SCIENTIFIC OPPORTUNITIES ENABLED BY HUMAN EXPLORATION BEYOND LOW-EARTH ORBIT

AN ISECG SCIENCE WHITE PAPER

ISECG
International Space Exploration Coordination Group

ABOUT ISECG

Space agencies participating in the International Space Exploration Coordination Group (ISECG) are discussing an international approach for human and robotic space exploration to achieve broad societal, intellectual and economic benefits. This document is a White Paper of scientific opportunities enabled by the presence of humans, and their supporting infrastructure, as they explore the Solar System, as documented in ISECG's Global Exploration Roadmap. The Science White Paper informs the evolution of the Global Exploration Roadmap. It was developed by ISECG agencies together with a Science Advisory Group, including representatives from the international science community and reflecting the views and inputs from an open interaction with this community.

ISECG was established to advance the Global Exploration Strategy by providing a non-binding forum where space agencies share their objectives and plans, and explore synergistic concepts. ISECG agencies are committed to the development of non-binding products that enable participating agencies to take concrete steps toward partnerships that reflect a globally coordinated exploration effort.

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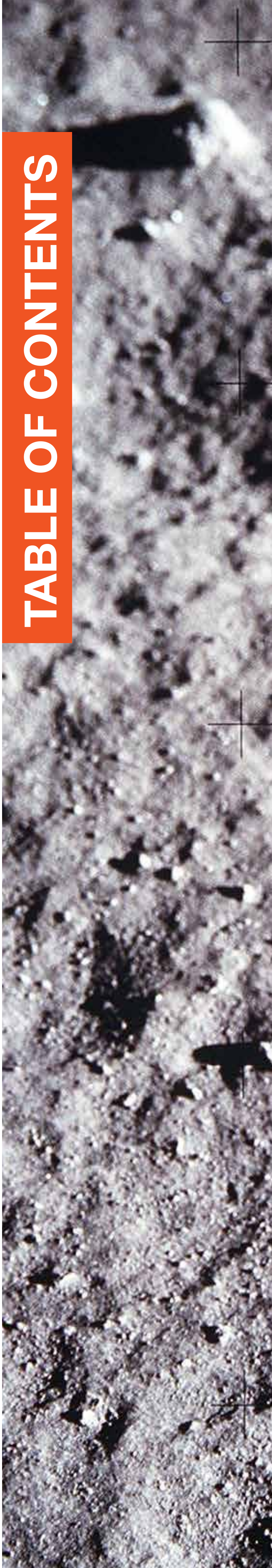

EXECUTIVE SUMMARY

The Global Exploration Roadmap reflects a coordinated international effort to prepare for space exploration missions beginning with the International Space Station and continuing to the lunar vicinity, the Moon, asteroids and Mars. These missions are part of an exploration endeavour available for pursuit by all space agencies, on their own or in collaboration with others. Human exploration drives innovation and economic expansion, addresses space and terrestrial challenges to improve life on Earth, and inspires people around the world. Integral to these benefits are scientific investigation and discovery.

The Scientific Imperative: Space exploration will result in scientific discoveries that have significance not only to the international science community but to humanity as a whole. Opportunities for scientific discovery associated with exploration missions are broadly captured in two themes: "Understanding Our Place in the Universe" and "Living and Working in Space".

> Understanding Our Place in the Universe: This theme is about discerning the physical nature of the Universe around us and our place within it. We want to understand the Earth-Moon system, asteroids and Mars and how they formed and developed. We will conduct new observations of the cosmos, including our own Earth. Finally, we will attempt to understand the formation and the evolution of life.
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> Living and Working in Space: This theme is reflecting the drive for humans to extend our reach into space, which also provides important scientific and technological advances to improve life on Earth. We want to learn more about how humans safely explore the Solar System, and reduce risks that humans face in space. We also want to learn about the local resources in our planetary neighbourhood, and how explorers can maximise the use of what we find around us.

The Next Step Beyond Low-Earth Orbit: The vicinity of the Moon is the ideal location as the next step in the expansion of human space activity from the International Space Station leading to investigations of the Moon, asteroids, and Mars. This deep space environment enables testing and validation of habitation systems and related operations techniques, while remaining close enough to Earth as we learn to manage exploration mission risks. Increasingly longer duration missions to a habitat in the deep space environment enable study of the interplay of radiation, microgravity and isolation on human health valuable for future spaceflight to more distant destinations, notably Mars, as well as health research applicable back on Earth. The infrastructure can support CubeSats and small satellites by providing services such as deployment and communication relay. It can facilitate remote controlled robotic exploration on the lunar surface. It can also be used for investigations in areas such as astronomy, fundamental physics, collecting interplanetary materials, and heliophysics.

The Lunar Surface: Scientific investigations, including collecting the right samples, on the Moon will improve our understanding of the origin and evolution of the Earth-Moon system, and of terrestrial planets in general. The Moon has experienced many of the geologic processes that have shaped the terrestrial planets in our Solar System (e.g. impact cratering, volcanism, tectonics, etc.). We can date impact events and decipher the impact flux for the Earth-Moon system over geologic time to better understand its role for the evolution or extinction of life on Earth. The lunar soil and subsurface also provide a historical repository of the Solar System's evolution. Human presence could permit the emplacement of delicate surface instrumentation on the lunar surface. Indeed, the far side of the Moon is unique in that it is "radio quiet", offering the opportunity for sensitive radio astronomy measurements that look back in time to the earliest moments of the Universe. Investigating the physiological response to working in reduced gravity on the lunar surface could help prepare for keeping humans healthy on the surface of Mars, whilst providing new insights into a range of human health issues for Earth.

Near-Earth Asteroids: Near-Earth asteroids exhibit considerable diversity within their population and they have witnessed events and conditions throughout the history of the Solar System. The presence of humans will permit placement of complex instruments on the asteroid surface, as well as the ability to sample surface and subsurface sites to obtain information on the ancient history of the Solar System which larger, evolved planetary bodies have lost. Carefully chosen samples by a trained explorer can also help us to better understand the thousands of meteorites we already have available for study by scientists, providing geologic context to meteorites that have formed much of the paradigm for the origin of the Solar System. We will also work to better understand the internal structures of Near-Earth Asteroids, a vital part of the puzzle needed in order to develop mitigation strategies for addressing threats from an Earth-bound asteroid.

Mars: Mars is the shared horizon goal driving sustainable human exploration. Mars has the greatest similarity to Earth in past and current planetary processes, and may have the best record of when life started in our Solar System and of catastrophic change in planetary evolution. Our robotic missions have shown that Mars has significant water that is promising for the possible existence of life (past and/or present) and supporting humans. Exploration of Mars will result in answers to profound scientific and philosophical questions such as: How did life start in our Solar System? Did life exist on Mars and does it exist today? What can we learn about Earth's past and future by studying Mars? Building on over 50 years of robotic-enabled science and eventually, sample return, human explorers on the surface of Mars will be critical to reveal the subtleties needed to answer these complex and fundamental questions. Humans will make possible intelligent sampling in geologic context, iterative environmental field investigations and sample preparation/analyses in a habitat-based laboratory. Humans will advance a multi-disciplinary set of scientific objectives, such as investigations into astrobiology, atmospheric science, medicine, and geoscience.

The Value of Human Explorers for Science: Human exploration brings the human element to the forefront of scientific discovery, bringing flexibility, adaptability, experience, dexterity, creativity, intuition, and the ability to make real time decisions. This was demonstrated by the Apollo missions to the lunar surface. While some science objectives can be achieved by suitably implemented robotic missions, many are greatly facilitated by a human presence, and some may even be wholly impractical otherwise.

- Humans can efficiently and intelligently select and collect samples from a diverse range of localities. Trained explorers will also provide a broader geological context due to integrated observations, thus returning the best samples to address specific science and exploration questions. In addition, human missions typically return larger amounts of samples per flight.

- Humans are uniquely capable of installing, maintaining, upgrading, and troubleshooting problems with complex scientific equipment, as historically exemplified with the Hubble telescope servicing missions.

- Humans can often achieve tasks faster than robots and act intelligently in exploratory science.

- As demonstrated by Apollo and on the International Space Station, humans are unique in their ability to recognize and to adapt their response to new observations or serendipitous discoveries.

In addition to scientific benefits, gaining operational experience in deep space or on a planetary surface is extremely beneficial for the later exploration of more distant targets, such as Mars.

Humans have long looked to the stars and asked, "What is out there?" Exploration, investigation, and scientific discovery are essential elements in the history of humanity, and the same will be true in our future. Human exploration missions significantly increase the potential for scientific discovery at the lunar vicinity, the Moon, asteroids, and Mars.

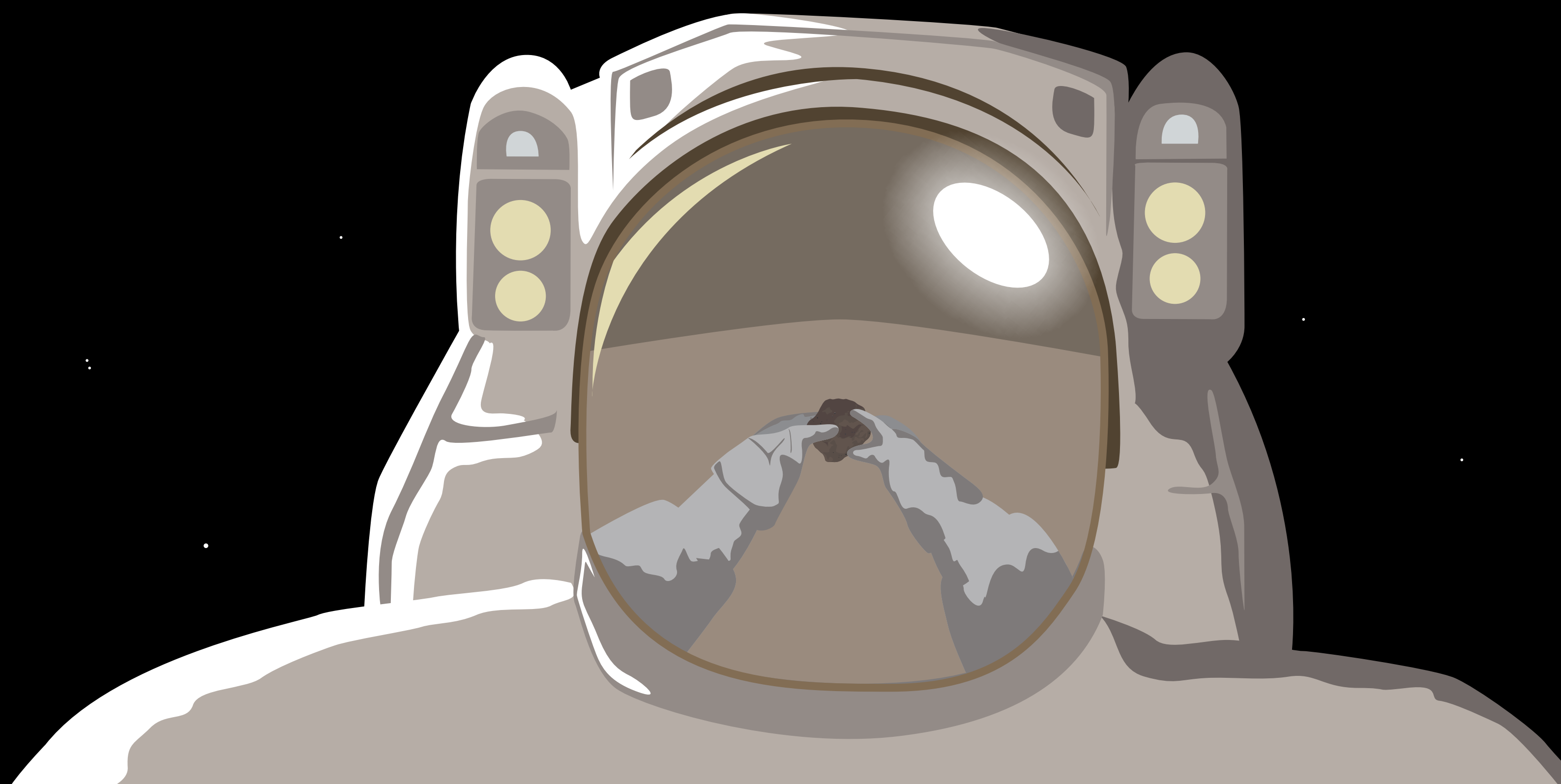


image courtesy of NASA

CHAPTER 1: INTRODUCTION

Purpose and Scope

Since its emergence over 50 years ago, space exploration has garnered significant governmental support across the world and established a profound legacy for all humankind. The resulting advances in science and knowledge have delivered invaluable improvements to the quality of life on Earth. Propelled by ongoing technology investments in the public and private sectors, the next steps include opportunities for human exploration beyond low-Earth orbit. The rapid progression of technologies and capabilities has enabled human and robotic explorers to generate even more new expertise and perspectives about our place in the Universe. The exploration of space is an engine of innovation and inspiration, and science continues to be an important part of this endeavour.

The International Space Exploration Coordination Group (ISECG) is examining a global approach for human and robotic space exploration that maximises societal, intellectual and economic benefits. The status of this work is documented in the ISECG Global Exploration Roadmap and the ISECG white paper, "Benefits Stemming from Space Exploration". The Global Exploration Roadmap reflects a coordinated global effort to prepare for collaborative space exploration missions beginning with the International Space Station (ISS) and continuing to the vicinity of the Moon, the lunar surface, asteroids and Mars.

This document highlights opportunities for scientific investigation related to humanity's greatest questions, created as humans explore the Solar System incrementally leading to exploration of Mars. The collaborative missions envisioned in the Global Exploration Roadmap will contribute to the achievement of many of these investigations, and participating agencies will determine the specific nature of scientific activities undertaken. This paper focuses on the science enabled by the near-term targets for human exploration: a gateway in the lunar vicinity, the lunar surface, and asteroids. A detailed study of science enabled by humans to Mars is left to a future white paper.

This paper discusses science enabled by the presence of humans and facilitated by the infrastructure associated with human exploration. The latter often enables "opportunistic science" by permitting measurements that would otherwise be less practical and/or affordable, and indeed might not occur. Additionally, the presence of humans may represent the capability to service or upgrade these instruments.

The scientific opportunities presented in this document reflect the collective views of a science community representing a variety of nations and science disciplines. An international Science Advisory Group closely linked to organizational structures of national agencies was chartered by ISECG to lead this engagement. The group requested inputs broadly, in coordination with the International Council for Science's Committee on Space Research (COSPAR) Panel for Exploration, NASA's Solar System Exploration Research Virtual Institute

Figure 1: From the earliest civilisations to the present day, it has always been part of human nature to explore the unknown. Throughout history, exploration has led to new scientific discoveries and transformed our way of living (Image courtesy of ESA)

(SSERVI), the European Science Foundation, and ISECG participating agencies.

Space agencies maintain individualized processes for defining the highest priority science questions for their specific programmes or communities. These approaches often include substantial and extended interactions with relevant science communities, resulting in a report that guides science exploration direction for a set time-period. This document does not refer to any single agency publication, nor define the scientific priority of specific activities; it draws from and builds upon the significant scientific reviews and individual agency interactions demonstrated in the reports listed in Appendix 1.

Global Space Exploration – the ISECG Global Exploration Roadmap

The ISECG Global Exploration Roadmap highlights participating agency efforts to prepare for human and robotic exploration of worlds that may someday support a continuous human presence. Sustainable, affordable, productive, and safe human exploration of the surface of Mars is a long-term, internationally shared objective that shapes the Global Exploration Roadmap. The pathway to the horizon goal of Mars informs capability evolution and technology investments, enabling human journeys to multiple destinations outlined further in the paper. We acknowledge that these targets (including Mars) offer various merits and benefits, and their prioritization may differ across agencies.

The Global Exploration Roadmap is a synergistic human and robotic space exploration roadmap that recognises the criticality of increased interplay between human and robotic missions, and supports the partnerships needed to implement human exploration missions beyond low-Earth orbit. This international and cooperative vision encourages multiple partners to play key roles, meet their national objectives, and achieve individual and shared scientific priorities. The strategy commences with low-Earth orbit activities including ISS utilisation and expands into the Solar System, eventually leading to human exploration of the Red Planet. The GER reflects a step-wise journey that advances critical human space exploration capabilities to accomplish a range of science and exploration objectives with human crews. The first steps of this integrated strategy are the focus of this paper, including missions within the near-term planning horizon. Space agencies currently are formulating these programmes and developing the necessary infrastructure for future implementation. Human mission planning will rely on direct observations acquired by robotic missions ("ground truth"), and create opportunities to leverage the unique contributions of human and robotic explorers.

The lunar vicinity, often referred to as cislunar space, is the strategy's next phase beyond low-Earth orbit. This region of deep space enables testing and affirmation of exploration capabilities and operations, in an environment near Earth that fosters experiential learning of the risks and challenges of spaceflight. The lunar vicinity is also an appropriate staging post for exploration missions to the Moon, asteroids and Mars. A driving objective for lunar vicinity missions is validation of the habitation capabilities that will keep humans safe and productive for the long duration missions beyond the Earth-Moon system, where the deep-space environment is dangerous and there are limited options for timely return to the Earth's surface in case of emergency. The current strategy calls for astronaut missions of increasing length conducted at a platform in the lunar vicinity. Internal and external volume and services will be available to science payloads. This infrastructure will also feature a communications relay terminal for interaction with assets on the lunar surface or in Earth-Moon space.

Human missions to the lunar surface could be enabled by a lunar lander that uses such cislunar infrastructure, while many robotic lander missions may also choose to go directly to the lunar surface.. A limited campaign of human missions to the lunar surface can contribute to addressing the highest priority science and exploration goals and allow agencies to advance and demonstrate capabilities needed for future missions (e.g., sampling and curation techniques, planetary protection protocols, dust mitigation technologies, rover tests, development of human-robotic synergies in a hostile environment, etc.). Surface support systems, such as pressurized rovers, can be positioned prior to crew arrival by cargo lander or relocation of assets during crew missions to the surface.

Missions further into the Solar System will follow, and may include missions to asteroids in their native orbits, Venus orbit and flyby, and to the Mars system, including its moons, Phobos and Deimos, prior to sending humans to the surface of Mars. If a Near-Earth asteroid becomes a threat, a mission to deal with that issue might be possible with the capabilities demonstrated in the lunar vicinity. These deep-space missions are not specifically addressed in the Global Exploration Roadmap for several reasons. New advanced technologies can be expected to be available in the next decade. In addition, discoveries made during earlier missions will likely influence subsequent plans and missions.

This Science White Paper purposely focuses on the scientific opportunities of space explorations beyond low-Earth orbit. However, it needs to be understood and clearly articulated, that these activities are not assumed to compete against or to replace robotic science missions undertaken under space science programs or fundamental and applied research in low Earth orbit. Research under microgravity and other qualities of the space environment is expected to continue well beyond the lifetime of the International Space Station with excellent potential for benefits to society, however, those activities are not subject of discussion in this particular document.

Value Added by Human Scientific Exploration

The Apollo programme demonstrated that humans on the lunar surface brought human cognition to the forefront of scientific discovery. Although the pursuit of many science objectives is feasible with suitable robotic missions, a human presence greatly enhances the process for some activities and becomes wholly necessary for others. Human crews bring additional flexibility, adaptability, experience, motivation, and sampling ability to certain missions that can be impractical to replicate with an entirely robotic telepresence. Specifically, renewed exploration with a human-robotic partnership presents the following scientific advantages over solely robotic missions:

- Sample Selection and Collection: Humans can perform efficient and sophisticated collection of samples from more diverse localities, broader geographical areas, and greater physical properties than possible through purely robotic means. Apollo revealed that suitably trained astronauts equipped with surface mobility are significantly more efficient at sample selection and collection. Additionally, it is likely that human missions can return a greater quantity of geological samples.

- Development of Geologic Context: Humans can develop large-, medium- and small-scale context in real time. Understanding the geologic history of a given field area is key to intelligent sample collection, particularly when selecting for diversity. The Apollo Program illustrated the value of humans on planetary surfaces in this regard. Similarly, observational studies of asteroids and laboratory studies of meteorites have shown that the surfaces of near-Earth asteroids experience continued mixing of often diverse materials. Consequently, determining the geologic history of a given area and using that information to conduct intelligent sample selection will be the key to returning optimal samples related to specific scientific questions. The cognition of trained human explorers adds real-time observation, knowledge synthesis, and decision-making that are beyond current robotic capability and key to exploring planetary surfaces and enabling new discoveries.

- Surface Experiments and Equipment Maintenance: Humans are uniquely capable of maintaining, upgrading, evaluating, and repairing large and complex equipment. Examples include: (a) long-range surface rovers and drilling equipment in support of sample collection; (b) the establishment of complex geophysical networks to probe the interior and astrophysical observatories; (c) equipment for manipulating and characterizing the geotechnical properties of the regolith, and; (d) collection of repetitive, geographically-spaced data (e.g., geologic mapping).

- Large-Scale Exploratory Activities: This includes those activities that may be required to locate, identify, and sample important but rare and/or buried geological materials. Human presence on the surface makes these types of activities far more efficient. Lunar examples include possible mantle outcrops, buried lava flows, impact-melt sheets, paleoregolith layers, possible 'exotic' materials derived from the Earth and other terrestrial planets, and lunar volatile deposits.

- Feedforward Activities: Anticipatory in nature, these actions occur in response to changes in our understanding of the exploration risks, challenges, and elements that result from near-term missions. Gaining operational experience on a planetary surface is essential for later exploration of more distant targets (e.g., the martian moons Phobos and Deimos, and the surface of Mars).

- Serendipitous Discoveries: Human beings are uniquely able to recognize new observations or phenomena and adapt their responses, even to unanticipated, immediate, or novel situations. Relevant examples include the discoveries of "seatbelt rock" during Apollo 15 and orange soil on Apollo 17. Both of these instances were key to enabling critical discoveries that increased our understanding of the age and nature of lunar volcanism, as well as volatile contributions to lunar magma genesis and crustal evolution.

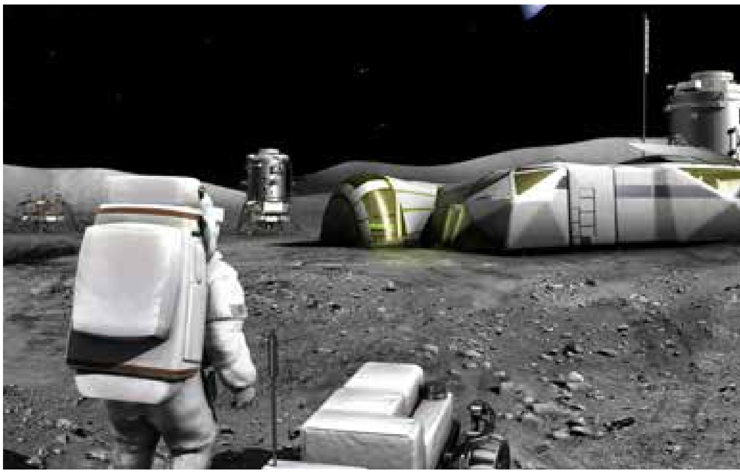


Figure 2: Artist impression of human lunar surface infrastructure. (Image courtesy of ESA)

Figure 3: One particular value of humans for planetary surface science is the ability to emplace and to service delicate scientific instruments. The Apollo missions brought important science packages to the lunar surface that were deployed by the astronauts and continued to deliver high-value science well beyond the human surface mission. (Image courtesy of NASA)

CHAPTER 2: THE SCIENTIFIC IMPERATIVE – OVERARCHING SCIENCE THEMES

The search for knowledge is an essential part of why humans explore. Scientific exploration addresses overarching questions that society seeks to answer:- “Where did we come from?”, “Are we alone in the Universe?”, “What will happen to us in the future?”, “How far can humans safely travel in space?”. This search for knowledge is best achieved by a combination of humans and robots acting synergistically, because exploration without humans lacks important societal perspectives. In addition, many scientific objectives depend on the presence of humans in space, which requires them to live and work in extreme environments. Drivers for human exploratory missions include scientific, technological, cultural and economic aspects. Above all, the search for habitability and the possibility of life beyond Earth is one of the intellectual driving forces in the endeavour to explore our Solar System.

The Global Exploration Roadmap and this White Paper focus on the first steps on a sustainable pathway to Mars; namely, the Moon and Near-Earth asteroids. Therefore, a vision for an international Solar System exploration venture should prepare for the long-term global endeavour with the horizon goal of sending humans to Mars. This paper will address how exploration of the Moon and asteroids, specifically with scientific discoveries and findings enabled by human exploration, helps to prepare the maximum scientific return from human missions to Mars. Necessary intermediate steps include robotic exploration programmes with strong scientific and exploration content, such as a robotic Mars sample return mission, that has been identified as a high science priority.

The Global Exploration Roadmap offers remarkable opportunities for science. In some cases, the proposed exploration location is the ideal location for that science, in others the existence of the infrastructure associated with the human missions permits investigations for science per se as well as for achieving new understanding of the implications and applications of science for future exploration. Given the significant logistic and mass constraints, science associated with deep space missions will likely be focused on the essential scientific research that cannot be performed in any current platform on or near Earth. For example, applied human physiology, fundamental studies of life science processes, and testing of life support equipment all depend on a range of test conditions, and require experimentation across different platforms.

In this paper, we describe the science associated with deep space missions using the following two themes, *“Understanding Our Place in the Universe”*, and *“Living and Working in Space”*.

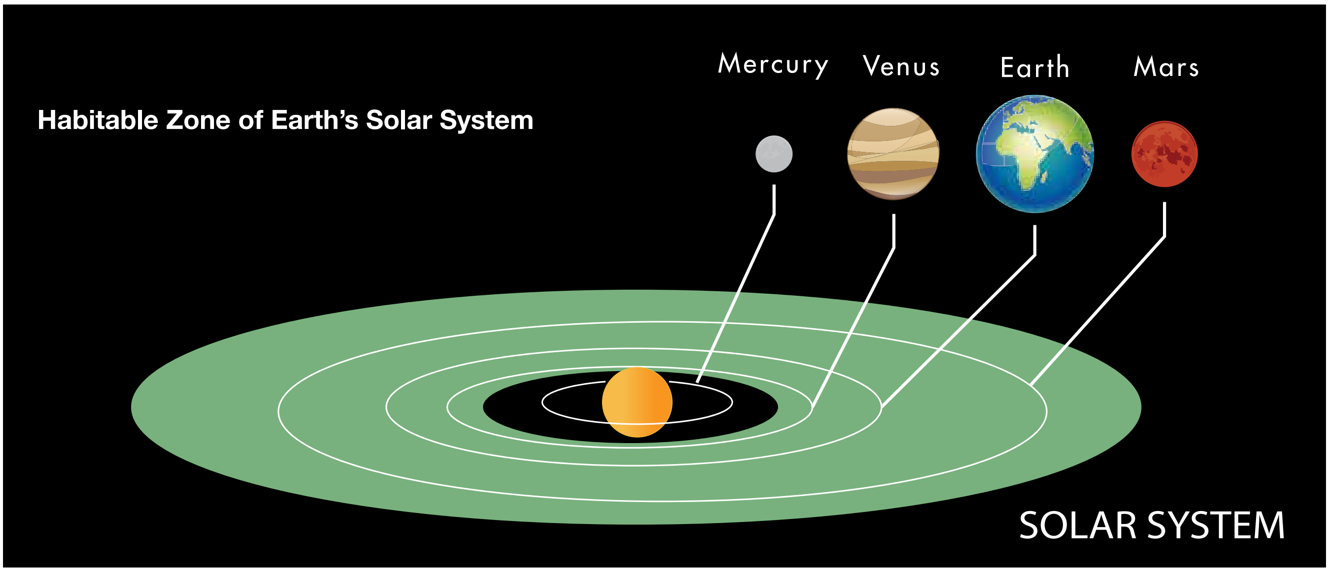


Figure 4: A key topic of the science that will be enabled by human exploration into the solar system is connected to the co-evolution of life with the planetary environment and life sciences. The current exploration destinations where humans can go are within the so-called habitable zone of Earth’s solar system, i.e. the orbital distance from the Sun where the environmental conditions allow for liquid water to exist on the planetary surface. (Image courtesy of ESA)

Understanding Our Place in the Universe

This theme covers a multitude of scientific disciplines that collectively will further understanding of the physical nature of the Universe and our place within it. It includes the Earth-Moon system and near-Earth asteroids, and their formation and development. Overarching questions include “How did the terrestrial planets and asteroids form and evolve?” and “How does life evolve with its planetary environment?”

This effort will feature new observations of the cosmos and Earth as well as research to understand the building blocks for the evolution of life. Key disciplines include astronomy, planetary geology and geophysics, solar physics, life sciences, medicine, psychology, space physics, astrobiology, and many others.

Note that these distinct scientific themes and exploration goals are intricately interconnected; just as science and exploration enable and support one another.

Living and Working in Space

This theme combines many scientific topics associated with humanity’s drive to extend its reach further into the Solar System. Overarching questions include: “How do we become a spacefaring species?” “How do we sustain life outside Earth?” Addressing both of these questions may also provide important advancements in scientific and technological knowledge that can improve life on Earth. This theme encompasses both science and engineering. We want to learn more about how humans are physically able to explore the Solar System, and reduce risks that humans face in space. We also want to use scientific results to determine how explorers will use local resources, to maximize the use of what we find around us by “living off the land”. This would be a shift from the current paradigm of taking everything with us from Earth. Additionally, these resources have high intrinsic scientific value. The key disciplines involved in this theme include human physiology, behaviour and performance, life sciences, planetary geology, astrobiology and engineering sciences related to life support and spaceflight.

The next three chapters describe the international science community’s priorities in relation to the missions described in the Global Exploration Roadmap. Although it is possible that these missions may not achieve all of the priority objectives, they demonstrate the richness of the scientific potential of each step and will inform future human mission planning efforts. These mission themes are presented in the order that they are most likely to occur.

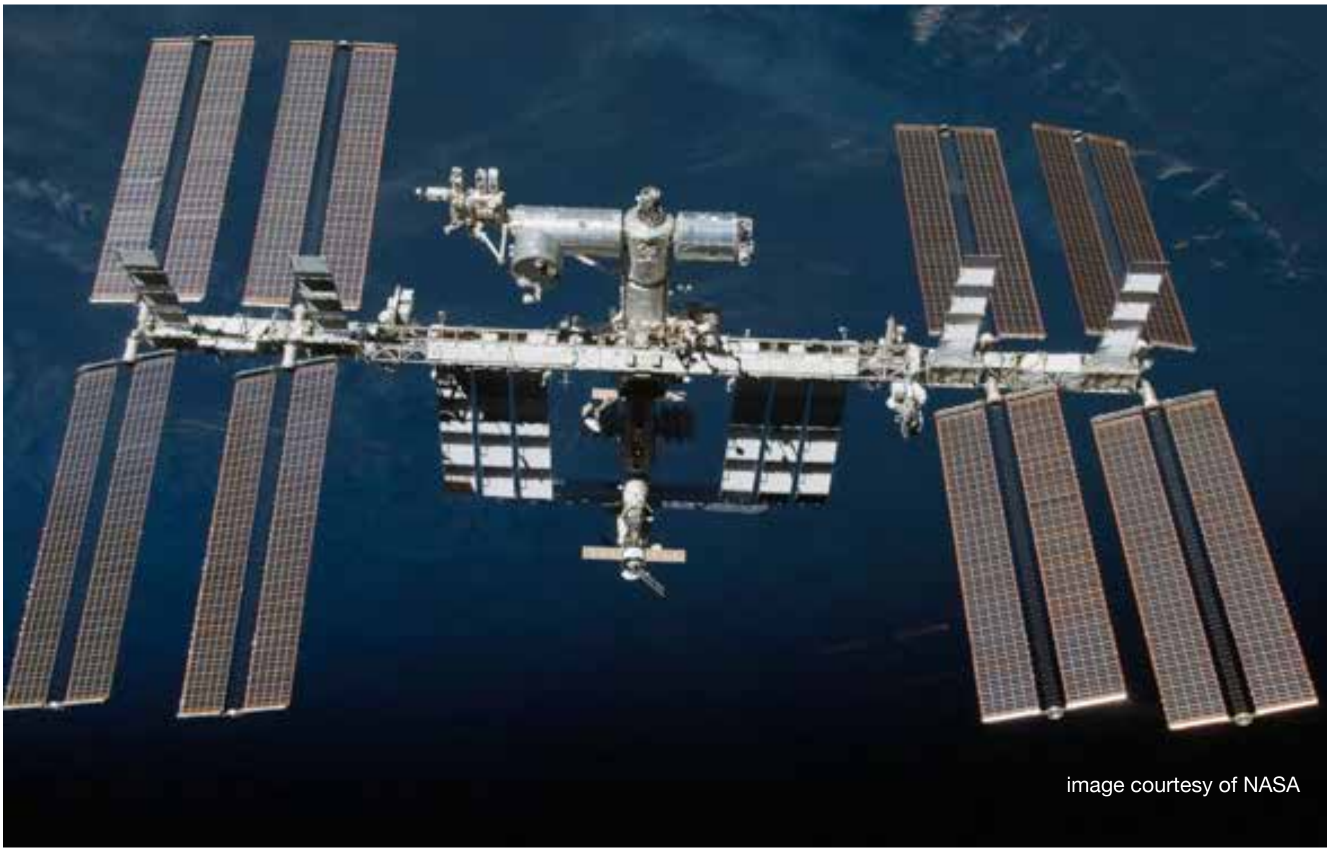


Figure 5: The International Space Station is a fitting example of an international human exploration endeavour that enables world-class scientific research.

CHAPTER 3: HUMANS TO A GATEWAY IN THE LUNAR VICINITY

Building on the achievements of the International Space Station, the vicinity of the Moon is a potential next step leading to sustainable human exploration of the Moon, asteroids, and Mars. Although any deep space environment presents significant challenges when compared with low-Earth orbit missions, the Moon's close proximity to Earth can enable development of the techniques and advanced capabilities needed for further human exploration of the Solar System. Stable orbits in this region of space will be used for staging and long-term support of capabilities such as reusable human lunar landers and spacecraft for Mars exploration. The infrastructure in the lunar vicinity will offer numerous opportunities for scientific benefit based on readily available resources, crew interaction and an ideal vantage point for the study of deep space, the Sun, the Moon, and Earth.

The GER envisions assembling this human-tended infrastructure and conducting a series of extended-duration crewed missions including a potential Mars mission simulation, as preparation for missions beyond the Earth-Moon system. ISECG agencies are continuing to engage the broad scientific community in identifying specific investigations well-suited to leverage this capability, and this chapter introduces several potential opportunities.

The term "lunar vicinity" encompasses a variety of lunar orbits as well as the Earth-Moon Lagrangian points. The proposed gateway will be capable of moving among such locations based on various science and utilisation goals.

One scenario involves a crew traveling to the gateway and conducting scientific experiments that benefit from its current location before returning to Earth. The uncrewed gateway would then move to a new location with a different selection of scientific opportunities for future crew visits. It is likely that the initial gateway will not be permanently occupied. As will be discussed in this chapter, the gateway offers scientific opportunities even when uninhabited.

Figure 6 illustrates several orbits that a gateway could occupy (or deployable instruments could reach) in addition to the Earth-Moon Lagrangian (EML) points. Each orbit provides certain advantages. For example, EML2 orbits provide direct access to the unexplored lunar far side while simultaneously being visible from Earth for communications.

Orbit Type	Orbit Period	Lunar (or L-Point) Amplitude Range	E-M Orientation
Distant Retrograde Orbit	~14 days	70,000 km	Equatorial
Earth-Moon L2 Halo	8 to 14 days	0 to 60,000 km (L2)	Dependent on size
Near-Rectilinear Halo Orbit (NRHO)	6 to 8 days	2,000 to 75,000 km	Roughly Polar
Elliptical Lunar Orbit (ELO)	~14 hrs	100 to 10,000 km	Equatorial
Low Lunar Orbit (LLO)	~2 hrs	100 km	Any inclination

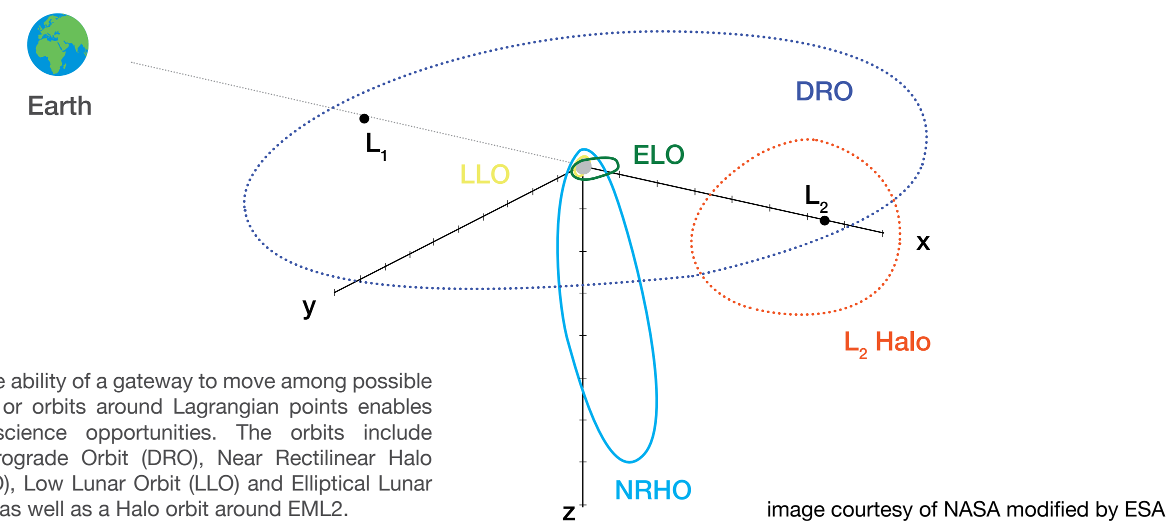


Figure 6: The ability of a gateway to move among possible lunar orbits or orbits around Lagrangian points enables additional science opportunities. The orbits include Distant Retrograde Orbit (DRO), Near Rectilinear Halo Orbit (NRHO), Low Lunar Orbit (LLO) and Elliptical Lunar Orbit (ELO), as well as a Halo orbit around EML2.

New science data also can be acquired before the gateway reaches the Moon, or during crew transit to the gateway. During the journey from Earth orbit to the Moon, experiments can be conducted on phenomena affected by distance from the Sun, Earth or the Moon, and changes in the radiation environment with passage through the Van Allen belts. Examples include experiments that:

- Monitor lunar exosphere evolution of the entire Moon through a monthly cycle
- Quantify impact flashes through the lunar night
- Monitor human physiology and biomedical changes as the habitat or vehicle moves outside the Earth's magnetic field
- Install cosmic dust/micrometeorite collectors
- Target the trajectory to facilitate a lunar eclipse of the Sun to study coronae/Sun compositions that are not distorted by Earth's atmosphere
- Monitor Earth exosphere (geocorona) in the far UV which extends halfway to the Moon, attempting to estimate radiation pressure and its accurate extension that could change with solar activity.

Understanding Our Place in the Universe

The next steps that humans and robots take into the Solar System show great promise for significant technological advancement, scientific discovery, and cultural/societal impact. Crews living and working in close proximity to the Moon will provide unprecedented opportunities for lunar exploration through the application of human-robotic partnership. Such a programme will use the Moon as a test bed for future collaboration on asteroids and Mars, thus reducing risk and increasing operational expertise for missions far away from Earth. These activities will enhance our understanding of the Moon, the Universe, and the human experience by advancing scientific knowledge across multiple scientific fields. This compelling rationale for the exploration of the lunar surface is described further in Chapter 4: Humans to the Lunar Surface.

- Lunar Surface Science Using Telepresence: Telepresence requires that a human operator controls the actions of a remotely operated robot. The teleoperation of robotic assets on the lunar surface by humans from a gateway would permit very low-latency robotic control that could significantly enhance exploration of the Moon. Initially, telepresence provides the opportunity to conduct new science before sending humans to a planetary surface, which has implications for future human Mars missions. Tele-operations also allow human presence at sites that are too difficult or dangerous for humans to visit in person. Tele-operation of agile robotic precursor missions to scout and prepare sites identified for human surface operations could reduce risk through better characterization of the proposed landing site. Such operations can also achieve science objectives, such as returning a sample from the Moon's South Pole Aitken Basin. This is recognized as a high scientific priority and conducting a human-assisted sample return mission using the gateway would permit efficient selection of carefully chosen samples to return. A mission where the samples come from the lunar surface to the gateway, and return with the crew, could potentially result in an increased amount of returned sample, compared to a purely robotic mission. While lunar telepresence can be conducted from Earth, the latency is an order of magnitude lower (<0.5 seconds versus ~5 seconds) which enables streamlined operations in addition to other potential benefits. For example, the Moon's permanently shadowed regions (PSRs) have high scientific and exploration value, but are difficult to explore due to extremely low temperatures. A rover investigating a PSR will have limited time to conduct operations, and the very low latency enabled by control from a gateway could significantly maximize the results. It is generally accepted that a latency of less than half a second permits "real time" operations, i.e. the latency does not affect activities. Low-latency teleoperated robots can also install scientific instruments on the lunar surface. For example, advanced mission scenarios for exploring the Cosmic Dawn epoch of the Universe could be accomplished with the deployment of a low radio frequency telescope on the lunar surface. In addition to the science that could be achieved by tele-operation of a rover on the Moon's surface, another benefit is maximizing the efficiency of the human-robotic partnership. One example of potential tele-presence in future human exploration is operation of rovers on the surface of Mars, controlled by humans in martian orbit or on one of the martian moons Phobos or Deimos.

Figure 7: Low latency tele-robotics offers a range of new scientific opportunities. One example is a concept where a crew on the deep space habitat would use a rover on the lunar surface to collect high-value samples that are launched to the habitat, and then returned with the crew. Preparatory work for such a concept is advanced by the METERON activities on ISS.

As well as the advantages of low latency, a key operational aspect is learning to factor in increased crew autonomy. As the opportunities to communicate with Earth decreases, the crew's ability to make real-time decisions takes on increased importance. The experience learned from tele-operations from a gateway around the Moon will improve the science return from similar activities on Mars.

Living and Working in Space

The establishment of a gateway in the lunar vicinity is a potential next step in expanding human presence beyond low-Earth orbit. Such infrastructure in the deep space environment will enable science and technology demonstrations that help keep the astronauts healthy on longer duration missions into the Solar System. New scientific discoveries can also be expected. Examples of the science enabled by missions to a lunar gateway include:

- Understanding the Effects of Deep Space Radiation, Reduced Gravity and Closed Habitat Environments: A gateway offers a unique opportunity to study the harmful effects of the deep space radiation environment on human physiology, plant physiology, and the microbiome of the spacecraft environment. The effects of lower total pressure, lower oxygen concentration, and higher carbon dioxide concentration that might be found in future exploration vehicles and habitats can first be studied in the environment of space radiation and fractional gravity in a crewed platform. Comparison of radiation biology experiments on ISS and the lunar vicinity, as well as ground-based research, can provide insights leading to the identification and validation of protective countermeasures. Science results from studying the combination of radiation, fractional gravity and altered atmosphere will complement the experience gained from more than 50 years of microgravity research in LEO. It will improve our understanding of adaptive responses in astronaut bone, muscle, cardiovascular, and neural systems as well as which changes in space are reversible upon return to Earth. Furthermore, the effects on medicines and the nutritional value of certain foods is critical data that will inform future mission planning. In preparation for future exploration missions, it is crucial to understand the fundamental effects on human physiology and performance of prolonged exposure to radiation and the habitat environment aboard deep space transit vehicles and the fractional gravity (between 1g and microgravity) of final destinations. Studying these effects in humans or model organisms in a deep space habitat environment (which cannot be replicated on Earth or ISS), would improve designs for biomedical and countermeasure equipment, labs, tools, habitats and associated hardware, thus realising significant health risk reductions.

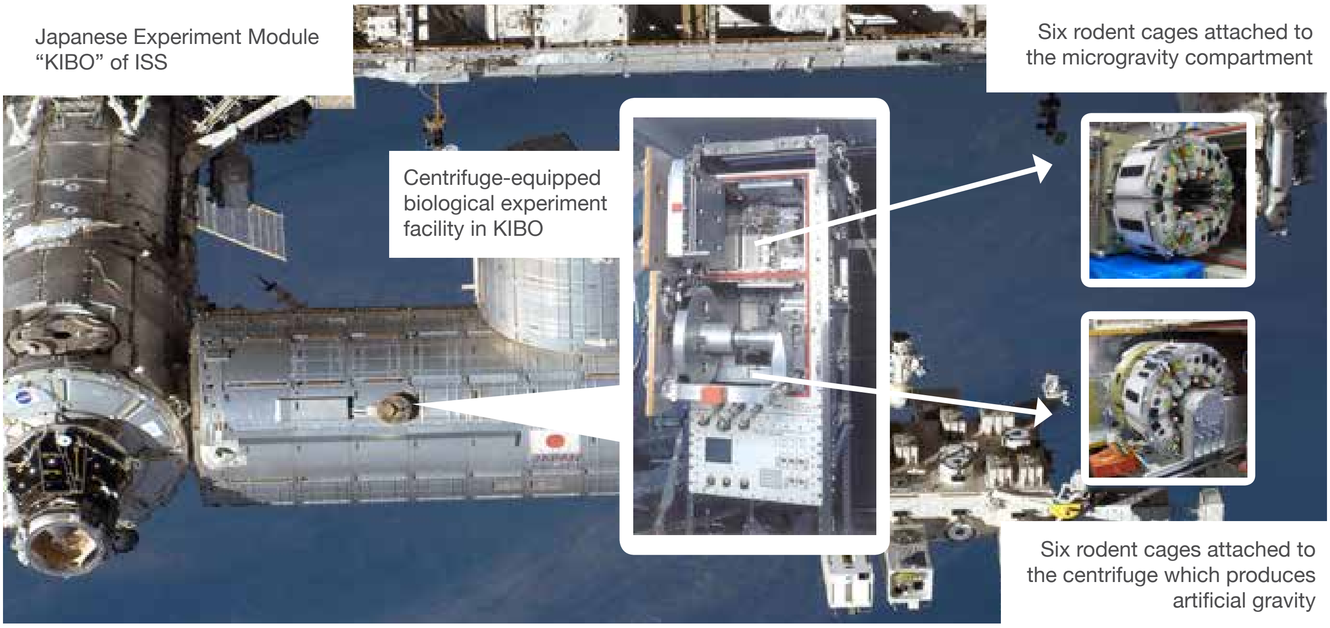


Figure 8: The Japan Aerospace Exploration Agency (JAXA) newly developed mouse habitat cage units that can be installed in the centrifuge-equipped biological experiment facility in the Japanese Experiment Module ("Kibo") of ISS. The facility provides both microgravity (μg) and artificial gravity environments. Earth's gravity (1 g), the Moon's gravity (0.16 g) and Mars' gravity (0.38 g) on the bottom floor of the cage can be mimicked by the rotating the centrifuge at 77, 31 and 48 rpm, respectively. In the first mission conducted in 2016, 12 mice were launched, divided into two groups of 6 mice each, and housed under μg or artificial earth-gravity (1 g). After 35 days of habitation in ISS, all mice were returned to the Earth in a live condition (image courtesy of JAXA).

Additional Science Opportunities:
The existence of the gateway infrastructure (i.e. instrument-hosting with power and communications capability that also can accommodate greater mass than small satellites) may facilitate high-quality scientific activities in many disciplines. The following examples leverage the infrastructure to obtain knowledge through "opportunistic science" activities which otherwise might be too costly or low priority to implement using standalone automated spacecraft.

- Observation post for monitoring Earth's environment: A gateway in the lunar vicinity could serve as a scientific outpost to conduct full disk synoptic observations of Earth over a range of phases. Such observations could provide information useful for environmental studies. Studies of Earth can also inform the design of instruments for detecting life on exoplanets.

- Construction and servicing of large telescopes: A gateway's human crew could construct telescopes that are larger than those that must be launched fully assembled. Additionally, future telescopes could be designed to move between their primary orbits and the lunar vicinity using modest amounts of fuel. Such functionality would allow these telescopes to be moved to EML2 for humans to repair or enhance (e.g. swap out instruments), before the telescope returns to its ideal observing location.

- Fundamental physics: The gateway would permit experiments that further our understanding of aspects of fundamental physics. Examples include the study of galactic cosmic rays and particle physics (from outside the Earth's magnetosphere), tests of general relativity, and long baseline experiments for quantum mechanics.

- Collecting planetary material: Several missions have collected non-surface planetary material for return to Earth for analysis. Experiments conducted in a gateway could collect interplanetary and interstellar dust over long periods of time by deploying collectors on the outside of the habitat. Moreover, addressing the lunar dust environment with microbalances and optical cameras will be key to understanding near-Moon conditions.

- Heliophysics: The lunar region is immersed in a plasma environment whose fields have significant influence on the terrestrial environment. A stable platform at in the lunar vicinity affords long-term global viewing of Geospace (radiation belts, plasmasphere, equatorial and polar cap ionosphere), the Sun and in-situ observations of the particles and fields that will advance our understanding of the Sun-Earth system.

- A platform for astronomical observations: A gateway in the lunar vicinity permits certain astronomical observations.

A reusable lander staged at an orbital gateway could potentially offer routine access to the lunar surface. Ultimately, utilisation of lunar resources could provide fuel for such a capability, greatly reducing the associated logistics. Regular crewed and robotic missions to the lunar surface would permit exploration of a wide variety of scientifically noteworthy locales. Examples of such lunar surface science are described in the next chapter.

The growing body of experience in low-Earth orbit - particularly on ISS - has led to new scientific investigations that leverage ISS as a research outpost in space. Similarly, when a gateway has been installed in the lunar vicinity, new and previously unanticipated utilisation opportunities may be identified.

Conclusions
A gateway in the lunar vicinity is a potential next step in expanding the capabilities for humans to explore beyond low-Earth orbit, and provides many opportunities for scientific discovery. The presence of humans in the lunar vicinity will enable the development of technologies and procedures that reduce risk to human missions deeper into the Solar System. We can explore the lunar surface, including regions too difficult to explore with humans, with robots tele-operated from a gateway, yielding significant scientific benefits across multiple disciplines. We can learn efficient low-latency human/robotic operations in a planetary environment with relevance to future Mars missions.

Understanding the deep space environment's radiation and reduced gravity effects on human physiological systems is essential to keeping humans safe and healthy as we venture further into the Solar System. The gateway could add the ability to study the interplay of radiation, microgravity, fractional gravity, and isolation. The value of data obtained under these circumstances to future mission planning cannot be overstated. It is also important to learn how the effectiveness of drugs, and the nutritional value of foods, degrade with time in this deep space environment.

The infrastructure of a gateway in the lunar vicinity could also be leveraged for a wealth of opportunistic science including astronomy, fundamental physics, interplanetary materials collection, and heliophysics.

CHAPTER 4: HUMANS TO THE LUNAR SURFACE

The Moon is a cornerstone for Solar System science and exploration. Its proximity to Earth, coupled with reduced gravity and natural resources make it an ideal location to prepare humans and machines for venturing farther into space. It is a natural nearby test bed for reducing risk in sending humans farther into the Solar System. A new era of human lunar exploration will be able to make use of global remote sensing datasets and detailed imagery that will reduce risk and maximise the science return associated with sending humans to the lunar surface. As a repository of Solar System history and as a vantage point from which to observe the Earth and the Universe, it also has great potential as a base for fundamental scientific research that would also inform future space exploration.

In addition to scientific benefits, human lunar exploration will also contribute to the wider exploration goal to enhance the prospects for humans to live and thrive in space while reaping associated societal benefits. The Moon's resources can potentially facilitate sustainable long-duration missions, dramatically increasing the science returns while reducing costs and demonstrating the exploration-enhancing nature of in-situ resource utilisation (ISRU) strategies.

The lunar poles are a noteworthy option for initial exploration activities because they remain unexplored and can yield new scientific insights and samples. Logistically, several locations offer abundant solar energy (near continuous sunlight) and proximity to water ice and other volatiles that can increase understanding of inner Solar System volatile delivery and perhaps the building blocks for life. In addition, these deposits could become a significant resource for facilitating human missions beyond the Earth-Moon system.

Understanding Our Place in the Universe

A programme of lunar surface exploration will advance our understanding of the wider universe and our place within it, by advancing scientific knowledge in numerous fields. These include planetary geology, geochemistry and geophysics, astrophysics and cosmology, astrobiology, life sciences (including human physiology, psychology, and medicine), materials science, and fundamental physics.

From a planetary science perspective, the primary scientific importance of the Moon lies within its ancient surface, forming the foundation of our understanding of how rocky planets formed and evolved. It preserves a record of the earliest geological evolution that more complex bodies (e.g. Earth, Venus and Mars) have lost due to continued geologic activity. Moreover, the Moon's surface preserves a record of the inner Solar System environment (e.g. impactor flux from small body migrations, as well as solar and galactic processes) that nearly coincides with the age of the Solar System. This accounting of Solar System history gives considerable astrobiological significance to the Moon's geologic past, as it provides clues to early conditions on Earth during which life arose and its continued habitability through time. Furthermore, the Moon preserves the impact record of the early Solar System and provides insights into the frequency of major events over time, such as the environment-disrupting asteroid strike that led to the mass extinction of non-avian dinosaurs and many other species. No other place in the inner Solar System can provide similar information about the timing and type of impacts during its primordial phases. Comparing impact histories of large asteroids provides clues for understanding the material delivery and mixing from the outer Solar System to the rocky planets. In particular, the polar regions of the Moon may have preserved traces of cometary and meteoritic impact material rich in organic matter and volatiles – the building blocks of life.

Specific, top-level science objectives that would be addressed by a programme of human lunar surface exploration include the following:

- Planetary evolution: The Moon enlightens us about the primary differentiation (i.e. formation of compositionally distinct layers) of rocky planets. The small size of our Moon, coupled with knowledge gained from the Apollo program, shows that much of its interior heat was lost approximately three billion years ago. Thus, a majority of the primary differentiation of the Moon has been preserved. Therefore, our understanding of how terrestrial planets and other smaller rocky bodies form and evolve can be significantly enhanced through detailed global lunar investigations. This should include sampling of ancient crust/mantle material and global geophysical investigations that will define the interior structure and composition of the Moon and its geologic evolution.

- Samples of new rock types: Orbital lunar missions have identified surface rock types that are not part of the existing sample collection. Our understanding of the origin and evolution of the Moon will be greatly advanced by collecting representative, previously un-sampled lunar lithologies. For example, samples of the lunar mantle are not definitively present in current catalogue but may be found on the far side of the Moon and isolated outcrops associated with impact basins of the Moon's near side. Sample return can provide orders of magnitude more science value than in situ analysis, demonstrated by Apollo 15 samples that were analysed by new techniques in 2008. The new analysis discovered the presence of water (and other volatiles) in the lunar interior for the first time.

- Volcanic processes: Volcanic products from different geologic ages will provide information about the evolutionary history of the lunar interior. Detailed sampling of such products can be used to understand the preserved initial stages of terrestrial planet evolution. Our understanding of Earth and Mars has broadened to include the magma oceans concept that was developed based on Apollo 11 samples, demonstrating the application of lunar science to general solar system processes. Investigations of lunar volcanic processes will provide knowledge on various eruption styles, dates and duration periods, helping us to better understand the nature of the lunar interior, thermal history, and extraterrestrial-volcanism in general.

- Earth-Moon impact flux. The Moon preserves the impact record of the inner Solar System and provides insights into the impacts on terrestrial planets that have caused mass extinction events. Sampling materials from areas of different geologic ages will provide important information about the populations of impactors that shaped the inner Solar System, providing the volatile and organic materials needed for the emergence of life.

- Cratering processes. Detailed in situ study of structure and morphology over various crater sizes and target materials will define the impact process and its effects on multiple scales, which can then be applied to distant and inaccessible Solar System objects. Large impact craters and basins develop extensive impact melt pools, some of which contain sub-lunarean caverns (as can volcanic lava flows in mare regions). These caverns represent subsurface sampling opportunities and also potential habitats for extended human visits.

- Absolute age determination: Lunar exploration has the potential to revolutionize our understanding of the impact cratering rate and record in the inner Solar System. This can occur through the collection, return, and dating of samples from a wider range of cratered surfaces and impact-generated materials than possible with the Apollo and Luna missions. This will constrain the bombardment history of the inner Solar System, and improve model age-dating of all planetary surfaces. The absolute cratering record of the Moon, derived from the crater density of the lunar surface combined with ages of lunar samples, has been extrapolated to Mars in order to determine the age of its surface. In addition, understanding the lunar cratering record is key to understanding the evolution of the asteroid belt, which also informs us on the early formation of the inner and outer Solar System planets.

- Origin of life: How did life originate? The Moon could help in unlocking this mystery. The record of Solar System history gives the Moon's geologic history considerable astrobiological significance, as it provides clues to conditions on the early Earth under which life became established on our planet and its continued habitability through time. Investigation of lunar polar ices could reveal the inventory of organic molecules that may have been delivered to the Earth-Moon system by asteroids/comets and were subsequently trapped and preserved in permanently shadowed regions, and/or formed and evolved as a result of radiolysis in polar ices by galactic cosmic rays. Such exogenic organic molecules are of great astrobiological interest, and are thought to occur on icy bodies in the outer Solar System and on interstellar dust particles. However, the lunar poles are the closest locations to obtain samples and investigate these astrobiological possibilities.

- Volatiles: Delivery of volatiles from external sources is also critical for planetary surface evolution. Current knowledge indicates that the lunar poles may contain a record of the flux and composition of volatiles delivered to the inner Solar System (including Earth). Through in situ studies and sample return of ices and icy regolith, compositional data would enable evaluation of these external sources and delivery mechanisms for the first time. In situ measurements would also facilitate determination of the properties and variability of the tenuous lunar atmosphere and the migration of lunar volatiles to polar cold traps. Additionally, rock samples from lava flows and subsurface caverns may contain information about volatiles that are endogenic to the Moon.

- Solar and galactic evolution: The evolution of the Sun and the Milky Way galaxy is a subject primarily restricted to theoretical modelling. Analysis of the Moon's surface could contain "snap shots of ground truth" that confirm data collected or derived from direct observations and constrain such theoretical models. For example, ancient lunar regoliths lodged between lava flows will preserve historic records of the solar wind and galactic cosmic rays.
- Astronomical observations: The Moon presents

a unique opportunity for powerful new radio astronomical observations. The radio-quiet far side of the Moon is the ideal location to conduct radio observations of the early Universe. In addition, astronomical instruments on the lunar surface would be well-suited to study the Earth's magnetosphere and heliosphere, and telescopes located on the near side of the Moon could conduct long-duration observations of the Earth as an analogue for studying extrasolar Earth-like planets. Studies of galactic cosmic rays from the lunar surface are another possible astronomical application, as their particle flux rate beyond Earth's magnetosphere increases compared to equivalent rates in low-Earth orbit. For the past several centuries, seminal astronomical discoveries have occurred with new observing capabilities. These developments can be unpredictable—however, observing the cosmos from the Moon offers potential for future scientific serendipity.

- Fundamental physics: The distinctive lunar surface environment, coupled with infrastructure of lunar exploration is a possible platform for fundamental physics activities. These could include tests of general relativity and gravitational physics (via Earth-based lunar laser ranging using sensitive, new-generation corner cube reflectors on the near side lunar surface), and tests of quantum entanglement over large baselines (e.g. between Earth and the Moon). The Moon offers an advantageous platform for studies of galactic cosmic rays and neutrinos. Neutrino interactions with the lunar regolith might allow radio Cerenkov studies of non-standard neutrino-nucleon interactions or neutrinos from astrophysical sources.

Figure 9: Among the multitude of science activities that will be enabled by human exploration of the lunar surface, impact cratering offers a breadth of topics. The research will increase understanding of the impact flux in the inner Solar System (including the cadence of extinction events) and the physics of the impact cratering process (which is not possible on Earth due to active geology and weather). This image shows an artist impression of the Kaguya/SELENE spacecraft above the cratered Moon. (image courtesy of JAXA)

Living and Working in Space

Human operations on the lunar surface will significantly contribute to the objective of establishing humanity as a permanently space-faring species. Many of the resulting discoveries made, technologies refined, and techniques developed will be applied to future efforts to send humans beyond the Earth-Moon system, and some may also benefit human society on Earth.

Examples of "applied" scientific and technological benefits of lunar exploration include:

- Contributing to human health and medical benefits on Earth: Experiments conducted on the ISS have shown that physiological responses to microgravity can mimic those associated with a range of human conditions—like osteoporosis and, perhaps most significantly, aging. Observing human adaptation to prolonged exposure to fractional gravity is critical for monitoring health and safety during lunar missions, and offers significant insights into vestibular disorders, aging, and disuse pathology. In addition, experiments in cell and organismal biology within the fractional gravity and high-radiation environment of the lunar surface will provide insights into impacts of gravity on fundamental biological processes. Finally, humans on the Moon enable the study of the interplay of radiation, variable gravity, team effectiveness and isolation.

- Understanding the physiological effects of the lunar environment on human health with applicability to more distant destinations: Studies of human physiology in the reduced gravity, high-radiation and dusty environment of the lunar surface will yield the knowledge required to send crews safely to deep space Solar System destinations. Lunar physiological research would supplement the knowledge accrued by microgravity exposure on the ISS by adding data at 1/6th g from which to investigate gravity dose-dependence. Lunar gravity (1/6th Earth) is an interim point between microgravity and Mars gravity (~1/3rd Earth), providing opportunities to better understand the dose-dependence of living organisms' need for gravity.

- Understanding how non-human forms of life adapt to, or can be protected from, the conditions on extreme planetary surface environments: Understanding how low-gravity, high-radiation environments affect plants and microorganisms is important due to the need for food and/or bio-regenerative life support systems for future space exploration. In addition, this aspect of understanding is critical from the perspective of the "human-microbiome" symbiotic relationship that is essential for maintaining multiple physiologic functions.

- Testing of Planetary Protection protocols: Lunar operations may provide a relevant test-bed for planetary protection research in ways that inform future Solar System exploration. For example, understanding the long-term survivability (and escape) of human-associated bacteria and viruses inside and outside structures on the lunar surface could provide useful information about facility designs for other planetary surfaces. The Moon also presents an ideal environment for test cleaning and repair protocols for removing contaminants from instruments and sampling devices, thereby minimizing the potential for "false-positive" results in experiments aimed at detecting life on other planets.

- Identifying potential lunar habitats: Potential locations for human habitats include areas of significant scientific interest related to their origin, evolution and physical properties. Such areas include surface locations with relatively high local magnetic field strength, floors of pits within impact melt flows, and interiors of subsurface caverns (e.g., lava tubes with skylights that can act as entrances). Subsurface caverns could provide protection from daily temperature fluctuations and the extreme space radiation environment, possibly making them ideal locations for a permanent base. Such features exist on the Moon and on Mars, and the practicality of utilizing them as habitats could first be demonstrated on the Moon.

- Learning how to "live off the land": It is generally understood that sustainable exploration of the Solar System will be dependent on the use of local resources. Human lunar surface scientific exploration will enable further evaluation of the resources on the Moon as potential reserves. The investigations will help determine appropriate methods for resource extraction and processing, and maximising their use to enhance human exploration capabilities while reducing cost. Those activities could synergistically enable access to lunar samples for science, while scientific investigations of polar ice deposits will also reveal their potential as resources. Learning to use local resources effectively ultimately increases science returns because increased ISRU activities allow crews to spend additional time conducting scientific activities.

- Providing a test bed for human-robotic planetary surface exploration: The proximity of the Moon permits an assessment of human-robotic partnerships/synergies in a harsh planetary environment, as is discussed in Chapter 3. Human-robotic partnerships and teleoperations are of particular importance in terrestrial applications for mining and resource extraction in polar or deep ocean environments and other remote locations. A synergistic approach between robots and humans will be a key-factor in efficiently exploring the Moon, asteroids, and other Solar System locations. The success of the human-robotic partnership requires sound knowledge for the development and application of the human-machine interface. The Moon provides the opportunity to advance the science underlying the design of ergonomically sound machines to ensure exemplary performance at distant destinations.

Figure 10: One of the most iconic images taken during the Apollo project was the "Earthrise" image acquired as the Apollo 8 command module emerged from flying over the far side of the Moon. This "replica" image was acquired by the camera on NASA's Lunar Reconnaissance Orbiter (image courtesy of NASA/Arizona State University).

Conclusion

Scientific investigations on the Moon will be vital preparation for human visits to more distant solar system destinations. In addition, the investigations will improve our understanding of the origin and evolution of the Earth-Moon system and terrestrial planets in general. The Moon has experienced many of the geologic processes that shape the diverse terrestrial planets in the Solar System: Mercury, Venus, Earth, and Mars. These phenomena (i.e. impact cratering, volcanism, and tectonics) can be studied on the lunar surface to provide insights on the earliest history of the Solar System including the formation and evolution of the terrestrial planets.

The geological complexity of the Moon necessitates careful selection of samples for return to Earth in order to address the plethora of scientific questions related to the lunar surface. Sample return is a significant scientific benefit of human exploration, and lessons learned from the Apollo program include the use of geologically trained explorers for selecting the best samples for analysis.

An example of scientific study that can be advanced by the analysis of new lunar material is the dating of impact events, which will shed light on the impact flux for the Earth-Moon system over geologic time. This will advance scientific knowledge of all planetary bodies as they are dated based on the lunar chronologic record, in addition to various astrobiological ramifications, e.g. meteorite impacts implicated in extinction events on Earth.

Humans will also facilitate the placement of delicate surface instrumentation on planetary surfaces. The far side of the Moon is “radio quiet”, offering the unique opportunity for sensitive measurements of the earliest moments of the Universe.

Several life sciences questions pursued by human exploration of the lunar surface will inform and facilitate progress beyond the Earth-Moon system. Long-duration human exposure to the fractional gravity of the Moon may provide insight on a range of health issues such as osteoporosis. It will also guide the protection of astronauts during travel to Mars and extended stays on its surface. Similarly, efficient plant growth in hostile (gravity/radiation) environments is important for sustained human exploration.
To become a truly space-faring-species, humans must use local resources instead of launching all support materials from Earth. The Moon is an ideal location to learn how to “live off the land”, and polar ice deposits present opportunities for synergistic science and exploration investigations.

Finally, serendipitous discoveries make human surface exploration such an exciting prospect because so much will be learned that cannot be predicted. The Apollo expeditions show numerous examples of unplanned scientific discoveries occurring due to the sharp eye of a geologically trained astronaut.

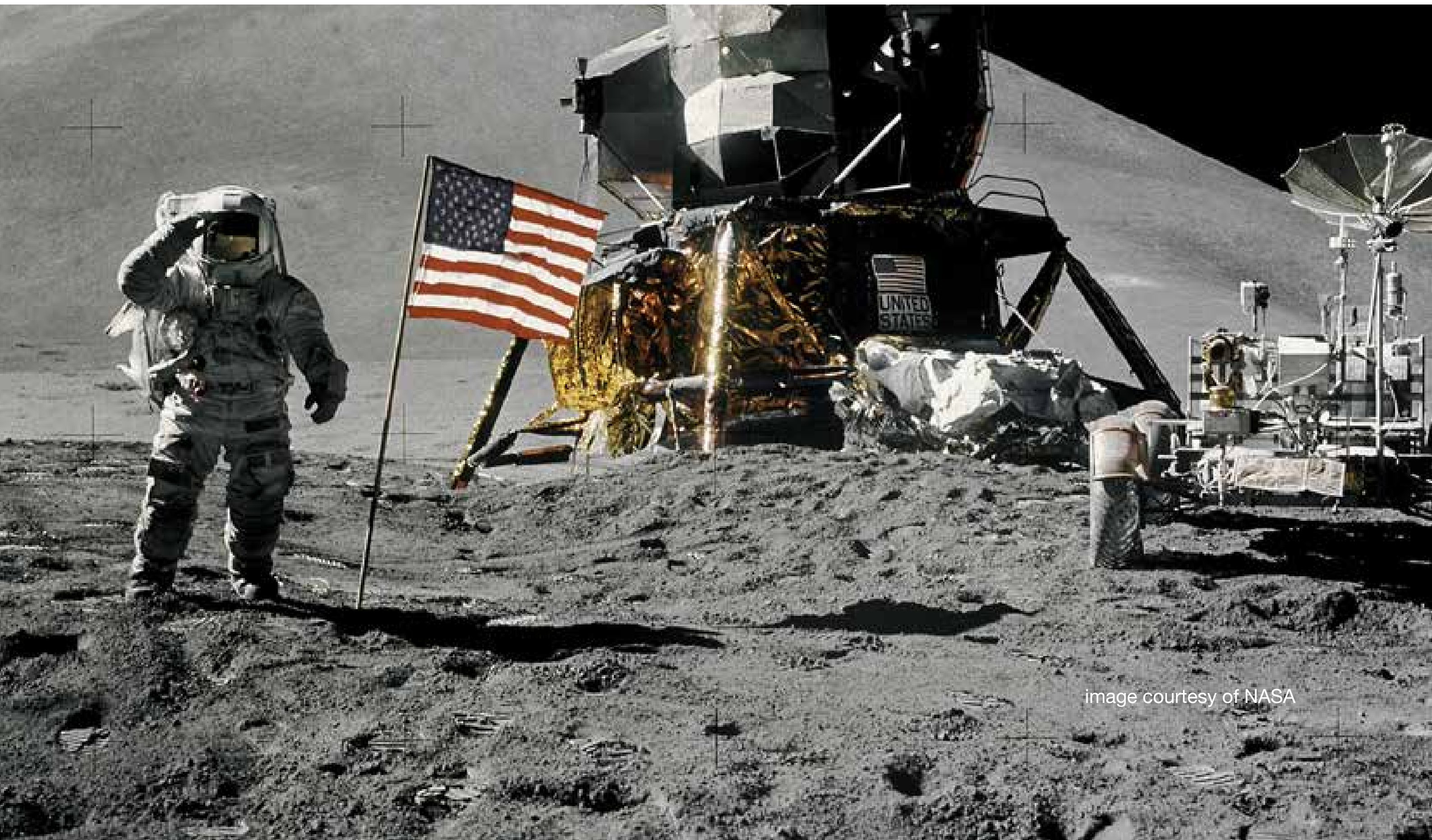


image courtesy of NASA

CHAPTER 5: HUMANS TO A NEAR-EARTH ASTEROID

Near Earth Asteroids (NEAs) present unique potential to enable scientific and human exploration of the Solar System. They can provide lessons for developing human exploration capabilities and advancing the scientific understanding of the formation and evolution of the Solar System. NEAs are bodies that have witnessed events and conditions throughout the history of the Solar System, often retaining information that larger planetary bodies lost during their evolution. NEAs also contain clues to biological history because they have a common pre-solar and early nebular record, but also because asteroid bombardment has been a significant part of planet histories. NEAs essentially are time capsules of the water and organic materials that may have played a key role in the origins of life; and recorders of processes ranging from the production of materials that became parts of the Solar System, processes in the earliest days of the solar nebula, and mechanisms occurring today.

NEAs also may provide crucial resources like water that could enable novel robotic and human exploration strategies in the future, and may have economic potential. Additionally, advancing knowledge of NEAs will enable humankind to better evaluate their potential hazard to Earth and develop mitigation strategies. The goals of planetary defence complement those of scientific investigation and human exploration, allowing simultaneous advancement of all three efforts. Human exploration of NEAs will be enabled by technologies developed during the next decade. Such technologies could eventually be applied to human exploration of the martian moons, which share many characteristics with NEAs. This chapter discusses science enabled by human exploration of asteroids in their native orbits.

Accessible Near-Earth Asteroids

Over the past six years, NASA's Near-Earth Object Human Space Flight Accessible Targets Study (NHATS) significantly increased the body of knowledge about the accessibility of NEAs. NHATS aims to identify all NEAs more astrodynamically accessible than Mars, i.e. round-trip visits requiring less total change-in-velocity ("delta-V") and/or less mission duration than round-trip visits to Mars. The NHATS system automatically monitors NEAs and keeps pace with updated orbit information and new discoveries, with data publicly available at http://neo.jpl.nasa.gov/nhats.

As of July 2017, 2092 of the currently known NEAs (~13%) are classified as accessible by NHATS, offering at least one round-trip mission opportunity between 2015 and 2040 with delta-V less than 12 km/s and mission duration less than 450 days. All missions to Mars (flyby, enter/exit orbit, or travel to/from the surface) either require more delta-V, longer duration, or both.

Figure 11: The nucleus of comet Churyumov-Gerasimenko was imaged and investigated closely in recent years due to ESA's Rosetta mission and the Philae lander, provided by DLR and other European partners. It revealed many new insights into the early formation of our Solar System.(Image courtesy of ESA)

To provide an example of known potential NEA mission opportunities, there are 20 selected NEAs from NHATS data that offer at least one mission opportunity between the years 2020 and 2030. The first 17 NEAs listed require less than 6 km/s delta-V. For the 7 km/s delta-V range, a total of 62 NEAs would be included. For reference, a round-trip mission to low lunar orbit requires approximately 5 km/s delta-V, and a round-trip mission to the lunar surface will need about 9 km/s delta-V.

Some of the science activities described in the rest of this chapter require humans to visit particular types (known as taxonomies) of asteroids. Therefore, not all of the science described here can be achieved at all asteroids. The taxonomy of the majority of the accessible asteroids is unknown. However, future survey telescopes will likely find and classify many more achievable target asteroids.

Understanding Our Place in the Universe

Small bodies are exceptionally varied, as evidenced by spectroscopic studies of surfaces and meteorites derived from asteroids. From ice-rich comets and primitive carbonaceous asteroids to differentiated asteroids consisting of core, mantle and crust, investigation of these diverse classes of objects through missions designed and equipped to exploit their unique properties will reveal the range of materials and processes of the early Solar System. Additionally, the study of small bodies offers insights into the dynamical evolution of the Solar System, and physical and chemical processes that have continued through present day. Specific, top-level science objectives that would be addressed by human missions to asteroids include the following:

- Understand asteroid surface processes: While robotic spacecraft are typically constrained to resolution-limited mapping and single-site sampling, human explorers can document the full range of materials on asteroids including exogenic substances delivered by impacts. Asteroids that are considered the most primitive are thought to have remained primarily unchanged since their formation more than 4.5 billion years ago, but even these objects have been subject to potential modification by heating and/or interaction with water, and alteration of near surfaces by space weathering. How these processes occur on a single asteroid is poorly known, as are the details of their resulting materials. In many cases, meteorite groups once regarded as disparate may be found to be closely related - perhaps even originating from the same asteroid. The ability to collect larger, macroscopic representative samples, acquired with geologic context, will further understanding of the nature of these processes in the early history of the Solar System.

- Unique new samples: The world's meteorite collections are biased because they consist entirely of material impacting Earth that was strong enough to survive the passage through Earth's atmosphere. Impacting Earth involves exposure to its atmosphere, surface, and weathering processes, which can contaminate any samples that remain intact. For example, a meteorite was observed as a fireball in the Tagish Lake area of Canada in early 2000, and samples were collected within days of impact. These were found to be pristine compared to other meteorite samples, and chemical analysis revealed the meteorite to be "ultra-primitive" with an abundance of organic materials including amino acids. However, it was also discovered that the Tagish Lake meteorite had considerably low density and contained weak material. An estimated 97% of the meteorite was destroyed during its descent, and samples collected a few months after impact were found to have been significantly modified by chemical interactions on Earth's surface. Acquiring, preserving, returning, and analysing material directly from an asteroid would provide new and unique samples for scientific studies. In particular, samples from primitive, carbon-bearing bodies could provide diversity not represented in current meteorite collected samples, and include weak materials such as direct regolith samples.

- History of solar activity. The ability to sample the subsurface of Solar System objects in multiple locations will permit the study of solar evolution. Asteroidal regolith is a complex mixture of materials that are: indigenous to the asteroid; blended from impacts, and; formed by interaction with the solar wind, micrometeorites and the space environment. The upper few metres of an asteroid's regolith hold clues to these processes, and might shed light on the evolution of the Sun. Deep drill cores up to three metres in length could provide a record of surface-space interactions over millions of years. Although no comparable drilling of an asteroid has been attempted, this could be more feasible during a human mission.

- Increase the value of current asteroid samples: In addition to asteroid samples returned by Hayabusa (from asteroid Itokawa) and samples to be returned by the Origins, Spectral Interpretation, Resource Identification, Security, Regolith Explorer {OSIRIS-Rex} (Bennu) and Hayabusa 2 (Ryugu), the world's meteorite collections contain tens of thousands of samples that span a wide range of materials and processes. In the case of meteorites, these samples are without geologic context. For example, based on their composition we can determine that some meteorites originated from the Moon, but an exact location of where on the Moon they were ejected remains unclear. Human exploration of selected asteroids can provide the ground truth that allows us to place meteorites in the context of their parent asteroids through reflectance spectroscopy and remote observations of chemistry and mineralogy, thus vastly increasing the scientific value of the current meteorite collections.

- Provide an archive of samples with geologic context for analysis on Earth: Carefully documented samples returned by human exploration of asteroids will provide a permanent archive of materials for future scientists. Decades after Apollo, new analytical techniques revealed the importance of water in the evolution of the Moon. Similarly, robust asteroid samples are essential for labour-intensive, high-precision analyses of properties ranging from the abundance of solar wind implanted gases to the Solar System age of formation. Unlike the current robotically-secured samples, samples of known spatial relationships and orientation will enable new types of measurements (e.g., paleomagnetic strength and orientation). Leveraging human cognitive abilities to obtain well-documented geologic context for samples through deliberate evaluation, selection, and collection, will enable scientific analyses not currently possible.

- Organic compounds and the origins of life: NEAs can help unlock the age-old mystery of how life took shape on this world. Primitive NEAs represent the building blocks of the Solar System's terrestrial planets, and serve as time capsules for the early materials that contributed to Earth's formation. Determining the inventory of organic materials in these NEAs will provide key insights into the availability of such materials during the emergence of life on Earth. Many organic compounds are volatile and easily destroyed by higher temperatures or contact with water. Contamination from terrestrial organic compounds can also occur rapidly and diminish the science potential of samples. Thus, while meteorites provide numerous samples from asteroids, their study cannot fully address this question due to damage and contamination caused by Earth's atmosphere and surface. The ability to carefully select and collect samples directly from primitive carbon-bearing asteroids, and preserve robust samples by protecting them from contamination, would enable critical scientific advancements.

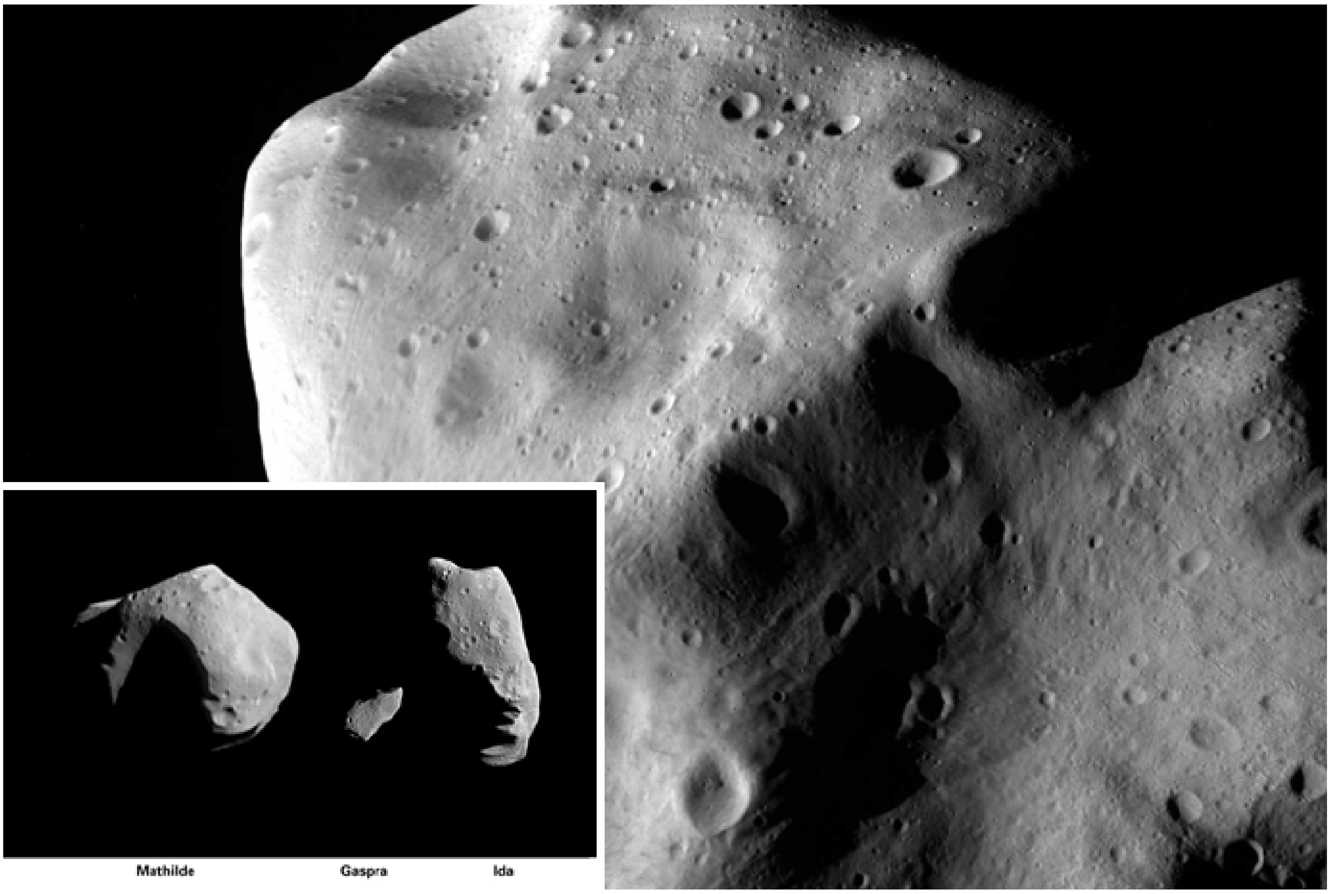


Figure 12: Asteroids are remnants of the early history of our Solar System and provide many scientific clues to its formation. The above images show different asteroids that were imaged by space probes in recent years. (Image courtesy of ESA)

Living and Working in Space

The human exploration of NEAs presents a unique opportunity to study the space environment and utilise the resources of a diverse range of materials, some of which are inaccessible on either the Earth or Moon. These materials may provide resources that can be used to explore other asteroids as well as exploration beyond low-Earth orbit and into the Solar System. Examples of the benefits of a human mission to an NEA include:

- Long-term instrument deployment to study the asteroid and space environment: A key advantage of the human exploration of asteroids is the ability to attach critical, delicate instruments to an unknown and unseen surface. These instruments can enable key investigations like seismology of the asteroid interior that requires careful coupling and long-term monitoring for small impacts. Likewise, long-term instrumentation may prove essential to understanding the interaction between the surface and the space environment, including dust created by human exploration. Understanding the duration and extent of a tenuous dust envelope, as well as the plasma environment created by interaction between the asteroid and the solar wind, will enable planning for longer-term exploration.

- Testing of planetary protection protocols: NEA operations may provide a relevant test-bed for martian exploration. Interplanetary contamination occurs in two directions: "forward" is the transfer of contaminants from Earth to another Solar System body, while "back" contaminants bring extraterrestrial compounds and life to Earth. For example, long-term survivability of terrestrial forward contaminants (i.e. spacecraft-transported or human-associated bacteria and viruses) detected in the asteroid environment can serve as an indicator of survival durations elsewhere (e.g. Mars). An NEA also presents an ideal environment to test cleaning protocols for removing potential "false-positive" results from experiments or instruments designed to detect life on other Solar System bodies. Indeed, NEA missions may offer opportunities to address key research and technology development knowledge gaps identified as important for planetary protection and human missions.

- Understanding asteroid structure as a key to planetary defence: Large asteroids visited by spacecraft appear to have remained primarily intact since their formation during the dawn of the Solar System, although their surfaces have been modified by impacts. In contrast, smaller asteroids are considered fragments of larger asteroids or piles of weakly consolidated rubble formed by catastrophic fragmentation of earlier generations of asteroids. Deciphering this macrostructure for individual asteroids is an elusive but essential part of understanding their threat to Earth and developing corresponding mitigation techniques. A human exploration mission could utilise a method that probes the deep interior of an asteroid and provides insights about its structure. The choice of technical approach to alleviating a potentially hazardous impact may depend on whether the asteroid is solid, fractured, or a loosely consolidated rubble pile.

- Learning how to extract resources to enable sustainable scientific exploration: Water is perhaps the most straightforward and attractive target resource for exploration, with its ability to provide feedstock for breathable air, drinking supply, and rocket propulsion. Additionally, water is an interesting subject for scientific study. However, the majority of water found in asteroids is most likely in the form of hydrated silicates, with some asteroids containing 10 to 20 percent bound water. As a result, water extraction will be a complex process that is ideally suited to human explorers. The ability to extract this resource will yield science through its examination and by enabling sustainable human exploration.

- Learning how to operate safely near the surface of a low-gravity object: The low gravity of an NEA is a challenging environment in which to navigate, with highly irregular gravity fields and comparable non-gravitational forces such as radiation pressure. Missions like Hayabusa, Hayabusa 2, OSIRIS-REx, and Rosetta have taken cautious and lengthy approaches to addressing the complexity of close encounters with the surfaces of such small Solar System bodies. The presence of humans will enable effective investigation of any complications and rapid decision-making in an environment that is not yet fully characterised. Developing such capabilities and experience will have direct application to potential future human exploration of the martian moons.

- Optimising the Human-Robotic Partnership. Human crews will be critical to the success of a mission to an asteroid. Performance of mission operations must be impeccable given that little is known of the constraints and challenges of the harsh asteroid environment, including details of the landing and working terrain. To mitigate mission risk, humans offer flexibility, creativity, ingenuity, and adaptability as well as finesse and dexterity beyond that of current robots. To fully leverage the potential of human explorers, it is essential to: develop interfaces that reduce the need for human learning and adaptation related to the machine, and; design the machine to maximise the effectiveness of the human-machine system. The optimization of the human-robotic partnership will also benefit the future exploration of Mars.

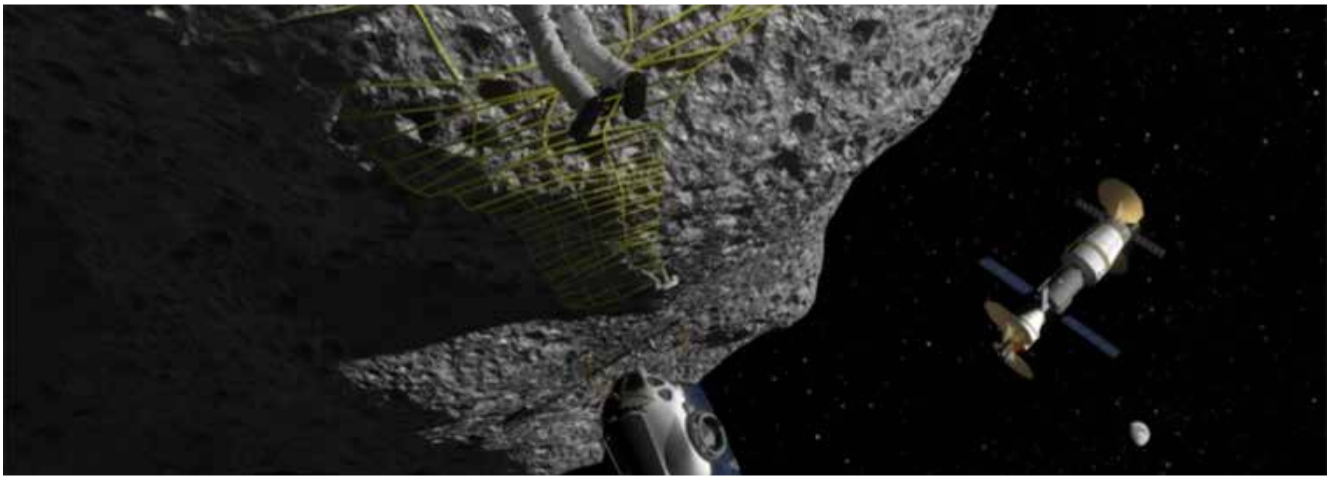


Figure 13: Astronauts visiting an asteroid would be able to handle delicate scientific instrumentation that could provide information on the internal structure of asteroids. This is of scientific interest, and it can also help with planetary defence.

Conclusion

Missions to asteroids would represent a new challenge for human endeavours in space, permitting the type of surface exploration not feasible with orbiting spacecraft. The NEA population exhibits considerable diversity, providing a wide range of opportunities for scientific exploration. Additionally, NEAs have witnessed events and conditions throughout the history of the Solar System, often retaining information that larger, evolved planetary bodies have lost.

Returning carefully selected samples of materials from Solar System bodies can enable key new scientific investigations. Meteorites provide asteroid samples that are biased toward materials strong enough to survive the journey to Earth's surface while subject to contamination from Earth's atmosphere and processes. A sample collected directly from an asteroid would not undergo this scenario, which would enable critical new studies such as determining the content of organic materials and evaluating their role in the origins of life on Earth. Additionally, careful sample collection that is enabled by humans can lead to a better understanding of the thousands of meteorites already available for study by scientists, providing geologic context to these meteorites that have formed much of the paradigm for the evolution of the Solar System.

The presence of humans will permit the handling of complex instruments to be attached to the surface of an asteroid, as well as the ability to sample below its surface. These subsurface samples could provide unique information on the ancient history of the Sun. As with the lunar surface, the ability of a trained explorer to select the best samples to return to Earth is a key component to maximising the science yield of these missions.

Studies made possible by the presence of humans include obtaining key information for planetary defence. Better understanding of the internal structure of asteroids, provided by in situ geophysical exploration, will be key to developing the mitigation strategies for an Earth-bound asteroid.

The accessibility of NEAs will enable extraction and analysis of volatiles, with some asteroids thought to contain 10 to 20 percent bound water. In addition to their compelling scientific possibilities, efficiently extracted volatiles represent a resource that could enable sustainable scientific exploration.

Developing the important capabilities needed to enable future human exploration of low-gravity bodies involves learning how to operate safely on and near their surfaces, obtaining samples, characterising surface properties, and studying geologic history. In particular, experience gained from the exploration of NEAs would have applications to potential future human exploration of the martian moons.

Finally, serendipitous discoveries may also occur as a result of human exploration, as the Apollo experience demonstrated. Since human beings have never set foot on the surface of an NEA, the potential for unanticipated discoveries is substantial.

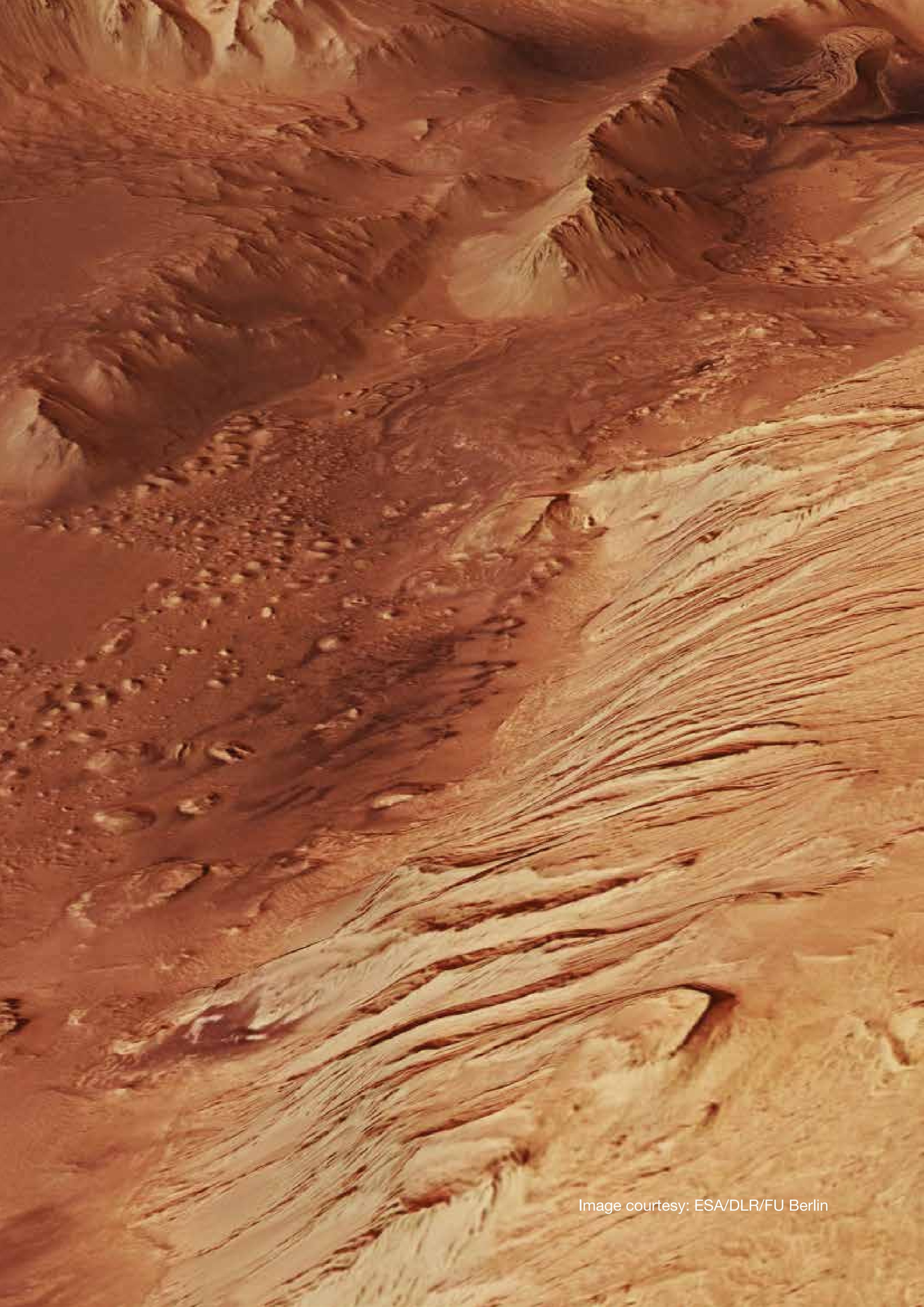


Image courtesy: ESA/DLR/FU Berlin

CHAPTER 6: MARS – THE HORIZON GOAL

Human missions to Mars present an unprecedented opportunity to investigate the closest and most Earth-like planetary neighbour. Mars has undergone geologic evolution not unlike that of early Earth, with fundamental differences (such as the lack of plate tectonic recycling) that have resulted in the preservation of ancient (> 3.5-billion-year-old) rocks, offering the best record in the Solar System of the first billion years of Earth-like planetary evolution. The ancient terrains of Mars have recorded evidence of widespread interaction between neutral water and crustal rocks, at the time that life first appeared on Earth. A dramatic transition occurred on Mars approximately 3.8 billion years ago, involving a change to acidic waters, a reduction in geologic activity, suspension of the magnetic field, and depletion of the atmosphere - although glacial, wind-driven, and volcanic processes continue.

Human missions to Mars could develop step-wise from a staging post in the Mars vicinity, from which teleoperation of robotic assets on the surface will provide significant operational efficiencies. Such a staging post might take the form of a base on the Mars moons Phobos and Deimos, which are also two destinations of scientific interest in their own right. Eventually, human missions to the surface of Mars would provide substantial capabilities to explore the surface. We expect that crews would be able to traverse to sites up to 100 km away from the original landing site using robust rovers. A habitat outfitted with state-of-the-art laboratory facilities could enable astronauts to perform cutting-edge science on the surface of Mars. A human-robotic partnership during exploration would further enhance the science return of these missions.

The scientific themes described in Chapter 2 were framed to address a wide breadth of scientific disciplines and destinations, many of those themes naturally also apply to the scientific exploration of Mars. Mars significantly differs from other destinations given its sheer size, dynamic environment, and potential for past or extant life. Finding evidence of life, past or present, would be an extraordinary discovery and would allow us to study the only other example of known life. The primary goal of this white paper, though, is to detail science enabled by near-term human exploration.

Figure 14: The Curiosity Rover needed five years to make its 14-km journey to Mt. Sharp on Mars. In its 13 years of operation, the Opportunity Rover has covered 43 km of martian terrain. Conversely, the crew of Apollo 17 traversed nearly 32 km across the lunar surface in just three days. (Image courtesy of NASA)


image courtesy of NASA

CHAPTER 7: CONCLUSION

The previous chapters describe the breadth of scientific opportunities made available by the presence of humans and associated infrastructure at destinations highlighted in the Global Exploration Roadmap. As an ongoing process that reflects the continuing maturity of planning, ISECG has developed Design Reference Missions (DRMs) that represent notional missions to the GER destinations and respond to the goals, objectives, and strategic considerations of participating agencies. The purpose of the DRMs is to represent a realistic scale for missions to these locations rather than describe the plans of agencies. As such, they are useful as a framework for required engineering solutions as well as a guide to understanding the amount and type of science that could be achieved by that class of exploration.

The current Global Exploration Roadmap DRM scenario envisions lunar vicinity infrastructure as the deep space gateway visited by crews in a cadence of approximately one mission per year. Initially, the gateway would not be permanently occupied, and long-duration astronaut health investigations will be limited to the stay time at the gateway. As the scenario matures, the scope of the gateway will be defined further, within which potential for specific instrumentation and a detailed assessment of scientific opportunities can be addressed. Similarly, the eventual location of the gateway will determine its suitability for specific scientific investigations. While many parameters currently remain open, it is expected that the scientific activities on board would make use of the ability to conduct long-duration experiments on the gateway. This will be combined with the advantages associated with periodic crew presence, allowing for scientific benefits over a wide range of fields (e.g. radiation experiments and dust/grain collectors). In addition, significant exploration of the lunar surface by telepresence of surface robotics is feasible with this mission scale, and will depend on gateway capabilities for teleoperation of robots and receiving samples from the lunar surface.

Mobility is a key factor in the science that is achieved during lunar surface exploration. The Global Exploration Roadmap DRM involves a crew living in a pressurized rover, which would essentially serve as a mobile habitat. From a scientific perspective, this architecture is particularly enabling for science, with future implications for human exploration of the martian surface. Such missions will facilitate regional investigations (e.g. the lunar South Pole-Aitken Basin) and young lava flows rather than global exploration. The study of polar ice deposits on the Moon can advance science questions regarding volatile delivery to the inner Solar System as well as the delivery of key building blocks required for life.

Concerning human missions to an NEA, the science addressed will hinge upon the asteroid that is selected. The scientific community has clearly formulated its interest in visiting different asteroids in their native orbits to maximise the scientific return.

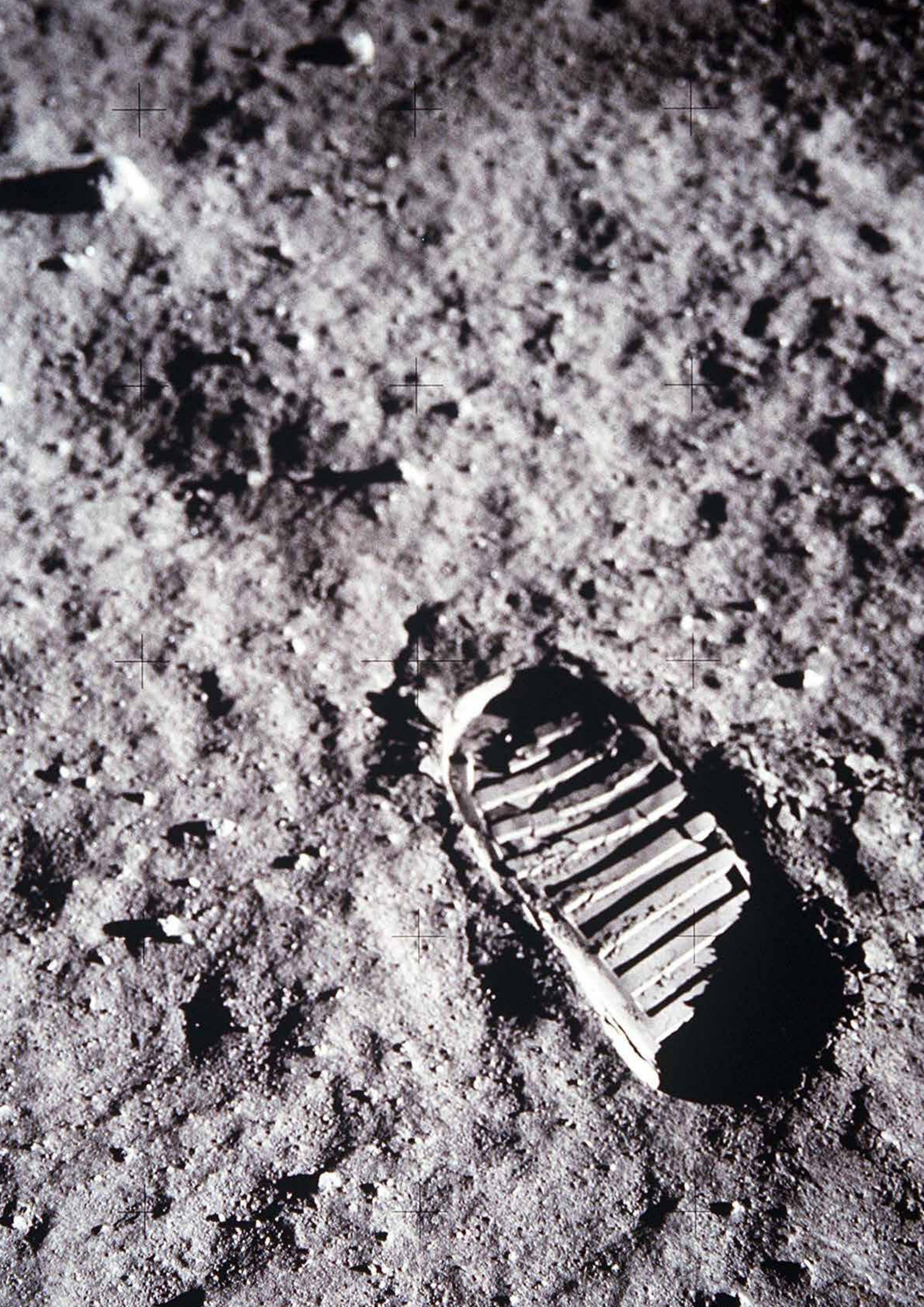
Mars is unparalleled as a horizon goal for human exploration and scientific value, but the actual path to the red planet is still being developed. In order to achieve this goal, more in-depth study utilizing our current capabilities is required.

Looking forward, it should be understood that future activities will most likely address a subset of the scientific opportunities described in this paper, and that this subset will reflect specific mission scope and associated capabilities. The implementation of actual missions will be a focus of international partnership and cooperation with new partners, similar to the very successful ISS partnership. In parallel, participating agencies will choose scientific priorities and instrumentation to ensure that the endeavour of human space exploration continues to deliver outstanding science for the benefit of citizens on Earth.


image courtesy of NASA

APPENDIX 1: SELECTED INTERNATIONAL SCIENCE AND STRATEGY DOCUMENTS

No.	Document Title	Year	Agency link
1	Moon: The 8th Continent: Final Report of ESA's Human Spaceflight Vision Group	2003	ESA
2	Report of the Commission on the Scientific Case for Human Space Exploration (Royal Astronomical Society, UK)	2005	
3	The Global Exploration Strategy	2007	ISECG participating agencies
4	The Scientific Context for Exploration of the Moon: Final Report (National Academy of Sciences, USA)	2007	NASA
5	NASA Advisory Council Workshop on Science Associated with the Lunar Exploration Architecture	2007	NASA
6	Science-Driven Scenario for Space Exploration (European Science Foundation)	2008	ESA
7	New Worlds, new Horizons in Astronomy and Astrophysics (National Academy of Sciences, USA)	2010	NASA
8	Vision and Voyages for Planetary Science in the Decade 2013-2022 (National Academy of Sciences, USA)	2011	NASA
9	THESEUS – Towards Human Exploration of Space: A European Strategy Roadmap (EU project, European Science Foundation)	2012	
10	Solar and Space Physics: A Science for a Technological Society (National Academy of Sciences, USA)	2013	NASA
11	Science and Challenges of Lunar Sample Return – Workshop Outcomes and Recommendations	2014	ESA
12	Pathways to Exploration: Rationales and Approaches for a U.S. Program of Human Space Exploration (National Academy of Sciences, USA)	2014	NASA
13	ESA Space Exploration Strategy	2015	ESA, ASI, CNES, DLR, UKSA
14	Canadian Space Exploration: Science and Space Health Priorities for Next Decade and Beyond	2017	CSA



APPENDIX 2: SCIENCE ADVISORY GROUP

The production of this science white paper was supported by a science advisory group (SAG) that consisted of an international cadre of scientists with a breadth of expertise. A list of the SAG members is shown below.

Co-chairs:

1.	Ben Bussey	(NASA, USA)
2.	Jean-Claude Worms	(ESF, France)

Members

3.	Gilles Clement	(University of Lyon, France)
4.	Ian Crawford	(University of London, UK)
5.	Mike Cruise	(University of Birmingham, UK)
6.	Masaki Fujimoto	(JAXA, Japan)
7.	Dave Hart	(University of Calgary, Canada)
8.	Ralf Jaumann	(DLR, Germany)
9.	Tim McCoy	(Smithsonian Institute, USA)
10.	Clive Neal	(University of Notre Dame, USA)
11.	Gordon Osinski	(University of Western Ontario, Canada)
12.	Maria Cristina De Sanctis	(INAF, Italy)
13.	Masaki Shirakawa	(JAXA, Japan)

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