoly Thege Miklós Astronomical Institute, HUN-REN Research Centre for Astronomy and Earth Sciences; ORCID: https://orcid.org/0000-0001-6420-510X; e-mail: kereszturi.akos@csfk.org

DOI: https://doi.org/10.36250/01209_14

Figure 1
Artist's concept of a future manned Mars surface base
Source: NASA 2019

Main difficulties

- *Low* atmospheric *pressure:* the surface air pressure on Mars is about 1% of that on Earth, so the pressure conditions on the Martian surface are similar to those on Earth at an altitude of about 40 km above the ground. The pressure varies between 4 and 6 mbar in a day and also shows a seasonal variation of about a factor of two, as up to a third of the atmospheric carbon dioxide freezes out on the polar icecap in the winter hemisphere. The low atmospheric pressure is physiologically very uncomfortable, and correspondingly higher pressures must be maintained in the habitat and inside the spacesuit during the fieldwork. In the space suit it is possible to reduce the pressure modestly, but only gradually, to avoid astronauts getting "decompression sickness".
- The *temperature* is also very low at the surface, varying between about +10 and –120 °C, even on a daily cycle. The minimum around –120 °C would probably be very rare at the planned low-latitude landing sites.

The extreme coldness favours atmospheric carbon dioxide precipitation, and this frost can be technically damaging to some external equipment – but this is also something to be prepared for because such extremely low temperatures can rarely occur at low latitudes in the second half of cold nights, occasionally creating low-temperature carbon dioxide ice patches (Hargitai et al. 2021). Nevertheless, establishing and maintaining the right temperature is not a major challenge, even in the spacesuit of the astronauts.

- *The main component of the atmosphere is CO2,* which does not pose a major challenge, as astronauts breathe the oxygen produced or recirculated on site. Atmospheric gas does not cause a chemical problem either, as it does not react with the external surfaces of various equipment. However, it can be used as an important source of materials (see the ISRU section below).
- The Martian surface is generally *dry* (about 0.1% relative humidity during the day, but rarely <100% at night), which is also "pleasant" from a chemical point of view, as it rarely causes reactions on the surface of the outer units, and frost formation is rare on the planet. At the same time, atmospheric vapour could be an easy source of H_2O for on-site acquisition, but its concentration is generally very low.
- The *regolith is chemically aggressive* due to the peroxides and hyperoxides it contains. This partly causes chemical corrosion of external surfaces, but is also harmful to health, like the metal content in regolith. All this would not be a problem if grains and dust of the regolith never enter the human body, but when manned work is carried out outside the spacecraft regularly, the outer surface of the spacesuits should not come into contact with the interior of the habitat. (A similar unpleasant situation was experienced by the astronauts during the Apollo space expedition, because the lunar dust was also chemically unpleasant, irritating the astronauts' noses and eyes after they entered the Lunar Module with the spacesuit.) The current idea for solving the Martian situation is to keep the spacesuits hanging outside the habitat, and there will be a smooth surface metal or plastic door

at the back, the surface of which could be cleaned easily. This technical solution is a bit complicated but easily excludes the dust from the habitat interior. However, if an astronaut breaks her/his leg outdoors, it is much more difficult to climb out of the spacesuit.

- *UV radiation* is intense at the surface due to the rare atmosphere and the lack of an ozone layer. This is dangerous to health but can be shielded by using a suitable UV filter, for example by covering the visor window of the helmet with it. The external surfaces of the various technical units can also be slightly damaged by UV radiation, which can be avoided by appropriate surface treatment or proper selection of materials. It is possible that UV radiation may have contributed to the deterioration of the wheels of Curiosity together with the rough surface (Arvidson et al. 2017).
- One of the most dangerous environmental effects on the surface of Mars is the *ionising charged particle radiation,* which mainly consists of protons and alpha particles from the solar wind (more common but lower energy component), and larger nuclei from galactic cosmic rays (less common but higher energy component). The Earth's surface is protected against these particles mainly by the global magnetosphere of our planet, with the atmosphere also contributing to a smaller amount. The dose of such charged particles at the surface of Mars varies significantly over time *(Figure 2),* partly as a function of the solar cycle (which sometimes releases fewer or more charged particles and also lets more or less galactic origin particles to the inner parts of the solar system). For protection against ionising radiation, a layer of rock (or a slightly thinner layer of solid metal) nearly a metre thick is adequate. For comparison, a 500-day stay outdoors on the surface of Mars is roughly equivalent to 100 years of exposure on the International Space Station. Accordingly, an almost metre thick radiation shielding above the habitation unit provides full protection. This shielding material is not worth transporting from Earth because of its great mass, but in practice, it could be created from local materials. This shield could be produced of excavated regolith material and consolidated grains, which are built up by robotic machines before

the astronauts are even arrived – but it is also possible to put the habitat in a cave, which is also suitable for radiation protection. The latter can provide additional weight reduction: in this case, a particularly strong and solid habitat unit is not needed, and an inflatable unit can be placed there, with the shape and size of the latter being much less constrained than for a solid unit. The consequences and management of ionising radiation are similar to those of an operating nuclear reactor on Earth, where the staff members have personal dosimeters and need to monitor their total radiation exposure continuously. Accordingly, there may be days (especially during the arrival of a coronal mass ejection cloud to Mars) when astronauts should not go out to the Martian surface from their safe habitat.

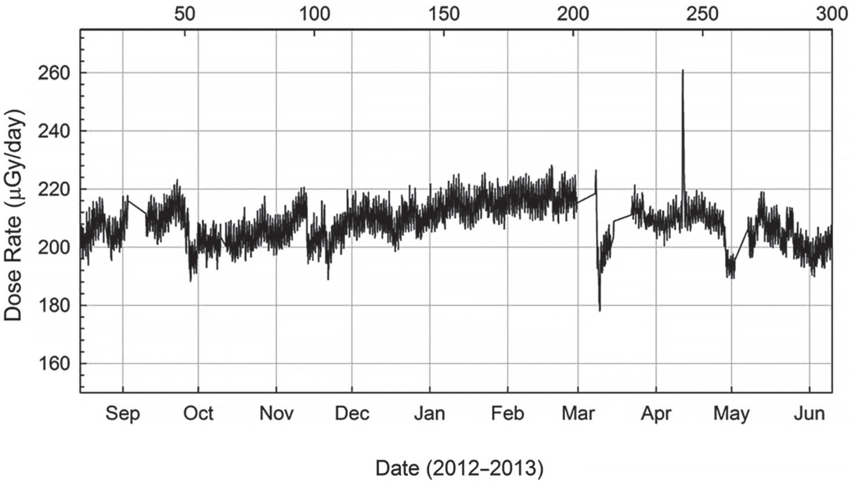

Figure 2
Data from the RAD instrument onboard the Curiosity rover showing the variation of the galactic cosmic rays mainly, and to a lesser extent the solar wind
Note: The vertical axis shows the microgravity/sun dose and the prominent peak marks the arrival of a large particle mass ejected from the Sun
Source: NASA/JPL-Caltech/SwRI 2013

Other hazards include dust storms, but these are likely to be able to pick up only very fine-grained dust. They can, however, corrode external surfaces and cause electrostatic charging. The main inconvenience here may be dust attached to the surfaces of external instruments.

SUSTAINING CONDITIONS FOR LIFE ON MARS

The main needs for life support can be outlined below. A key priority is to use as many local resources as possible, e.g. to avoid transporting most of the water or oxygen from Earth to Mars, which would increase the cost of the expedition enormously. Another important factor is to recycle as much of the materials used on Mars as possible. The energy needed for the activities listed below can be found in the chapter of this book entitled *Bon Voyage: Sources of Energy for Space Exploration and Its Current Regulatory Insights* authored by Zsolt Hetesi and Zsófia Biró.

An ideal, stable and safe environment can be maintained in an enclosed volume of space, known as a *habitat unit,* or simply HAB. Optimal HAB design solutions should combine radiation protection, exclusion of external toxic regolith, stable temperature and energy saving aspects. The whole system should be as self-sustaining as possible, and the "smart solutions" that are proliferating on Earth today are expected to help in optimising this *(Figure 3).* Continuous monitoring of the indoor environment should also include microbial conditions – as a single unpleasant bacteria can cause serious problems in the internal air or in systems that maintain the recirculation of fluids, food production, etc. The development of the necessary solutions relies heavily on ground trials, which have included the construction of solid, inflatable, site-built living units using local materials.

The main sites of such Earth-based analogue tests on habitation units are the Mars Desert Research Station (MDRS, Utah, desert region, USA) (Westenberg–Nelson 2010; Boros-Olah et al. 2009), the Flashline Mars Arctic Research Station (FMARS, Devon Island, Northern Canada) (Binsted et al. 2010), ESA's Concordia Station in Antarctica, where effects of isolation and health maintenance are tested, but also the extreme surrounding environment could be analysed (Napoli et al. 2022), and the Mars 500 experiment, an indoor experiment in Russia, partly to test group behaviour (Groemer–Ozdemir 2020). Useful experiments and developments have been carried out on board the International Space Station (ISS) on radiation exposure and physiology, as well as on the usability of human end-products, water recirculation and exhaled carbon dioxide sequestration.

In-Situ Research Utilization (ISRU) is a key element of the human Mars expedition. The idea is to bring as small mass and volume of material and equipment from Earth as possible and to produce as much as possible on Mars (in the same way we do not take drinking water, stored electricity or air with us when we travel abroad – but of course, the situation is different on Earth). Under ISRU activities, one needs to produce oxygen mainly for inhalation and also as fuel, drinking water, methane or hydrogen as fuel, as well as energy and some building materials on site. This significantly reduces the mass to be launched from Earth to Mars and the difficulty and the cost of the whole mission.

ISRU activities require the transport of sophisticated equipment from Earth but also use on-site raw materials to make the targeted products. It is also worth taking advantage of the fact that this production does not necessarily require human presence – for example, the fuel or other materials needed to lift off the Martian surface can already be produced by automated systems that landed before the arrival of the manned mission. The technology to do all this is not yet mature, but in theory and simpler experimental form, it has already been tested with several success in Earth based laboratories. In addition to the use of on-site resources, recycling and recirculation are of high importance (in this respect, the manned Mars expedition will be particularly environmentally friendly). The purification of used water will save energy and increase the security of the supply of the system, and the solid human end product will be valuable and useful as a "manure" resource to support crop production. The expedition will produce little waste, which is also important for the protection of the Martian environment and to ensure the representativity of the measurements there (free from terrestrial contamination).

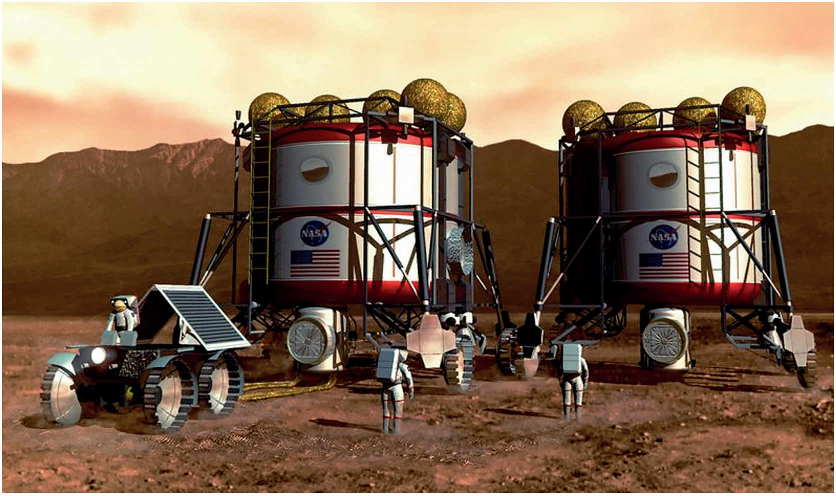

Figure 3
Artist's concept of landed habitation units on the surface of Mars
Source: Launius 2019

One of the important ISRU products is oxygen, which can be extracted from the atmospheric carbon dioxide or from water ice extracted on site. The most popular chemical method for producing oxygen from CO_2 is the Sabatier process (see below for methane production), but other electrolysis-based methods also exist. The instrument called MOXIE (Mars Oxygen In-Situ Resource Utilisation Experiment) has been successfully tested on the Perseverance rover on the Martian surface. The 17 kg, 30 cm long device produces oxygen by solid oxide electrolysis of atmospheric carbon dioxide at a rate of 5–6 g/hour, with an atmospheric gas inflow of 55 g/h. This amount produced in one hour is enough oxygen for a person for nearly 10 minutes, about the same level as the daily oxygen production of an average tree. Martian atmospheric gas is sucked in through a HEPA filter and compressed by a pump, heated to 800 °C and then sent through a solid oxide electrolysis (SOXE) unit, where CO_2 flows along nickel-based cathode and zirconium oxide ceramics to catalyse the separation of oxygen ions, which eventually got combined to form molecular oxygen. At the end of the process, CO_2, CO and inert atmospheric gases (N, Ar) are exhalated. MOXIE has been successfully operated under different conditions (day, night, lower and higher atmospheric pressure, different seasons). Its future larger version would start operating on the red planet before the human mission arrives to Mars and continue during the expedition. Among other oxygen production methods, biogenic ones are worth mentioning. For example, the bacterium Chroococcidiopsis cubana produces oxygen by reducing atmospheric CO_2 and is still cost-effective if the system is properly designed. Moreover, the microbe in question is highly resistant, requires little "protection" and can ideally produce oxygen equivalent to 40% of its body weight per day (Krings et al. 2023).

The production of water, which is needed for food processing, cooking and cleaning, in addition to drinking and maintaining the humidity of the air to breathe, is a priority. Martian river valleys have long been dried up (Hargitai et al. 2019; Steinmann et al. 2020), and atmospheric humidity is not significant on the planet. The term "water ore" is used in the literature to describe sites of interest for extraction, such as H_2O on Mars that are worth exploiting, both for processing and transport. The main on-site sources of H_2O are:

– Large amount of *ice or snow mass*: the most prominent of these are the permanent polar caps, but a manned base is expected to avoid the polar regions due to the very low temperatures there during winter nights, including the formation of a permanent CO_2 ice there. Below the polar caps, in a larger area especially in the south, the polar layered sediments contain a large mass of water ice and dust mixture – but even these are at very high latitudes. Outside the polar caps, important sites are the snow-ice masses buried at mid-latitudes. Beneath the thin dust and regolith cover, buried H_2O is more easily accessible in the 50°–70° latitude range, while ice masses in valleys and craters are covered by a thicker dry debris cover of about 10 m thick. A separate issue is whether the excavated H_2O should be transported for final usage. However, the cementation of the debris cover is not known, but the difficulty of accessing the underlying ice is primarily affected by the physical thickness of the dry cover.

- There are also *water-bearing minerals* on Mars, such as polyhydrated sulphates and phyllosilicates. Extracting water from them may generally require more effort than extracting buried ice masses, but these minerals may be more widespread, especially at lower latitudes, than buried H_2O masses. These minerals generally hold low H_2O contents, sometimes up to 8–10% (Milliken et al. 2007).
- There are several other ways to extract H_2O, including mining and processing of *permafrost* (frozen mixture of ice and rock debris), which may be present at shallow depths at high latitudes but can occur in deep regions at lower latitudes. However, permafrost is much harder than pure ice or hydrated minerals. Some H_2O can also be extracted from the generally dry atmosphere (Pal 2019), but only at a very small rate of about 1 kg H_2O from 200,000–300,000 m^3 of atmospheric gas, and accordingly, atmospheric origin is probably not an appropriate method for extracting H_2O. Despite some theoretical models and questionable observations by the MARSIS instrument onboard the Mars Express spacecraft, it is unlikely that there is currently any liquid groundwater on the planet.

Many technological aspects of extraction methods are under development. When comparing the occurrence of H_2O with the demand and supply potential, the most likely sources are buried snow or ice masses at mid-latitudes. One option for their acquisition is surface mining (after removal of the dry overburden), but in this case, the exploitation of water ice deepens and widens horizontally with extraction, while surface sublimation may also be a problem. Drilling assisted extraction would be more efficient and simpler when the overburden does not need to be removed. In this case, maintaining the heating and pressure needed to produce liquid water would be a fast but energy-intensive method while pumping the molten water. A more energy-efficient solution is dry hot gas flow downward, which involves sublimation of ice at depth and cold trapping of the outflowing water vapour at the surface. During exploitation, especially in shallow (1–2 m deep) cover, the decreasing subsurface H_2O mass will result surface subsidence over time, which must be taken into account. Any exploitation should also be used to obtain scientific data, as the ice is expected to contain paleoclimatic information.

In further processing, if H_2O is extracted from minerals, pulverisation and heating to an even higher temperature than mentioned above are required. Based on field and laboratory studies, extraction rates of the order of 100 kg/hour are realistic for an expedition of 4–6 people, while for soil processing a few kg/h are more likely – theoretically, the latter production rate may be sufficient to supply the crew, even including fuel production (Sanders 2016). In case of fuel processing (production of liquid hydrogen and oxygen), electrolysis of water and separation of the produced components is expected to take place under high pressure and low temperature (cryogenic) conditions for storage in the liquid phase. The distance between the H_2O mine, the processing plant and the final point of use of H_2O is also a factor, as the extracted material has to be transported if not recovered on site.

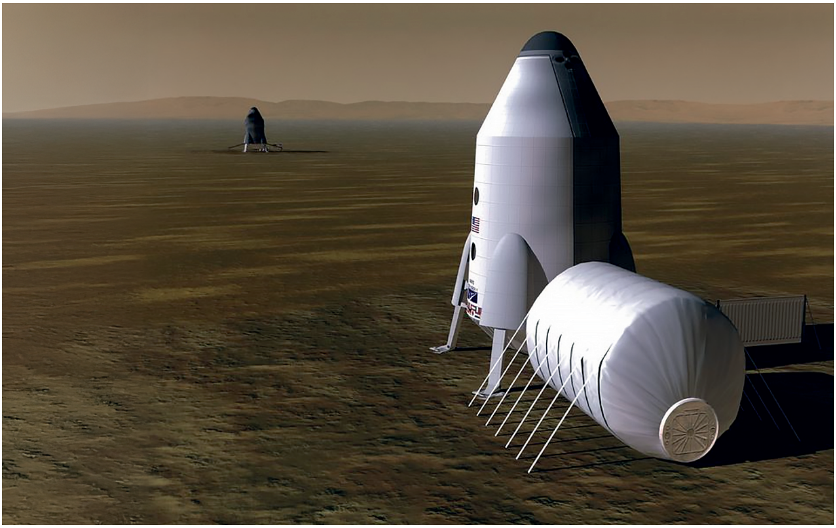

Figure 4
Artist's concept used to return from the surface of Mars, with an inflatable unit next to it and a fuel-producing unit in the distance
Source: NASA/JSC by John Frassanito and Associates 1997

Methane is mainly important as a fuel on Mars, both as a propellant for rockets *(Figure 4)* and for rovers or other surface and possibly airborne transport vehicles (although a mixture of liquid hydrogen and oxygen is more efficient as a rocket propellant, but methane is more easily used in rovers). Methane is currently present in the Martian atmosphere in very small and varying amount. There are no known local sources of methane that could be exploited in significant quantities – but the easiest way is to use atmospheric carbon dioxide. The most widely known and tested methane production method is the Sabatier process (Zlindra et al. 2021), where hydrogen is produced from atmospheric carbon dioxide using terrestrial hydrogen (or locally from H_2O by electrolysis) at temperatures of 300–400 degrees Celsius and elevated pressures (3 MPa) by the following reaction: $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2$ O can be recovered, but there is a low temperature electrolysis of CO_2–H_2O around 255 K that can support the production of both methane and oxygen (Shahid et al. 2022). The Sabatier process for methane production on Mars was proposed early on by Robert Zubrin (Zubrin et al. 1996).

By using local carbon-dioxide, sunlight and H_2O, a special group of cyanobacteria can produce sugars from the Martian atmosphere (under proper conditions but in the Martian open air also). Another group of bacteria converts these sugars into propellant, such as butanediol. However, the process is much slower than a chemical one, but requires only a third as much energy and roughly 3 times the equipment compared to a chemical one (Kruyer et al. 2021). Storage must be cold and pressurised, temperatures that are easier to maintain on Mars than on Earth. In addition to methane, other hydrocarbons have been proposed, such as methanol propane, which require additional or different processing (e.g. Fischer-Tropsch synthesis). Among them methane seems to be the simplest solution and the most "green" propellant. It is worth noting that the use of these materials as rocket fuel requires about twice as much oxygen as methane.

FOOD AND HEALTH ON MARS

Roughly about 1–2 kg of food per person per day is needed – it would be extremely expensive to transport all the food from Earth for a long expedition. The production of local solid nutrients can be done in greenhouses, but not necessarily in transparent foil tents exposed to sunlight, although growing plants with good radiation tolerance (good regeneration capacity) in inflatable, transparent but UV insulated tents would be promising. The selection of the vegetables produced should be based on high resistance (not only to possible unpleasant radiation conditions, but also to the nutrient and temperature–lighting conditions received) and high nutrient content. Among the "classical" crops, the cultivation of improved varieties is likely, as well as the cultivation and consumption of nutrients such as algae, which are not yet particularly popular, and of meat products of arthropods and molluscs. Although these are uncommon foods, being a good source of protein as rich as that of domesticated and familiar animal-based food.

A miniature ecosystem on Mars could also help to provide food, but also to convert carbon-dioxide into oxygen, process waste and purify water. The 43% of solar radiation that reaches the Mars compared to Earth is still abundant enough for photosynthesis. The creation of suitable soil is possible by cleaning and transforming the local regolith and supplementing it with special bacterial colonies of terrestrial origin – the resulting topsoil is not needed in large quantities inside the greenhouses. But some plants can also produce crops without conventional soil by their roots in a suitable nutrient solution (hydroponics) or by roots in humid air (aeroponics). Of course, such mini ecosystems could only be maintained with proper monitoring and regular intervention. Solutions to the difficulties encountered in the Biosphere 1 and 2 experiments on the Earth could be of great help (Nelson et al. 2008: 2199).

Figure 5
A greenhouse designed for crop production on the surface of Mars
Note: The natural light is supplemented by LED radiation, and the astronauts rarely visit the particle radiation-resistant genetically modified plant species, so the radiation total exposure is harmless to them
Source: Herridge 2016

An important aspect will be the reuse or repair of broken equipment – as little as possible should be thrown away. Protecting the Martin environment is also of high importance, so any waste should be stored hermetically or destroyed, including by bacterial decomposition, which can even provide a small amount of energy.

The most important health risks are the increased radiation exposure, lower gravity than on Earth, toxic substances in the regolith, and possible microbial infections in the confined internal volume of the habitat and spacesuits (Table 1).

Table 1.
Main biological and medical challenges and possible solutions on Mars

Topic	Difficulty	Possible solution
Ionising radiation	May be too large outdoors	Time-limited outdoor work, continuous dosimetry
Microbial balance in the housing unit	Unpleasant microbes can multiply	Continuous monitoring, chemical–biological intervention if necessary
Need for surgery	No specialist	Robotic surgery supported by artificial intelligence
Unexpected illness	Unknown illness, problematic diagnosis, missing drugs	Remote diagnosis and interpretation by Earth-based medical team, local microbial laboratory, pre-mission genetic screening of inclination
Accidents	Non movable persons, lack of experts	Specific safety protocols, robotic support

Source: Compiled by the author

Any diagnosis is supported by modern analytical instruments and methods, and by the detailed interpretation of chemical, biological and physiological test results sent to the Earth-based supporting team. There will be medicines to be carried by the astronauts, as well as surgical instruments that can be used in a modular way.

One of the problems of providing medical care on Mars missions is that it is not possible to return to Earth for specialised medical care, and the task has to be done with a small staff there. The currently planned crew of six is expected to have only one doctor or at most two. The Earth-based supporting team will therefore have a key role during the mission, including medical consultations – but active back-and-forth communication is subject to delays of around a quarter to a half hour due to the long distance. The most critical situations are likely to be the surgery actions that may be required, which, because of the time delays, cannot be easily performed by today's rapidly evolving remote robotic surgeons, but which could be supported in many ways by artificial intelligence and simulations, including microscale surgical procedures.

FURTHER TECHNICAL NEEDS

The technological challenges for working and sustaining life on Mars are wide-ranging, some of them have possibly concrete suggestions or even tested solutions, but most are not yet developed and put into practice – although there are no technical challenges that seem theoretically impossible – so almost all of them can be solved with the right development, but this requires concerted and sustained work and related funding.

Fuel is important for local transport. Here, oxygen, methane and hydrogen can be used as fuels, with the methane-oxygen mixture being used to power rovers and robots (including excavators and heavy machines to dig and transport regolith), while lower-powered equipment will presumably use electricity generated on the Martian surface. Fuel will also be needed to return to Mars orbit (from where, under most plans, the team will return to Earth via a space station there, or in a few plans the spacecraft will continue the way from the surface of Mars directly to Earth). The latter would, according to the models, require oxygen and methane, or a mixture of oxygen and hydrogen. In an ideal case, these would be produced locally.

Figure 6

Artist's concept of a field survey of a steep sedimentary sequence on the surface of Mars

Source: NASA/Pat Rawlings 1989 (https://www.humanmars.net/search/label/Pat Rawlings)

An important part of the expedition is the field work out on the surface of Mars *(Figure 6),* the so-called Extra Vehicular Activity (EVA). This requires a suitable spacesuit, which is technically feasible. Although today those used for EVA on the International Space Station are optimised for space, walking on the surface of Mars with even a rare atmosphere would be possible with slightly different (somewhat simpler) spacesuits. The main hazard of surface work is ionising radiation. Permanent protection is provided only by the habitation unit in the long term. However, it is the total radiation exposure suffered by the human body that counts. Therefore, work on the surface of the planet is safe up to a low level of total exposure. Accordingly, cumulated doses during the period spent outdoors should be monitored. It is estimated that several hours a day of outdoor work is sustainable in the long term, but on days of intense radiation (which can be estimated from space weather forecasts) astronauts should remain in the habitat unit.

Fieldwork will require a wide range of equipment, among them simpler ones can be carried by the astronaut, but there will also be more complex and heavy equipment, for example drilling equipment, excavators and equipment for repairing external units (Weidinger et al. 2008). It is expected that there will be also robots to assist with the more difficult operations. Presumably, all vehicles will be partially remote-controlled or autonomous, with some operations being carried out supported by autonomous methods.

Surface mobility will be provided by rovers *(Figure 7).* Among them the short-range ones will be open air vehicles, which can be used by astronauts in spacesuit. These vehicles will be used to transport heavy equipment, cover distances of 10–20 km quickly and can be controlled remotely. The closed-air cabin supported vehicles will allow longer surface expeditions, with astronauts spending the night in the vehicle and returning to the central habitation unit after days or weeks. A wide range of Mars analogue sites on Earth are suitable for testing surface operations, the tools and methods to be used, where the logistics of realisation can be developed, and targets similar to Mars can be analysed (Józsa–Bérczi 2004).

Figure 7
A ground copy of a manned vehicle developed for surface mobility on Mars as part of NASA's Desert Rats programme
Source: www.wikidata.org/wiki/Q4049635

Planetary protection for Mars has a dual purpose: on the one hand, Mars needs to be protected from living organisms originated form the Earth, including their dead remains and other contaminants from the terrestrial environment. All this would support the field studies carried out there, in particular some organic substances such as amino acids or proteins from the Earth would be highly misleading in the search for the possibility of life. On the other hand, planetary protection involves protecting the Earth's environment from samples and materials brought from Mars. The latter is close to the topics familiar from science fiction movies, in which a Martian "virus" or "disease" would destroy life on Earth. However, this is considered not realistic by experts (just as meteorites from Mars falling to Earth are not dangerous). Still, it should be avoided that terrestrial contaminants and organisms get into the samples from Mars and falsify the findings relevant to the red planet. The spacecraft to be sent to the surface of Mars are usually sterilised, which requires a very expensive procedure, and in the case of a human expedition, it is presumably not possible to completely isolate the Martian environment from human activity.

ADVANTAGES AND DISADVANTAGES

There is no doubt that human Mars travel requires huge resources and effort *(Figure 8)* – the question is what favours it and what is against its implementation. The main difficulty in getting there is the stable funding (Taylor 2010), which needs to be sustainable over a 10–20 years scale – longer than the typical average political lifetime of the leaders on research funding. The total cost could be in the order of USD 500–1,000 billion, and all this requires several large teams of scientists and engineers working jointly. It is interesting to compare the effort required to achieve a manned lunar landing. In the 1960s and 1970s there was a strong political will for manned lunar travel through the Cold War supporting the fast development and realisation. The Moon, on the other hand, is an order of magnitude closer – thus in contrast, all the units and equipment of a Mars mission must operate properly on yearly timescales, with no possibility of further supply from the Earth. However, there is no doubt that many of the planned tasks can be performed only with robots with much less money, less risk but with more time and less flexibility. However, the human conquest and "occupation" of extraterrestrial space by robots alone is not the same as the human expansion.

Figure 8
A fantasy sketch of a complex manned Mars base from the distant future, with a habitation unit, greenhouses, a flying drone, a surface mobility rover and a rocket about to take off
Source: NASA 2016

It is a big question what the long-term goals of mankind for the conquest and possible colonisation of Mars are. The creation of a permanent colony, as seen in science fiction films, would only be possible in the distant future. However, it is worth mentioning the topic of terraforming, which cover the process of making Mars 'Earth-like'. This idea also appears in science fiction, man would provide water by melting the ice cap, and by injecting carbon-dioxide trapped below the surface into the atmosphere, making the atmosphere denser and the greenhouse effect stronger and the surface temperature higher. However, the exact behaviour of a planet as an interacting system is not well known enough to adequately predict the impact of such a drastic action. It is not certain if a given intervention would produce the expected result, nor can it be predicted whether some unforeseen, possibly even more damaging consequence would emerge. Above all, operations considered under terraforming are in the category well beyond what humanity will be capable of in the next century.

It is also occasionally suggested in popular press that humanity might consider Mars as a "planet B" option, a place where humanity could move when Earth becomes uninhabitable or too unpleasant to live there. Even if we consider the expected cheaper space travel in the future, it is not realistic to put the population of even a single country to Mars, especially not all of humanity. It has to be accepted that Mars is a very valuable long-term option for humanity, but it cannot provide another habitable planet instead of Earth – it may only be transformed more habitable only as a result of the persistent work of a permanent Martian colony over many centuries or thousands of years, but even then, we cannot expect pleasant Earth-like conditions.

In conclusion, there does not seem to be any inevitable theoretical obstacle to the implementation of manned travel to Mars. However, it is also clear that a sustained and substantial investment is needed to carry out the first expedition, which will require, in addition to stable long-term funding, a permanent pool of experts to develop and test the system. This substantial investment will probably require not only the governmental sector but also other industrial and entrepreneurial partners, and sustained support from the general public – all in international cooperation.

THE IMPORTANCE OF MAKING MANNED MARS EXPEDITIONS

The key scientific questions that human expeditions can answer in 2023 are: to better understand the possibility of past or present life on Mars, to better understand the early evolution of Earth-like planets, to reconstruct the evolutionary history of the planet from ancient wet environment toward the current dry surface, thus better understand why its evolution has diverged gradually from those of Earth over time. An important question is the reason for launching a manned Mars expedition rather than exploration with robots only. Whereas the question of robot or human was the dominant one earlier, a scenario involving the joint activity of robot and human has emerged recently – indeed, no human expedition is currently planned without robots.

One of the main arguments in favour of human expeditions against robots (despite the many difficulties) is that a robot cannot (or can only do much less) development and realisation of unprogrammed procedures, apply completely new solutions, or even new tools by modifying available parts. Although artificial intelligence is developing rapidly, we cannot still make a robot with the creativity, expertise and flexibility of a well-trained human with many years of practical experience, capable of solving a wide range of problems. Another important group of arguments in favour of human expeditions over robots is that the significance of human expeditions is more than 'just' the scientific aspect: it is a huge step or leap in human history, motivated by the exploration and conquest of the unknown, going beyond the achievements and capabilities of our predecessors. From this point of view, difficulty can also be seen as trigger and motivation, as challenges lead to new discoveries and technical innovations. The logical way forward for humanity's development is to expand beyond our planet, which would not only enrich human knowledge, culture and history beyond measure, but would also increase the chances of survival of our species and human society. Of course, a human voyage to Mars would only be a small, early stage of such a long journey.

REFERENCES

Arvidson, R. E. – DeGrosse, P. – Grotzinger, J. P. – Heverly, M. C. – Shechet, J. – Moreland, S. J. – Newby, M. A. – Stein, N. – Steffy, A. C. – Zhou, F. – Zastrow, A. M. – Vasavada, A. R. – Fraeman, A. A. – Stilly, E. K. (2017): Relating Geologic Units and Mobility System Kinematics Contributing to Curiosity Wheel Damage at Gale Crater, Mars. *Journal of Terramechanics,* 73, 73–93. Online: https://doi.org/10.1016/j.jterra.2017.03.001

Binsted, K. – Kobrick, R. L. – Griofa, M. Ó. – Bishop, S. – Lapierre, J. (2010): Human Factors Research as Part of a Mars Exploration Analogue Mission on Devon Island. *Planetary and Space Science,* 58(7–8), 994–1006. Online: https://doi.org/10.1016/j.pss.2010.03.001

Boros-Olah, M. – Hargitai, H. – Hirsch, T. – Kereszturi, A. – Muhi, A. – Tepliczky, I. (2009): *HungaroMars2008: Analog Research in the Education of Planetary Science.* 40th Lunar and Planetary Science Conference. Online: www.lpi.usra.edu/meetings/lpsc2009/pdf/1492.pdf

Frassanito and Associates (1997): A Habitat on Mars. *NASA,* 1 July 1997. Online: https://science.nasa.gov/resource/a-habitat-on-mars/

Groemer, G. – Ozdemir, S. (2020): Planetary Analog Field Operations as a Learning Tool. *Front. Astronomy and Space Sciences,* 7. Online: https://doi.org/10.3389/fspas.2020.00032

Hargitai, H. (2021): *Model-Based Climate Zone Map and Climate Diagrams of Mars.* 52nd Lunar and Planetary Science Conference. Online: www.hou.usra.edu/meetings/lpsc2021/pdf/2102.pdf

Hargitai, H. – Gulick, V. C. – Glines, N. H. (2019): Evolution of the Navua Valles Region: Implications for Mars' Paleoclimatic History. *Icarus,* 330, 91–102. Online: https://doi.org/10.1016/j.icarus.2019.04.024

Herridge, L. (2016): NASA Plant Researchers Explore Question of Deep-Space Food Crops. *NASA,* 17 February 2016. Online: https://www.nasa.gov/science-research/nasa-plant-researchers-explore-question-of-deep-space-food-crops/

Józsa, S. – Bérczi, Sz. (2004): *Analog Sites in Field Work of Petrology: Rock Assembly Delivered to a Plain by Floods on Earth and Mars.* 35th Lunar and Planetary Science. Online: www.researchgate.net/publication/241469089_Analog_Sites_in_Field_Work_of_Petrology_Rock_Assembly_Delivered_to_a_Plain_by_Floods_on_Earth_and_Mars

Krings, S. – Chen, Y. – Keddie, J. L. – Hingley-Wilson, S. (2023): Oxygen Evolution from Extremophilic Cyanobacteria Confined in Hard Biocoatings. *Microbiology Spectrum,* 11(5). Online: https://doi.org/10.1128/spectrum.01870-23

Kruyer, N. S. – Realff, M. J. – Sun, W. – Genzale, C. L. – Peralta-Yahya, P. (2021): Designing the Bioproduction of Martian Rocket Propellant Via a Biotechnology-Enabled In Situ Resource Utilization Strategy. *Nature Communications,* 12. Online: https://doi.org/10.1038/s41467-021-26393-7

Milliken, R. E. – Mustard, J. F. – Poulet, F. – Jouglet, D. – Bibring, J.-P. – Gondet, B. – Langevin, Y. (2007): Hydration State of the Martian Surface as Seen by Mars Express OMEGA: 2. H_2O Content of the Surface. *Journal of Geophysical Research: Planets,* 112(E8). Online: https://doi.org/10.1029/2006JE002853

Launius, R. D. (2019): A Smithsonian Researcher Reflects on What It Will Take to Land Humans on Mars. *Smithsonian,* 31 January 2019. Online: https://www.smithsonianmag.com/smithsonian-institution/smithsonian-researcher-reflects-what-it-will-take-land-humans-mars-180971333/

Napoli, A. – Coleine, C. – Ulrich, N. J. – Moeller, R. – Billi, D. – Selbmann, L. (2022): Snow Surface Microbial Diversity at the Detection Limit within the Vicinity of the Concordia Station, Antarctica. *Life,* 13(1). Online: https://doi.org/10.3390/life13010113

NASA (2016): How a Solution for Mars Architecture Helped with Energy Efficiency in the Home. *NASA,* 21 July 2016. Online: https://www.nasa.gov/technology/tech-transfer-spinoffs/how-a-solution-for-mars-architecture-helped-with-energy-efficiency-in-the-home/

NASA (2019): First Humans on Mars (Artist's Concept). *NASA,* 12 June 2019. Online: https://www.jpl.nasa.gov/images/pia23302-first-humans-on-mars-artists-concept/Nelson, M. – Dempster, W. – Allen, J. P. (2008): *Carbon Dioxide Fixation and Respiration Relationships Observed During Closure Experiments in Biosphere 2.* 37th COSPAR Scientific Assembly. Online: www.researchgate.net/publication/241383398_Carbon_dioxide_fixation_and_respiration_relationships_observed_during_closure_experiments_in_Biosphere_2

Pal, B. (2019): *Global Distribution of Near-Surface Relative Humidity Levels on Mars.* 50th Lunar and Planetary Science Conference. Online: www.hou.usra.edu/meetings/lpsc2019/pdf/1831.pdf

Sanders, G. (2016): Mars Water Mining for Future Human Exploration. *NASA/JSC Press Release,* 13 January 2016.

Shahid, M. – Chambers, B. – Sankarasubramanian, S. (2022): Methane and Oxygen from Energy-Efficient, Low Temperature In Situ Resource Utilization Enables Missions to Mars. *AIChie Journal,* 69. Online: https://doi.org/10.1002/aic.18010

Steinmann, V. – Kereszturi, Á. – Mari, L. (2020): Geomorphological Analysis of Tinto-B Vallis on Mars. *Hungarian Geographical Bulletin,* 69(4), 333–348. Online: https://doi.org/10.15201/hungeobull.69.4.1

Taylor, F. (2010): *The Scientific Exploration of Mars.* Cambridge: Cambridge University Press.

Weidinger, T. – Istenes, Z. – Hargitai, H. – Tepliczky, I. – Bérczi, Sz. (2008): *Micrometeorological Station at the Mars Analog Field Work, Utah, April.* 40th Lunar and Planetary Science Conference. Online: www.researchgate.net/publication/238012830_Micrometeorological_Station_at_the_Mars_Analog_Field_Work_Utah_April_2008

Westenberg, A. – Nelson J. (2010): *The Mars Desert Research Station: Real Science, Real Education.* European Planetary Science Congress. Online: https://meetingorganizer.copernicus.org/EPSC2010/EPSC2010-895.pdf

Zlindra, A. – Schoen, D. – Mayer, F. – Shapiro, J. – Qazi, O. – Richmond, T. – Caleanu, N. – Adnani, Y. (2021): Development and Testing of Prototype Sabatier Reactor for Martian In Situ Propellant Production. In van Susante, P. J. – Dickason Roberts, A. (eds.): *Earth and Space 2021.* Reston: ASCE Press. 264–273. Online: https://ascelibrary.org/doi/10.1061/9780784483374.026

Zubrin, R. – Wagner, R. – Clarke, A. C. (1996): *The Case for Mars* (1st Touchstone ed.). [s. l.]: Free Press.

Humans have already visited the Moon. But how can we stay on other planets for long? Maybe even live there? Current lunar programs aim to establish bases on our celestial neighbour and there are plans for Mars or other planets. Opinions on such projects vary: just a dream, unnecessary, too expensive, too early, the only hope for humanity, an economic opportunity, the new military high-ground, and so on. This book does not claim to predict the future and settle the debate once and for all. Instead, the authors come from different scientific fields and offer a wide range of approaches. Psychology, medicine, engineering, architecture, law, settlement management, security, communications, robotics, planetary science, astronomy and many other disciplines will play a crucial role in realising the ambitious idea of humans settling and thriving on other planets. We hope the reader enjoys discovering the opportunities, dangers and challenges that await humanity in this new endeavour.

ISBN 978-963-653-139-3