White Paper #3: Planetary Science

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1 Foreword

The European Space Agency is a multi-facetted organization and comprises several directorates that are interested in inter-planetary flight. In the following sub-sections, we shall address scientific interests and specific goals for the Human and Robotic Exploration (HRE) directorate with respect to preparatory missions as precursors for human missions to the Moon, Mars, and near-Earth asteroids.

We note that the Science directorate (SCI) has a mandate to perform missions that are of interest to the European science community. The science programme (SCI) develops a bottom-up driven set of missions designed to answer major outstanding questions in planetary science and astronomy. This has, in the past, included missions to the Moon (SMART-1) and Mars (Mars Express). It is to be expected that the science programme (SCI) could also initiate missions to the targets discussed herein, but here we assume that HRE seeks to complement its missions, that are specifically designed to prepare for human exploration, by augmenting them with instrumentation that will provide support for future activities and also return valuable scientific data from these targets. It is important to recognize that there is no fundamental conflict between these two approaches –. Coordination and cooperation between D-HRE and D-SCI would clearly be desirable.

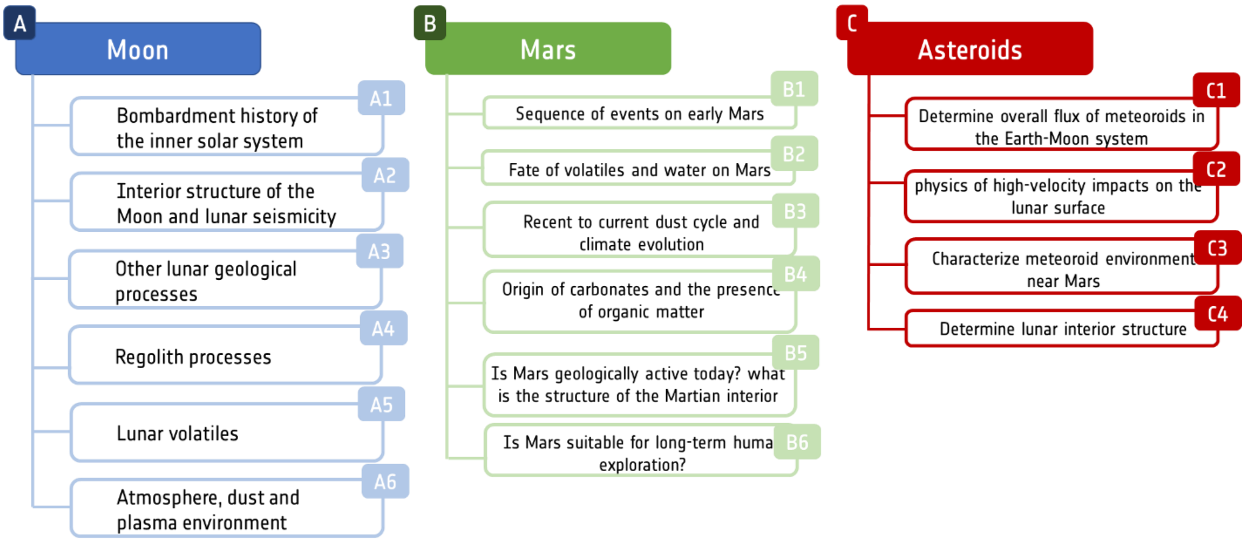
This type of cooperation has recently been evident in the HRE's ExoMars Trace Gas Orbiter (TGO) mission where SCI has contributed to the operations and the archiving of the data. For all the target bodies considered, many scientific questions are relevant and in fact mandatory pathways to identify the potential hazards and resource opportunities of the material on which human missions will one day land and explore. Similarly, another interest has been in studying whether the orbits of potentially dangerous near-Earth asteroids can be influenced by actions performed by spacecraft. The Hera mission is ESA's contribution as part of the international 'Asteroid Impact Deflection Assessment' collaboration with NASA and is of interest to the Space Safety programme within ESA. Although this is of importance and interest, it is separate from HRE-related aspects of direct human investigation of these objects, including their investigation as, for example, a potential resource of rare materials.

In preparing this document, the writing team has attempted to be inclusive. It has tried to incorporate a large array of lunar, Martian, and asteroidal objectives for HRE. There were two main reasons for this. First, the exact nature of any planned mission will constrain what additional science can be performed so that having multiple options is highly desirable. Second, although the writing team has clear scientific preferences, it comprises only a small minority of the European community, and it was considered necessary to try to be objective and fair to our colleagues by making sure that a breadth of scientific discipline was addressed. We point out that a call (Announcement of Opportunity) enunciating all the constraints followed by peer review of instrument proposals remains the most effective way of choosing primary payload elements.

The most important elements of this section are the tables which form matrices for linking instrumentation and timeline to fundamental science questions. The writing team envisages these tables as being the starting points for requirements matrices that will ultimately define the scientific capabilities of HRE's missions.

2 Key Planetary Science Topics

The Planetary Science community involved in ESA activities has defined and agreed on the following top science objectives and related sub-objectives for ESA's Human and Robotic Exploration Platforms.



2.1 Moon

2.1.1 Introduction

The Moon is a geological history book, preserving information about the early formation and evolution of the Earth-Moon system, that documents geological and astronomical events over more than 4.5 billion years. The surface of the Earth no longer retains this early history – the majority of terrestrial rocks being <300 million years old – due to its active plate tectonics and water cycle. The Moon therefore provides unique insights into early processes that are also no longer as well preserved on Mars, Venus, or other active planetary bodies. Thus, the Moon is an invaluable resource for understanding the history of bombardment in the inner Solar System, the formation and early evolution of terrestrial planetary bodies, the Solar System, our Sun and galaxy, as well as for providing insight into other fundamental Solar System processes. These topics form the basis for science "of the Moon", but the lunar surface is also a platform for science "on the Moon" and "from the Moon" – including investigations of habitability/survivability, physiology and medicine, fundamental physics, and astronomy [ESA, 2019a]. Finally, the Moon is a destination for technology research and development – in particular for developing in situ resources, manned exploration and habitation, and for its potential use as a waypoint for the human exploration of Mars [ESA, 2019b]. This document outlines key lunar science questions to be addressed over the next decades.

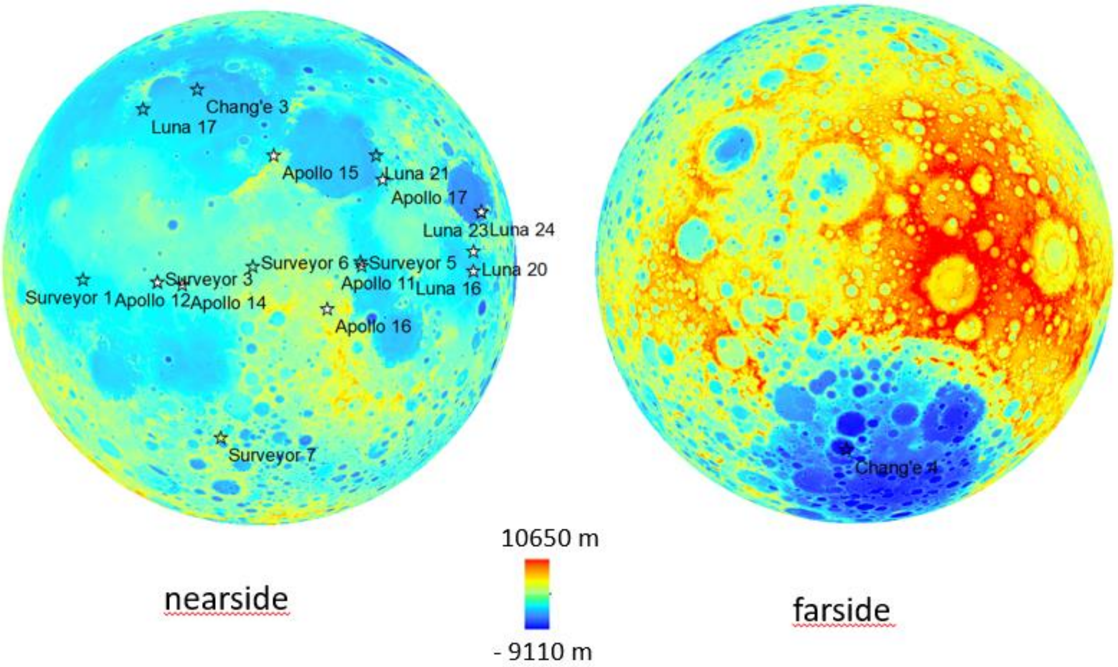


Figure 1: *Past lunar landing sites (stars) shown on the Lunar Orbiter Laser Altimeter digital terrain model showing lunar topography in meters. Filled stars indicate landing sites where samples were collected and returned to Earth.*

2.1.2 Key lunar science questions

Key lunar science questions have been compiled, discussed, and reviewed by the lunar science community in the course of several major studies. In particular, the American National Research Council published a report entitled “Scientific Context for Exploration of the Moon” [NRC, 2007], which has served as a reference for experiment, mission, and strategic planning since its publication. Recently, the Lunar Exploration and Analysis Group reviewed the progress made on achieving the goals outlined in the NRC report [LEAG, 2017], where they retired some goals and added new goals based on the results and questions arising from recent studies and missions. These and other reports and papers (e.g., Crawford et al., 2012; Pieters et al., 2018) were used to support the definition of ESA’s scientific and technological strategies for the Moon [ESA, 2019a; 2019b]. Outstanding lunar science questions are summarized below and in Table 1.

2.1.2.1 Bombardment history of the inner Solar System

The lunar surface provides a largely complete record of the impact history of the Earth-Moon system throughout Solar System history. Several aspects of this record are of compelling scientific interest, including whether or not there was a spike in the impact rate between 3.8 -4.1 billion years ago (the so-called Late Heavy Bombardment), and whether the impact flux has been mostly constant since then or has included episodic spikes (e.g., Kring & Cohen, 2002; Gomes et al., 2005; Strom et al., 2005; Head et al., 2010, Morbidelli et al., 2012; Bottke et al., 2012). An understanding of the modern impact history of the Moon is also important to estimate the current terrestrial impact hazard. The lunar impact rate or production function has been described by measuring the crater size-frequency distributions or spatial densities of various surfaces on the Moon. Additionally to the crater densities, the radiometric and exposure ages of the returned lunar samples helped to create the lunar chronology function (e.g. Neukum, 1983). The chronology function is used, with various assumptions, to estimate the ages of cratered surfaces throughout the Solar System. However, the calibration of the chronology function relies only on samples with ages of <1 billion and between 3.2 and 3.9 billion years old (Figure 1). Samples of well-established provenance (Figure 1) with ages older than 3.9 Ga and between ~1 and 3 Ga were missing from the sample collection until the Chang’e-5 sample return mission. Improving the calibration of the lunar cratering chronology model would be of great value for planetary science because it would: (1) provide better estimates for the ages of unsampled regions of the lunar surface; (2) give a more reliable estimate of the impact history of the inner Solar System, especially that of our own planet; and (3) enable better estimates for the ages of other planetary surfaces (e.g. that of Mars) from which samples have not yet been obtained. In order to meet these objectives, it will be necessary to visit geological units – e.g., ancient impact basins and young basalts – of a much wider range of ages than previously sampled and either return samples to Earth for radiometric dating or precisely radiometrically date the materials in situ. Activities that have been rated as highest priority in previous strategic documents include: (1) investigate the occurrence of an early impact spike or cataclysm, (2) determine the age of the oldest lunar basin (South Pole-Aitken basin), (3) improve calibration of the lunar cratering chronology, and (4) monitor the current impact flux.

2.1.2.2 Interior structure of the Moon and lunar seismicity

Improved understanding of the interior structure of the Moon will provide fundamental information on the evolution of differentiated planetary bodies. The Moon is especially important in this respect because the absence of internal activity associated with mantle convection (such as plate tectonics on the Earth) means that the interior of the Moon likely retains a record of early planetary differentiation processes (e.g. magma ocean crystallization). A record of such processes is no longer preserved in more evolved planetary bodies. Understanding the history of lunar magnetism, and its relationship to the evolution of the lunar core, will also provide insights into the mechanisms of magnetic field generation in terrestrial planets. Previous reports outline the following scientific goals: (1) investigate the thickness and lateral variability of the lunar crust (and of the nearside/farside crust asymmetry), (2) examine the chemical and physical stratification of the mantle, (3) characterize the lunar core, and (4) determine the current thermal state of the lunar interior. Making progress in these areas will require deploying geophysical instruments to the lunar surface. Key instruments include seismometers to probe the structure of the deep interior, heat-flow probes to measure the heat loss and the thermal conductivity from the lunar interior and its spatial variations, magnetometers to measure the local surface magnetic fields, and laser reflectors to measure the Moon's physical librations which are related to the distribution of mass in the interior. Such measurements will also yield relevant data for gravity and fundamental physics studies. Ideally, a lunar geophysical network would be assembled by equipping multiple landers (e.g., ESA's proposed European Large Logistic Lander (EL3) and/or commercial missions of opportunity) with a standard set of geophysical instruments including a seismometer, heat-flow probe, magnetometer, and laser reflector. Studies of lunar magnetism would additionally benefit from the collection of samples from which the remnant magnetic fields, including evidence for paleofield orientations and reversals, could be measured. Sample collection for magnetic analyses requires development of containment and curation protocols that can protect and preserve magnetic properties. Humans at the lunar surface can also support the accurate recording and preservation of original sample orientation in relation to the lunar surface, as well as facilitating the deployment of a wider range of geophysical instrumentation than could be deployed robotically.

In addition to the installation of a seismic network, continued high resolution imaging of the lunar surface would enable further identification of small tectonic features on the Moon and allow the assessment of the current seismic activity and identification of potential exploration hazards. Due to the fresh morphology of some small lunar scarps and related graben, it is possible that recent moonquakes might be associated with their formation. Active scarps, could pose a hazard for robotic and human surface activities.

2.1.2.3 Other lunar geological processes

Other geological processes prioritized for investigation are: (1) the formation and evolution of the crust, (2) volcanism, and (3) the impact cratering process.

The rich remote sensing data collected over the last decades has improved the understanding of lunar crustal rock compositions and mineralogy, and their global distribution across the Moon (e.g., Figure 2). With these data as a basis for selection of targets, for higher resolution and/or additional wavelength-range remote observations, and landing sites, for in situ analyses and sample collection/return, we can gain more information about key planetary processes that are revealed in the lunar crustal rocks. Goals outlined in earlier reports include: (1) investigating the compositions and distributions of the feldspathic crust, KREEP terrane (n.b. KREEP is is geochemical component), lower crustal materials, and the bulk Moon; (2) identification of new lunar rock types and their ages, distributions, and origins; (3) determining the local and regional complexity of the crust; and (4) exploring the vertical extent and structure of the megaregolith. Investigations of lunar crustal rocks can be driven forward by more advanced remote sensing measurements, in situ and returned sample analyses, and also by the installation of seismic stations and networks.

Volcanism is a major geological process on the Moon, which has significantly shaped the current lunar surface, and also provides information about its compositional and thermal evolution. Important questions regarding lunar volcanism include the determination of: (1) the origin and variability of lunar basalts; (2) the ages of the youngest and oldest basalts (which is also relevant for calibrating the lunar cratering chronology); (3) the compositional range and extent of pyroclastic deposits; and (4) the volcanic flux and evolution. Studies of lunar volcanism not only feed into the lunar cratering chronology, but also aid in the understanding of the nature and evolution of the lunar interior. Advanced remote sensing measurements, in situ analyses, and sample return missions can all contribute to the achievement of volcanism-related science goals.

Due to the absence of a substantial atmosphere, liquid water, and plate tectonics, the Moon also provides important information about impact cratering processes – from micro-impacts to basin-sized impacts (D = 300 km). Specific major goals for understanding impact cratering processes on the Moon include investigating: (1) impact melt sheet differentiation; (2) multi-ring impact basin structure; (3) the influence of planetary properties on crater formation and morphology; and (4) the extent of mixing of materials both proximal and distal to craters. Again, remote sensing, in situ analyses, and sample return missions, as well as geophysical observations, will provide input for these issues.

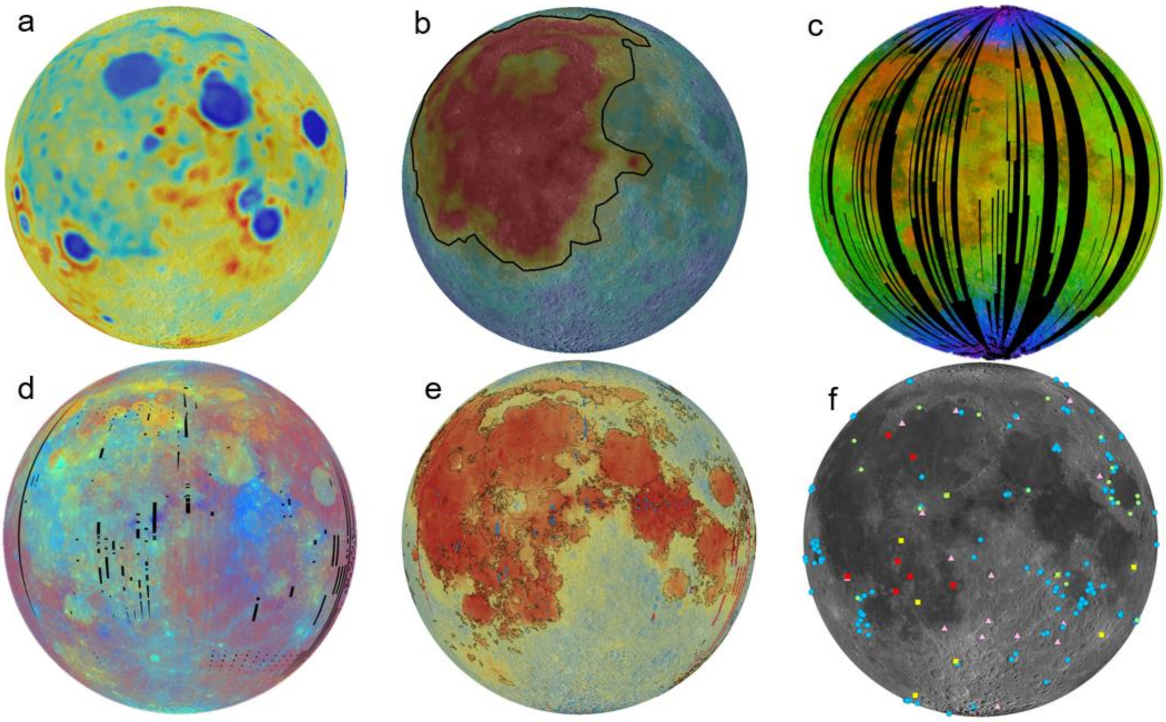


Figure 2: *Modern views of the lunar nearside (orthographic projection centered at longitude 0°).* ***a)*** *New crustal thickness models determined by the GRAIL mission (rainbow scale blue to red, 3-70 km) overlaid on the Lunar Reconnaissance Orbiter (LRO) Wide-Angle Camera (WAC) mosaic;* ***b)*** *Lunar Prospector Gamma Ray Spectrometer Th abundance (rainbow scale blue to red, 0.4-12.9 ppm) on the LRO WAC mosaic, where the black line outlines the limits of the Th-rich Procellarum KREEP terrane;* ***c)*** *Color composite of Chandrayaan-1 Moon Mineralogy Mapper (M3) low-resolution dataset, where red highlights the 2.0 µm pyroxene absorption, green the surface reflectance at 2.4 µm, and blue shows the 3 µm water/hydroxyl feature;* ***d)*** *Clementine UVVIS warped color-ratio map (red = 750 nm /415 nm, green = 750 nm /1000 nm, blue = 415 nm /750 nm) in which the red channel shows areas that are either low in titanium, high in glass (e.g., pyroclastics), or mature (e.g., pristine highlands), the green channel is sensitive to the amount of iron, and the blue channel reflects the surfaces with high titanium or bright slopes and high albedos;* ***e)*** *Clementine Fe abundances (rainbow scale blue to red, 0-20 wt%) are shown on the LRO WAC mosaic, where the black contours outline mare basalt units;* ***f)*** *M3 and SELENE Spectral Profiler high resolution observations allowed multiple, recent detections of spinel (pink triangles), olivine (green dots) and pure anorthosite (blue dots), "red spot" spectral anomalies (red*

squares), and occurrences of Mg-plutons (yellow squares) shown on the LROC WAC mosaic. For references please refer to [Mangold et al., 2019].

2.1.2.4 Regolith processes

Regolith is a several meter-thick layer of unconsolidated material that covers the lunar surface, and includes a mixture of both lunar soils (<1 mm) and rock fragments. Formed in large part via solar wind and galactic particle collision and implantation into lunar surface materials. The regolith retains a unique record of solar and galactic events over billions of years and is also the prime source for derivation of in situ oxygen, water, metals, and other important volatiles and building materials. After previous landed and orbital missions, a number of questions remain pertaining to (1) the formation mechanisms of regolith on airless bodies, (2) its modification (space weathering, deposition of volatile materials), (3) its physical properties (strength, cohesion, composition, grain size), and (4) its lateral and vertical variations. Analysing and collecting regolith from various locations outside of the to-date investigated areas at the Apollo, Luna, and Chang'e landing sites – in particular polar locations, feldspathic highlands, young terrains, pyroclastic deposits, and lunar swirls – would enhance our understanding of regolith properties and variability. Missions with mobility elements increase the opportunities to (1) understand and characterize lateral variations, (2) search for and investigate ancient regolith (and hence the ancient Solar System record), and 3) identify and study rare materials in the lunar regolith, such as meteorites derived from the early Earth.

2.1.2.5 Lunar volatiles

Both sample analyses and orbital remote sensing observations point to the existence of water in various forms at the lunar surface. Indigenous water has been found in lunar minerals, whereas solar wind is responsible for diurnally variable hydroxylation and hydration of the lunar surface by exogeneous processes. With annual maximum temperatures as low as 40K, some high latitude areas that never receive sunlight (Permanently Shadowed Regions or PSRs) are expected to concentrate and retain solid H_2O ice along with numerous other volatiles (e.g., CO_2, NH_3, SO_2). Lunar polar volatiles trapped in PSRs near the poles may hold clues to the origin of water in the inner Solar System and also have strong potential as a reservoir for extraction of water, oxygen, and other volatiles. The origin, whether by impact, from solar wind, or via volcanic degassing; vertical and lateral distribution; abundance; resource potential; age; and transportation/accumulation cycle of lunar volatiles are all poorly constrained and could be addressed with both in situ measurements and/or sample return from the polar regions. Non-polar volatiles could also be analyzed through sample return missions targeting specifically (1) equatorial mid-latitudes regions inside and outside of lunar swirls, to assess the role of solar wind implantation, (2) freshly exposed/young material which have not been affected by long term solar wind exposure to explore indigenous volatiles, and (3) volcanic provinces and pyroclastic deposits which may exhibit enhanced indigenous volatiles contents.

2.1.2.6 Atmosphere, dust and plasma environment

The lunar atmosphere is the most accessible surface boundary exosphere in the Solar System, and thus offers insights into surface sputtering, meteoritic vaporization processes, exospheric transport processes, and gas-surface thermal and chemical equilibration. This dynamic system also plays a role in the transportation and deposition of volatile elements. Still, its composition, sources (comets, asteroidal meteorites, transit of interstellar giant molecular clouds, Earth, Moon interior), sinks (photodissociation, Jeans escape, solar wind pickup, condensation), and variations due to impacts, diurnal cycles, and solar activity are poorly understood. Models show that once released by heating or sputtering, atmospheric volatiles migrate towards the poles where they are trapped in PSRs, but further measurements are needed to determine what processes control the atmospheric migration and the efficiency of the transport to the poles. The fragile lunar atmosphere should be characterized with instruments such as ion-mass spectrometers and optical/UV spectrometers onboard low-altitude orbiters or landers in the short-term, *before* surface activities further perturb it from its native state.

In addition to He, Ne, and Ar, lunar dust is a major component of the lunar atmosphere. Moon dust is formed by micron and sub-micron-sized particles charged by the local plasma environment and/or ejected by micrometeorids, and can travel via two mechanisms: levitation and lofting. Conjectured resulting transport phenomena range from the levitation of micron-size dust grains at low altitudes (centimetre to meter height) to the lofting of sub-micron particles to tens of kilometres. As lunar dust is surprisingly abrasive, understanding its physical properties (size, charge, distribution) is key to future exploration. Dust impacts were mostly observed to peak around the terminator region, suggesting a relationship with horizon glow, and illustrating the necessity to better understand the electric potential at the lunar surface and the dust/plasma interactions with the deployment of experimental packages at a network of monitoring stations.

2.1.3 The Moon as a platform for scientific investigations

In addition to its intrinsic interest to planetary science, the Moon is also a potential platform from which a diverse range of scientific investigations may be supported:

(a) Astronomy and astrophysics

One of the principal benefits of a lunar platform for astronomy is the usefulness of the radio-shielded farside for low-frequency radio astronomy. Radio waves with wavelengths longer than about 20 m cannot penetrate the Earth’s ionosphere, and so must be observed in space. These wavelengths are expected to be a rich source of astrophysical information – including highly red-shifted 21 cm lines absorbed against the cosmic microwave background by hydrogen clouds shortly after the Big Bang. The lunar farside is probably the best location in the Solar System from which such observations could be made. Observations at all other wavelengths could also be made from the lunar surface. Although to-date many such observations are made from free-flying spacecraft, the lunar surface may still offer some advantages (e.g. the possibility for passive cooling of IR instruments in permanently shadowed lunar craters, and the provision of a solid substrate on which to mount optical/IR interferometers). Moreover, in the context of ESA’s Exploration Programme, access to the infrastructure provided by human activities on the lunar surface would aid in the maintenance and up-grading of astronomical instruments compared to free-flying satellites. Finally, the lunar surface lends itself to studies on the interface between astrophysics and fundamental physics (e.g. by facilitating emplacement on the lunar surface of instruments to study ultra-high-energy cosmic rays, general relativity, and quantum entanglement over the Earth-Moon baseline).

(b) Life sciences

The Moon is a potential laboratory for understanding the environmental parameters that affect life in space. For example, the Moon can be used to investigate the biological effects of: low, but non-zero gravity, the radiation environment beyond the Earth’s magnetosphere, and the toxicity of lunar dust. A diverse range of organisms and biological models could also be taken to the lunar surface and used to carry out investigations *in situ* using surface laboratories. In the short term this can involve passive and active exposure facilities, with additional return of such facilities in the mid-term for detailed follow up analysis in terrestrial laboratories. These experiments would yield new insights into fundamental biological and physiological processes and the adaptation to, and evolution of, organisms in the space environment. This would feed into the implementation of bio-regenerative life support systems, food production, and the mitigation of adverse consequences of low gravity and high radiation environments to enable human exploration elsewhere in the Solar System, for example the surface of Mars.

2.1.4 Priorities for the HRE SciSpacE Programme

Key steps for future long-term exploration will require the development of enabling technologies such as:

- Precision landing and automated hazard avoidance
- Surface mobility
- Power and heating systems to enable survival during lunar night and within PSRs
- Tele-robotics
- Significant (>1000 kg) landed payload masses (e.g. EL3)
- Deep (10-100m) drilling capability
- Sample return
- Capability for extraction and caching of cold/icy samples (Cryogenic) sampling and caching
- Human operational capabilities in the lunar vicinity and/or on the lunar surface
- In-Situ Resource Utilization (ISRU)

As outlined in Table 1, short-term progress can be made on answering fundamental scientific questions about the Moon by leveraging existing technological capabilities and partnerships. Plans for mid- to long-term strategic technology development, including the capabilities listed above, will enable the achievement of higher level scientific goals. Many of the scientific goals can be accomplished via remote sensing and robotic missions. However, detailed geological studies and refined selection of lunar samples benefit significantly from the involvement of astronauts, either via tele-robotics in the lunar vicinity or on the lunar surface [ISECG, 2017]. The International Space Exploration Coordination Group produced a report describing human activities beyond low Earth orbit which open scientific opportunities. A station or Gateway in the lunar vicinity could serve as a platform for lunar surface operations, including remote collection and transfer of lunar samples. A human presence on the Moon not only allows the dexterous and dynamic collection of samples and measurements for investigation of scientific questions in real-time, but also provides a valuable testbed for technologies that enable exploration of more distant destinations.

This report does not rank specific scientific questions in order of priority, rather each topical area is accompanied by short, mid-, and long-term technological goals. Thus, a combination of scientific questions can be addressed within the strategic framework of current and future space exploration technologies. Nevertheless, progress on development of new and more capable technologies is a requirement for achieving higher level scientific goals – for example sample return for analysis in terrestrial laboratories.

Figure 3: Artistic view of ESA's European Large Logistic Lander (EL3) project [ESA].

2.1.5 Benefit for Earth and industrial relevance

Development of key payloads and technology drivers is expected to enable robotic and human exploration beyond low Earth orbit, in the vicinity of the Moon and on the lunar surface. Technologies developed during lunar-related activities will provide valuable input for missions to worlds more distant. For example, precision landing and automated hazard avoidance, tele-robotics, and surface mobility improvements can be applied to missions to all solid planetary bodies. Development of cryogenic sample return could be used on missions to comets and icy moons in the outer Solar System. ISRU and lunar construction technologies will serve as a basis for longer term habitation of the Moon and foster a lunar economy to support further research and development. Typical for the space exploration program, technological developments in robotics, communications, resource use, and other technologies will feed back to terrestrial applications.

2.1.6 Recommendations in short, middle and long term

Short term:

- Support European analyses of Chang'e-5 and Chang'e-6 lunar samples
- Continue geological training of ESA astronauts and development of their geological tools and tele-robotic capabilities
- Support continued geological and mineralogical mapping of the Moon and identification/characterisation of landing sites

- Support development of innovative geological, geophysical, astronomical, astrophysical and biological instruments for transport to the lunar surface on forthcoming ESA, international, and commercial lunar missions
- Support characterization of the lunar exosphere before it is altered or destroyed by frequent landed missions
- Prepare for future lunar sample return including curation, containment, sampling, cryogenic sample handling/storing etc.

Medium term:

- Support ESA's PROSPECT payload on Luna 27
- Support ESA participation in Artemis, Gateway, and other opportunities
- Support development of science payloads for EL3 (e.g. geophysical instruments, mineralogical and geochemical instruments, in situ radiometric age determination, biology experiments, astronomical instruments, drilling capability, etc.)
- Support development of ISRU payloads for EL3
- Support continued and improved remote-sensing of lunar surface, from small or opportunistic missions, such as VMMO, to larger survey orbiters that build on the success of LRO.

Long term:

- Deploy geophysical network(s) on the lunar surface
- Enable tele-robotic and/or human exploration of the lunar surface by ESA astronauts
- Implement lunar drilling capability
- Execute at least one ESA-led sample return mission
- Deploy farside low-frequency radio astronomy array
- Deploy life sciences payload(s)
- Surface exploration/prospecting of a lunar polar region and a previously unvisited non-polar location/lithology

2.1.7 Conclusions

Over the last half century, lunar missions have driven significant advances in our understanding of the nature, formation, and evolution of our moon, as well as the Earth and other planetary bodies. These advances have led to new, more refined questions that require more technologically-advanced observations and measurements, and the collection of additional samples that are not yet represented in our current collection. The accessible and unique ~4.5 billion year old record preserved on the Moon is a treasure that will reveal fundamental discoveries, not just about the Earth-Moon system and the development of life on Earth, but also about the geological processes involved in planetary formation and evolution in general. In addition, there are growing international opportunities to use the Moon as a platform for science (geology, biology, medicine, physics, etc.), for development of in situ resources, and as a gateway to more distant worlds, such as Mars. Major scientific breakthroughs are therefore expected in the near term, but depend on the development of key technologies and capabilities, including those outlined in this report. The synergies between scientific and technological exploration strategies for the Moon promise exciting advances in the next decades, including the return of humans to the lunar surface.

Open fundamental scientific question	Future HRE SciSpace experiments and suitable environment (LEO, Moon, Mars, BLEO)	Space relevance (importance of microgravity and/or relevance for space exploration)	Timeline (S: short; M: medium; L: long)
Bombardment in the inner Solar System *Ancient bombardment:* Nature of bombardment on the early Moon? Was there a lunar cataclysm or planet migration in the early Solar System? What is the age of the oldest impact structure? Relation to the emergence of life on Earth? *Present bombardment*: Understand the nature of bombardment in the last 1 Ga – constant or in swarms? What is the present flux?	In situ and/or sample return age analyses for (1) key lunar basins (including SPA), (2) young basalts, (3) key young craters Remote observations of newly formed craters, and installation of seismic networks to measure their frequency and magnitude	*Present bombardment:* Assess present hazard for the Earth and for lunar surface operations and future infrastructure. *Absolute chronology for the Solar System:* Improving the absolute chronology is critical for interpreting the geological history of all terrestrial planetary bodies to which it is applied; this fundamental information feeds into agency strategy and mission planning *Technology driver:* Development of communications, landing, payload, surface operations capability, and sample return capability	(S) Participation in Chang'e-5 and Chang'e-6 sample analyses; (S) Develop/support implementation of seismic/geophysical payloads (M) In situ analysis payload development for EL3; (M-L) At least one in-situ age or sample return mission to a key geological unit; (L) Gateway-based, human/robotic sample return concepts
Lunar interior, seismicity, tectonics Differentiation? Origin of subsequent asymmetric crustal, thermal and	Globally distributed seismic, magnetic and heat flow network; expanded retroreflector network	Evaluate present hazard for surface operations/construction *Technology driver:* Development of communications, landing, payload, and surface operations capability	(S) Develop/support payloads with geophysical instrumentation; (S) Support placement of geophysical network nodes at mission of opportunity sites; (L) Deploy geophysical network across the Moon

Open fundamental scientific question	Future HRE SciSpace experiments and suitable environment (LEO, Moon, Mars, BLEO)	Space relevance (importance of microgravity and/or relevance for space exploration)	Timeline (S: short; M: medium; L: long)
volcanic evolution? Current level of seismicity?			
Geological processes as revealed by the Moon *<u>Formation/evolution of crust:</u>* Crustal homogeneity (LMO, KREEP etc.)? *<u>Volcanism:</u>* How recent? Role of volatiles? Thermal evolution? Interior diversity? Resources? *<u>Impact cratering:</u>* Processes as revealed on a body with less active geology than the Earth?	Sample return and in situ measurements, chronology, and mineralogical/geochemical compositional measurements Orbital compositional observations at higher resolutions and expanded wavelength ranges Regional seismic networks for understanding subsurface structures Observation of changes over time (tectonics/impacts/mass-wasting)	Resource assessment for materials applicable to ISRU, construction, and other surface activities Scientific input for agency strategy and mission planning *<u>Technology driver:</u>* Development of communications, landing, payload, and surface operations capability	(S) Participation in Chang'e-5 and Chang'e-6 sample analyses; (S) Develop/support placement of basic mineralogical/geochemical packages on missions of opportunity; (S) Support additional studies of landing sites for assessment of science questions, including hazard assessment and specific site selection, for agency-directed use during missions of opportunity; (M) Support/develop remote observation of the lunar surface at extended thermal infrared wavelengths; (M) Support/develop follow-on mission for NASA's Lunar Reconnaissance Orbiter mission to provide high resolution imaging of the lunar surface; (M) In situ analysis payload development, sample return mission or payload development for EL3; (L) Gateway-based, human/robotic sample return and analysis concepts
Water and other volatiles	Orbital observations and ground-truth of nature, distribution,	Resource assessment for materials applicable to ISRU,	(S/M) PROSPECT on Luna-27; Viper; CLPS opportunities, similar missions;

Open fundamental scientific question	Future HRE SciSpace experiments and suitable environment (LEO, Moon, Mars, BLEO)	Space relevance (importance of microgravity and/or relevance for space exploration)	Timeline (S: short; M: medium; L: long)
Origins? Distribution? Abundances? Compositions? Processes? Lunar volatile cycles ? Resources?	extent, composition of water and volatiles Core samples to investigate vertical distribution, nature and origin Cryogenic sample return	construction, and other surface activities *Technology driver:* Development of communications, landing, payload, and surface operations capability; Development of ice/volatile handling and storage	(M) Support delivery of analytical/technical payloads to polar regions; (M) Orbital mapping of H_2O ice and other species at an unprecedented resolution, support payload development (M) Collaborate with CNSA on lunar research station at lunar south pole; (M) ESA EL3 contributions; (L) Cryogenic and other volatile rich sample return; multiple drill cores (L) Gateway-based, human/robotic sample return and analysis concepts
Regolith Formation and weathering processes? History of the Sun and Solar System? Resources?	Sample return, regolith stratigraphy /deep drill core, samples of paleoregolith; swirls	Resource assessment for materials applicable to ISRU, construction, and other surface activities *Technology driver:* Development of communications, landing, payload, and surface operations capability; Development of deep-drilling technologies	(S) Participation in Chang'e-5 and Chang'e-6 sample analyses; (S) Participation in analyses of recently opened Apollo samples; (S) Develop/support placement of basic mineralogical/geochemical/geotechnical packages on missions of opportunity;

Open fundamental scientific question	Future HRE SciSpace experiments and suitable environment (LEO, Moon, Mars, BLEO)	Space relevance (importance of microgravity and/or relevance for space exploration)	Timeline (S: short; M: medium; L: long)
			(M) ESA EL3(e.g. in situ analyses of geotechnical and geological/geochemical properties of lunar regolith); (M/L) Sample return, return of core samples and paleoregolith (L) Gateway-based, human/robotic sample return and analysis concepts
Atmosphere, dust, and plasma environment Exosphere formation, properties and evolution? Dust levitation and transport? Sources of mid-latitude surface hydroxyl and water? Migration of hydrogen to cold traps? Electrostatic lofting of dust associated with plasma anomalies/voids? Changes due to surface activities?	UV and mass spectrometers, material adhesion experiments, Langmuir probes	Assess hazards for future robotic and human exploration	(S) Develop/support placement of plasma, neutrals, magnetic and electric fields and dust particles instruments on missions of opportunity; Gateway and lunar surface (EL3) (M-L) Deploy a global network of long term monitoring stations (including ion-mass spectrometers, optical UV spectrometers, dust and plasma experiments)
Moon as a platform Astronomy, astrophysics, fundamental physics,	Low frequency radio-antennas, optical/IR telescopes, laser retroreflectors, cosmic ray	Prepare for long-term human habitation of the Moon and human missions to Mars and beyond	(S) Deploy laser reflectors on near-term robotic landers;

Open fundamental scientific question	Future HRE SciSpace experiments and suitable environment (LEO, Moon, Mars, BLEO)	Space relevance (importance of microgravity and/or relevance for space exploration)	Timeline (S: short; M: medium; L: long)
life sciences and astrobiology, e.g., adaptation of life (including human physiology) to low (but non-zero) gravity and enhanced radiation environments	detectors combined with boreholes; bio-regenerative life-support systems; agricultural systems; radiation protection; mitigation of long-term exposure to low gravity and the integrated lunar surface environment.		(M-L) Deploy farside low-frequency radio antennae; deploy cosmic ray detectors; deploy Earth-observing instruments (including instruments to study Earth's magnetosphere); deploy life sciences experiments (L) Gateway-based, human/robotic concepts

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2.2 Mars

2.2.1 Introduction

Mars' complexity is nearly equal to that of Earth. As a system it comprises an exosphere, atmosphere, surface including cryosphere or hydrosphere, shallow subsurface and deep differentiated interior. Each of these components has evolved substantially through interactions with one another and with the space environment.

Mars is intriguing because it is intermediate between a world frozen in the past and an ever-evolving planet like the Earth. It exhibits recent activity, while still broadly retaining its primordial fingerprint. The processes active on Mars were both exogenous and endogenous, and date back several billion years. Consequently, studying Mars not only provides a means of investigating present-day geological mechanisms, but also affords a window into early history, which can help understand the generic evolution of other bodies in our Solar System.

Mars possesses the added lure that it is a prime exobiological target. Mars has evidence of past extensive and pervasive water-rich environments - from its surface down to the upper crust. These are varied in nature. There were clearly a range of geochemical conditions, some of which may have been niches for past life. Mars also has the oldest sedimentary record in the Solar System, meaning that should prebiotic or biotic matter have existed at Mars, it may well have been preserved in the rock record for more than 3 billion years, and be amenable to sampling. That same period with perhaps similar water environments led to abiogenesis on Earth. While early Mars and Earth had important differences (*e.g.* size, distance from the Sun, supposed volatile content), their surface environments are thought to have shared a number of common traits. Early Mars is arguably the best available analogue to the young Earth's prebiotic era.

The proximity of Mars to Earth and its reasonably benign surface conditions largely accounts for the fact that it is the most explored planet in our Solar System. The wealth of data, from flybys to roving platforms (soon to be augmented by airborne devices), have provided an unparalleled level of detail. In turn, this has stimulated a large and vibrant Mars scientific community that is keen to unlock the secrets of the planet.

In the mid- to long-term, Mars human exploration is a likely goal. Scientific exploration results contribute essential feedback for mission planning because they provide information on hazards and local resources.

In the following section, we discuss major open questions that can be answered through new and/or improved instrumentation in the next 10-20 years.

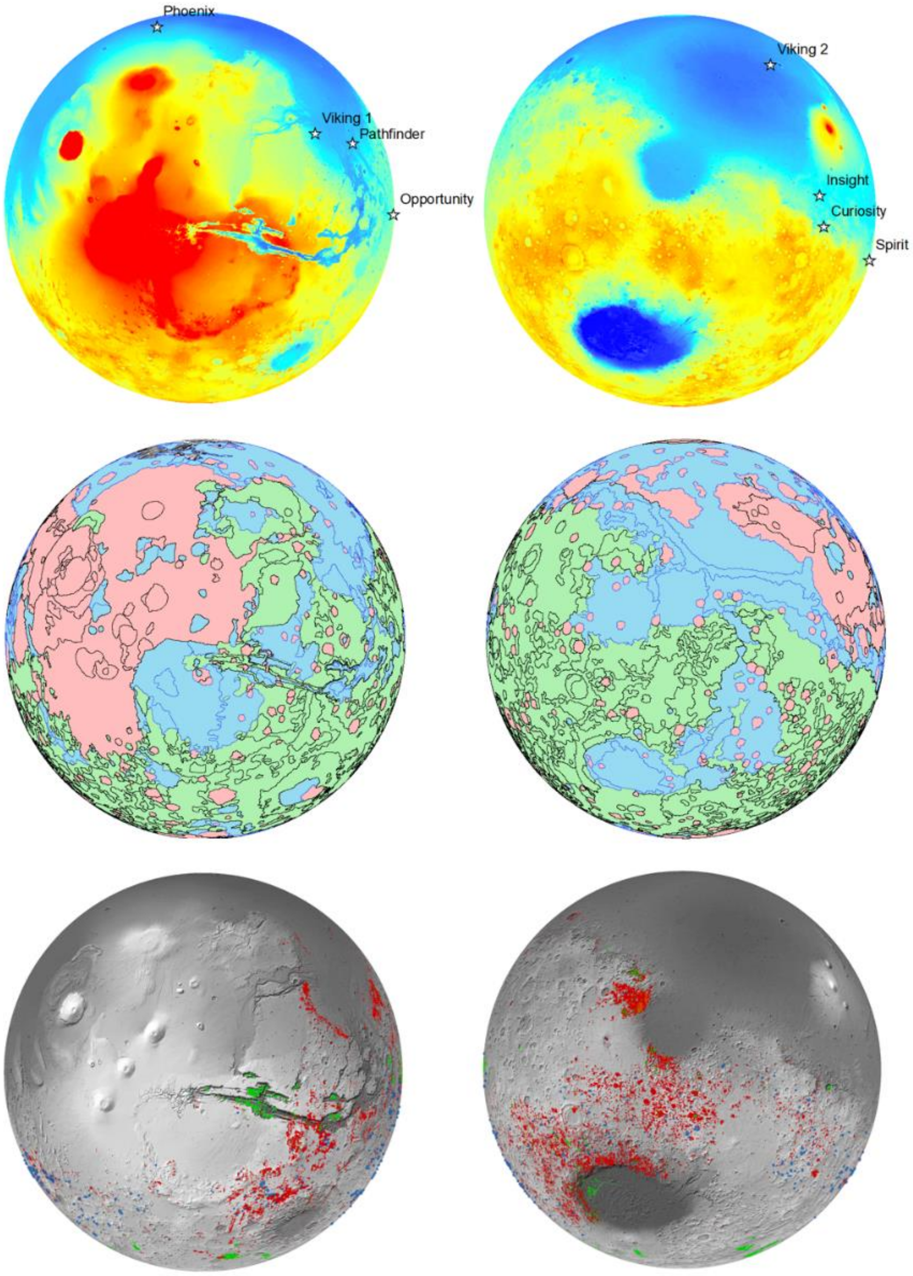

Figure 1 Top: The elevation of the Martian surface as determined by MOLA (rainbow scale). White stars indicate the location of successful landing sites. Middle: Simplified geologic map, representing the oldest (Noachian) terrains in green (not sampled by past landed missions), Hesperian terrains in blue and Amazonian terrains in pink. Bottom: Aqueous mineral detections are indicated in color (mineral deposit size enhanced for visibility): hydrated sulfate salts in green, hydrous silicates (including clays) in red, anhydrous chloride salts in blue and carbonate salts in orange. Background is MOLA elevation. Left: orthographic projection centred at longitude -90° and Right: centred at longitude +90°.

2.2.2 Key Mars science questions

2.2.2.1 Sequence of events on early Mars

Intermediate spatial resolution infrared spectroscopy (TES, THEMIS, OMEGA and CRISM instruments) have identified water ice as well as hydroxyl-, sulphate-, ferric- and carbonate-bearing phases that signal past interaction of surface minerals with liquid water. Improvements in resolution have increased the evidence for diversity in the mineralogy (Figure 1). Our current knowledge of the distributions and abundances of water-bearing minerals and their interrelationships is limited by the spatial resolution and thin skin depth of the available data from OMEGA and CRISM. A more complete inventory and stratigraphy of these materials can be obtained from Mars orbit using infrared remote sensing. This would allow us to define timelines of events that modified the mineralogical make-up of Mars' surface layers. Reliable mineral or resource abundance estimates will eventually require new approaches and/or landed platforms.

The study of the geologic context including the stratigraphic columns is key to understanding the sequence of events on Mars, as they record changes in the local to global geochemical conditions through Martian history. First order results wherein water alteration initially produced pervasive hydrous clays, then more localized salt deposits, is assumed to indicate a climatic change during the Hesperian from conditions where liquid water could be stable for an extended period to a more desiccated environment. This inference has not been reproduced by climatic evolutionary models. It has yet to be fully demonstrated that most water-bearing minerals at the surface formed in a climate-mediated environment. Of particular importance is to improve our understanding of the pervasiveness and duration of aqueous environments near or at the surface, which would help us better constrain habitability.

Individual sites can be investigated by landed assets, and informed site selection is key. An example is the investigation of Gale Crater by the Curiosity rover where clay-rich deposits from the early Hesperian are being studied (Figure 1). Future rovers at Oxia Planum (ExoMars 2022) and Jezero Crater (Mars 2020) should encounter clay-dominated sedimentary terrains (Figure 2). How representative any landing site is of global Mars water environments is still not well understood. The diversity of composition and morphology (as seen e.g. with CaSSIS on the Trace Gas Orbiter; Figure 1) implies that it is unrealistic to expect analysing the complete range of observed compositional and stratigraphic variability *in situ*. It is therefore critical to establish the significance of local differences. Did these result from topographic/morphological effects connected to global phenomena or were there regional differences in surface and/or atmospheric conditions due to regional changes in Martian "climate"?

Igneous minerals at Mars are diverse, suggesting more evolved sources able to produce felsic material than previously thought. Orbital and *in situ* data from MSL have revealed several types of such minerals, but major unknowns remain: What is the host rock in most cases? What is the timing and the origin of the parent magma? Late-stage plutons or eruptions, early Earth-like proto-continents or even a residual primordial anorthositic crust have been proposed. Each would have consequences on our understanding of Mars evolution. This warrants further study through *in situ* petrology with a mobile platform. Questions remain regarding Mars' geochronology. Isochrons in crater size frequency distributions used to estimate crater retention age for Mars surfaces are derived from lunar populations, which are tied to absolute radioisotope ages from Apollo samples. Retrieving absolute geochronologies for Mars requires radioisotope dating of Martian samples from well-known provenances. To do this, mass spectrometry of in-situ or strategically collected and returned samples is required. This could improve our understanding or, potentially, result in a serious paradigm change in our understanding of solar system chronology.

Figure 2 CaSSIS image of a graben in the Oxia Planum region of Mars. Oxia Planum will be the landing site of the ExoMars 2022 Rover Surface Platform mission. Differences in colour indicate compositional differences on the surface.

The Mars moons Phobos and Deimos represent a long-enduring enigma. Are they the result of asteroid capture or residual bodies from a debris disk formed by a giant impact on Early Mars? Their orbits are considered unstable on the Gyr (Giga year) scale, and dynamical studies show the possibility of multiple such moonlets in a transient disk whose orbits may have gradually decayed to impact Mars. If the moonlets are a result of a giant impactor and/or the remnants of a more massive ring, then these would have constituted major energy sources for the Mars environment and a major surface-sculpting agent. Could impact-driven transient habitable environments have existed? Most data today is provided by dynamical modelling, because spectroscopic and other measurements from flybys are somewhat scant. The study of the moons can address to what extent they may have constituted major evolutionary drivers for Mars. That study will be greatly enhanced in the short term by JAXA's ambitious Martian Moons eXploration mission (in which ESA participates via its Science Programme). Its observations will characterise both moons in unprecedented detail, and return to Earth ≥10 g of Phobos, which will provide profound new results on the moons' origin and nature. New science questions are expected to follow from discoveries by MMX, and hence follow-up activities to further explore, samples and analyse the Martian moons should be considered for the next decade. Whether the moons originated from Mars, or have sampled Mars material over geologic time in their orbits, sampling remnant Mars material in their subsurface, in particular for closer Phobos, will likely remain an overarching objective post-MMX and post-MSR. Study of the Martian moons offers value to future human exploration. A long-term platform, in particular on Phobos, may offer a literal stepping stone for Mars surface operations, support navigation in the Mars system, data relay for missions at Mars and elsewhere, and provide an opportunity for science of the moons, Mars and space environment. Continued exploration of Phobos and Deimos is thus of strong relevance to future Mars exploration and provides a number of strategic opportunities.

2.2.2.2 The fate of volatiles and water on Mars

Datasets providing constraint on the properties or the Mars surface and sub-surface (visible to IR imagery/spectroscopy, neutron and radar sounding) indicate that water ice exists below the surface of Mars both at equatorial to mid-latitudes and at the poles. Local abundances of several 10s of % to pure ice are likely.

The scoop of the Phoenix lander revealed bright material that subsequently sublimed (Mellon et al., 2009). Images of new meteorite impacts over a large range of northern latitudes have been observed to produce small craters with bluer, flat-bottoms and occasionally bright ejecta that faded with time (Byrne et al., 2009). The bright ejecta provided an infrared absorption consistent with water ice. Modelling has suggested that pressures resulting from meteorite impact are sufficient to liquefy the ice, albeit for a short time (Reufer et al., 2010).

While these observations clearly point to the presence of water ice just below the surface, we have little knowledge of the spatial distribution of the ice concentration or its heterogeneity. The vertical extent of these ice deposits is also poorly constrained. Neutron suppression by H in the near-surface layers (as identified by FREND on TGO is interpreted to represent substantial H_2O ice (in fractions of 30 - 80%), though can also be due to bound H in hydrated minerals. Sub-surface reservoirs of pure or bound water on Mars follow a history of aqueous events on the Martian surface that was likely episodic, rather than continuous over geologic epochs, as on Earth. However, we also know that obliquity cycle variation can result in large variations in water ice emplacement. Understanding the extent and distribution or buried ice is both important for resources and for planetary evolution science.

The mechanism(s) that provoked the appearance of liquid water on Mars remain poorly constrained. Investigation of the water ice deposits, however, potentially offers a window into this question. The ice may have preserved evidence of the chemistry involved through impurities and isotopic ratios. Of course, the ice may have a more recent origin and may have been modified by the climate cycle (Laskar et al., 2004, Forget et al., 2006). In either case, detailed analysis of the ice is needed and one can easily imagine that knowledge of the chemical constituents would also influence approaches to purification for future crewed exploration. The thermo-mechanical properties of the surface layer would also be of interest because the uppermost, partially desiccated, layer acts as a barrier to any sub-lying ice, preventing its escape into the atmosphere.

The residual polar caps, as their name suggests, are composed of young ice that survives the summertime sublimation in each hemisphere. The north polar residual cap (NPRC), is composed of water ice, is roughly 2 km thick, and is thought to be accumulating actively today (Landis et al. 2016; Brown et al. 2015). Initiation of its current form is thought to have occurred roughly 4-5 million years ago (e.g. Levrard et al., 2007). Its surface contains patterns and linear textures that appear to be the result of differential sublimation (Russell et al. 2019). The south polar residual cap (SPRC) is composed primarily of CO_2 ice over a thin substrate of water ice, and is offset from the geographic pole.

On the margins of the Planum Boreum, the north polar cap, massive dust-ice avalanches appear to be triggered by thermal expansion of water ice when heated in spring (Byrne et al. 2016). These avalanche events are extremely numerous and observations by NASA's Mars Reconnaissance Orbiter (MRO)'s High Resolution Imaging Science Experiment (HiRISE) have frequently caught more than one avalanche within one image swath, which typically take <10 seconds to acquire. Infrared spectroscopy indicates H_2O ice-rich layers exposed at the steep margins of the north polar layered deposits (NPLD) that exhibit varying dust content with depth. At these locations, the icy layers exposed along the scarp can receive direct sunlight during summer, and therefore experience intense thermoelastic stresses that may lead to avalanches. Hence, it is well accepted that these more northerly regions also have substantial quantities of sub-surface water ice (Fanara et al., 2020). Questions remain regarding fluxes in the water cycle including, importantly, accumulation rates. Radar sounding has been shown to be a very effective technique for the study of layers in the polar caps, but the vertical resolution of the instruments flown so far is unable to resolve detailed layering. Whether designed for sensing from orbit or on the surface, higher frequency instruments would enable improvements in resolution. Analysis of finer stratigraphic horizons than are currently resolvable would provide a better understanding of climate change on Mars, as driven by orbital mechanics.

Water is not the only volatile that could have both driven and recorded the geologic evolution of the Mars surface and climate. Other volatiles from geologic sources (volcanism, serpentinization, etc) include SO_4, CH_4, HCl, CO_2 are relevant in particular in discussion of the carbonate conundrum (section **Error! Reference source not found.**). To understand volatile cycles, an approach to quantify their sources and sinks is required. Fluxes of trace gases emitted or consumed by active geologic and atmospheric processes can be elucidated by remote sensing of the atmosphere, but higher sensitivity instruments as well as in-situ constraints from the surface and sub-surface would provide additional information to improve our understanding. A range of mineralogical hosts exist for volatiles aside from their pure solid phases (as for CO_2 and H_2O), including salts, and clathrates. Understanding volatile inventories and cycles on Mars provides for comparison with climate evolution models to better constrain its past, present and future climate.

2.2.2.3 The recent to current dust cycle and climate evolution

In a broad sense, the interaction of Mars' polar regions with the Martian planetary climate system can be split into three distinct timescales (Thomas et al., 2020). The seasonal polar caps are produced by the annual mass transfer of CO_2 between the atmosphere and the surface. These caps exist only during winter and comprise a 1-2 metre thick layer of mostly CO_2 ice. The polar residual caps that remain in summer months are composed of H_2O ice deposits in the north (the north polar residual cap - NPRC) and CO_2 ice in the south (SPRC), and they interact with the current Martian climate on timescales of decades to 100s of years (Byrne, 2009), growing to at most a few metres in the north and up to ten meters thick in the south. Finally, the Polar Layered Deposits (PLD) are kilometres-thick stratified sheets of nearly pure water ice (Nye et al. 2000; Picardi et al. 2005; Zuber et al. 2007; Grima et al., 2009), with small amounts of dust, trapped gases, and other refractory material, and they record climate oscillations, in an analogous way to terrestrial polar ice sheets and Milankovitch Cycles, from the last few to hundreds of millions of years of Martian history.

The polar environment therefore comprises geological information on the current state of Martian climate, as well as its relatively recent history. Deep understanding of the connection between the polar deposits and the Martian climate is necessary to understand the Martian climate system as a whole.

The polar layered deposits (NPLD in the north and SPLD in the south) of Mars record signals of climate over millions to hundreds of millions of years of accumulation and modification. Those signals have been influenced by changes of Mars' obliquity. The deposition and ablation of material from the PLD is driven by atmospheric dynamics. The global circulation models (GCMs) used to study the present behaviour of Mars's atmosphere readily reproduce the CO_2 cycle (e.g. Haberle et al., 2008), as well as the water cycle including cloud physics (e.g. Haberle et al., 2017). However, the interannual and longer-term variability of the dust cycle remains difficult to predict with current models.

Although GCMs are not fast enough to study dynamical changes in climate, steady-state solutions with past obliquities and inclinations are feasible. The CO_2 cycle is particularly affected and seasonal variations become more extreme as the obliquity increases. The regions on the surface where water ice is stable are also changed and current models of dust lifting and loading would predict enhanced dust activity as the obliquity increases (Kahre, 2017). On the other hand, there have been relatively few studies directly related to the PLD – the modelling of Newman et al. (2005) is an example although this is now becoming somewhat outdated. Measurements of current atmospheric properties near the PLD surface would provide additional constraints on models of present day Mars and would allow improved extrapolation to earlier times. We note here that GCMs are a strength of ESA and specifically the French and British communities.

Experiments would be incredibly useful to constrain these models. In particular, we need to know in more detail the dust cycle in the Martian atmosphere and how much dust deposition occurs at the poles. By a detailed study of the PLD (using high frequency radar or a rover driving over the PLD) one can determine how the climate on Mars has changed over the past 40 Myr to the present day. These topics have been the subject of a NASA Discovery proposal (COMPASS) in the last round although this failed to make the final four for the next down-selection.

Recurring Slope Lineae (RSL), first described by McEwen et al. (2011), are dark streaks that appear on steep sunward-facing slopes at mid-latitudes in spring, but fade during late autumn or winter, often leaving the affected surface appearing slightly brighter than the surroundings. The cyclic nature of RSL and seasonal influence led to the suggestion that they are produced by small amounts of liquid water being produced followed by subsequent sublimation or freezing in winter. The presence of a contaminant that can lower the freezing point of liquid water (e.g. perchlorate) has also been extensively studied. In recent years, however, dry mechanisms have been proposed (e.g. Vincendon et al. 2019, Dundas, 2020) which might produce similar albedo patterns. Although RSL are individually small (5-20 metres in width and length being typical), they are well observed by HiRISE on Mars Reconnaissance Orbiter and have been detected by CaSSIS at previously known sites (Munaretto et al., 2020). Despite this, the actual cause of RSL remains unknown and there is a still a possibility that they may be related to liquid water. Hence this is an issue that needs resolution – probably by a landed and/or a mobile platform. Unfortunately, RSL areas may be declared off-limits because of planetary protection. However, there is a strong case for selecting one isolated RSL area to establish clearly the darkening mechanism. An intermediate step might be a further attempt to use high resolution infrared spectroscopy (beyond the resolution of CRISM) to try to enhance the spectral contrast and identify if a specific compound (e.g. water but possibly others) is involved in RSL production.

2.2.2.4 The origin of carbonates and the presence of organic matter

The difficulty in sustaining liquid water on Mars for long periods to allow a carbonate-silicate cycle to be effective was pointed out 30 years ago (e.g. Kasting 1991). How much atmospheric CO_2 was sequestered into carbonate-rich rocks is of fundamental importance for understanding Mars' early evolution, and justifies the continued search, inventorying, and quantification of carbonate rocks on Mars. Thermal infrared spectra indicate the presence of small concentrations (2–5 wt%) of carbonates in the Martian dust, specifically dominated by magnesite ($MgCO_3$). Originally there was no indication of a concentrated source (Bandfield et al., 2003) but subsequent work has shown minor exposures in, for example, the Nilosyrtis Mensae region (Bandfield and Amador, 2016) and Nili Fossae (Ehlmann et al., 2008). The latter is the largest exposure of carbonate-bearing material identified to date (Brown et al., 2020). Carbonate has further been found in small quantities in isolated locations spread widely across the planet (Carter et al., 2013, Wray et al., 2016) including in-situ by the MER-Spirit and MER-Opportunity rovers.

On Earth, most of the carbon dioxide present in the primordial (or early) atmosphere was sequestered into carbonate rocks. This could have also happened on early Mars. However, if the process stopped, for example because the remaining atmosphere quickly thinned down, the very old carbonates may have been covered by later deposits.

Carbonates have been found exhumed from 5-6 km depth in large impact craters and basins (e.g. Huygens) suggesting vast amounts of deep sub-surface carbonate minerals (Michalski and Niles, 2010; Wray et al., 2016). Consequently, we still have questions concerning carbonate production and its timing in geological history. High spatial resolution thermal IR spectroscopy from orbit would be of benefit to localize these exposures further.

Brown et al. (2020) suggest that the carbonate we can see today is always associated with olivine, which provides a conundrum because olivine alters quickly in the presence of liquid water. But shouldn't there be much more evidence of carbonates in a system that, from morphological evidence, had abundant liquid water (often standing) and CO_2? The formation mechanism for Mars carbonate is clearly not understood yet. While Mars 2020 investigations of the lacustrine carbonates of Jezero crater may yield significant insight, it may not fully explain their pristine formation context throughout Mars.

Clearly, while inorganic carbon chemistry has great importance, proof of the existence of endogenic complex organic materials on Mars would have massive public impact. The Sample Analysis at Mars (SAM) instrument suite on board Curiosity has detected several chlorinated hydrocarbons (Freissinet et al., 2015; Glavin et al., 2013). Their origin and initial composition remains unknown.

But did Mars sequester and preserve past organic matter, both exogenous or endogenous? If so, where is it? Recently, Eigenbrode et al. (2018) reported detection of organic matter preserved in lacustrine mudstones (estimated to be 3 billion years old) in Gale crater. Diverse pyrolysis products, including thiophenic, aromatic, and aliphatic compounds were detected by evolved gas analysis. This suggests that Mars has preserved some organics, but would this be true for biotic organic matter? There is a need for sampling the very early sedimentary rock record of Mars, with dedicated instrumentation similar to the well-known SAM or MOMA instruments, or other concepts.

The presence of amino acids in carbonaceous chondrites (e.g. Botta et al., 2007) suggests that organic materials have arrived at Mars since solar system formation. Have these amino acids been preserved somewhere and what might have happened to this organic material when/if exposed to the past Martian environment, including hydrothermal alteration? Destruction of organics in simulated Mars conditions is being investigated in the laboratory (e.g. Royle et al., 2018; Fox et al., 2019) and experiments in the current actual Martian environment are of both scientific and future technological interest.

Finally, one of the most interesting questions yet to be answered. Did life appear on Mars? And if so, was it based on the same (or similar) chemical functional elements as life on Earth is?

2.2.2.5 Is Mars geologically active (driven by internal processes) today and what is the structure of the Martian interior?

The InSight mission carried a seismometer that has identified several Marsquakes (Lognonne et al., 2020). In general, however, Mars is rather quiet from a seismic point of view. It was inferred that the uppermost 8-11 km of the crust is highly altered and/or fractured. This, however, was derived from just one seismometer. European scientists have been advocating a network of landers for nearly 30 years (e.g. InterMarsNet within the ESA Science Programme; Chicarro et al., 1994) as a means of determining the internal structure of the planet and its current activity. It seems unlikely that InSight will answer all the geophysics questions that have been posed, but it provides a first assessment of what can be derived from such experiments at Mars.

Morphological evidence suggests that Mars has been active in geologically-recent times. When were the last major changes to the Martian surface and why have these changes now stopped? InSight measurements suggest some weak activity, but if Mars is no longer geologically active, when did this cease? What is the state of the core and how has this evolved over the past 3-4 billion years? All these issues require a static network of landers that can probe the interior. Additionally, one could imagine placing laser reflectors on the surface at strategic positions to identify (in combination with an orbital laser altimeter) whether there is movement or flexure of the crust. This requires excellent knowledge of the orbit, but centimetre-scale accuracies might be feasible with present-day technology.

Mars' remnant magnetic field is unique in the Solar System but the spatial distribution of that field is limited by the resolution of magnetometers in orbit. Measuring magnetic fields locally (i.e. via a mobile platform) might provide additional knowledge about the early dynamo and hence a mapping of the surface magnetic field strength at kilometre resolution is of interest.

Determining the heat flow at the Martian surface remains a vital component in the assessment of the internal properties. The atmosphere clearly influences the signal from the surface in the thermal IR and variations in mineralogy (emissivity) within resolution elements can affect the derived thermal flux from surfaces (McCarty and Moersch, 2020) such that orbital assessment of the integrated heat flow is challenging. However, the magnitude of the surface heat flow is an important constraint on interior models and because of this the difficulties encountered by the thermal probe during its deployment from InSight (Spohn et al., 2019) should not be seen as a barrier to further efforts to establish reliable values. Indeed there are few reasons to assume that the heat flow from the interior at the surface is isotropic. Morphological evidence would suggest that there are areas when the heat flow should be larger than elsewhere (e.g. Tharsis and Elysium).

2.2.2.6 Is Mars suitable for long-term human exploration?

The scientific exploration of Mars by a human crew is dependent on the demonstration that the Mars environments do not pose an overwhelming challenge. A number of key observables that should be acquired as a pre-requisite to a human landing attempt are lacking. These range from the feasibility of landing on Mars, staying healthy there, and the possibility to rove the Mars surface for shelter and resources.

Water is arguably the premier resource for pioneer human expeditions to Mars. Its prospective use is well documented and includes consumption, agriculture, sanitation, heat transfer, fuel, air, radiation shielding. The feasibility of Mars missions that would not exploit water through ISRU is likely not high. At high to polar latitudes, Mars is understood to host abundant and accessible seasonal frost and perennial water ice. Towards lower latitudes, water ice is increasingly scarce at the surface and not found near the equator. The existence of useable deposits of water ice in the shallow subsurface (few meters) at low latitude is suggested by previous missions (e.g. FREND/TGO, GRS/MO) but there are limitations: these detect hydrogen which is an indirect indicator of water implying a degree of uncertainty, the spatial resolution is too coarse to pinpoint useable deposits, and the actual ice abundance is poorly constrained. Refined knowledge is required here, including through prospective new instruments post-TGO, which would provide orbital resolution at the 10s km scale, or landed platforms that would scout the actual water content of prospective human landing sites.

The relative humidity of the Martian atmosphere is often high but represents a minute resource in absolute quantity. The possibility of efficiently trapping this humidity to useable levels is not demonstrated.

There are other sources of non-polar water that are not ice or vapour. These elusive sources have been quantified to range up to ~10 weight percent at the surface. At the local scale, water-bearing minerals including hydrous clays (phyllosilicates), hydrated salts and hydroxides are evident. This water is at times tightly bound as structural water (hydroxyl groups) in the crystal lattice, and other times more loosely bound as trapped H_2O absorbed or adsorbed in/on the mineral. The latter are more extractable than the former. There is yet another source of bound water in the Martian regolith, amounting to several weight percent superficially, the origin of which is not known. For all these rock-bound sources, the thickness and hence the volume of the deposits is not known - neither is the abundance within the rock or its extraction cost. These unknowns must be resolved before these deposits can be considered viable resources: through refined in-situ observations and modelling on Earth. Their main advantage is that there are present at the top surface, down to equatorial latitudes.

The existence of mineable pockets of other volatiles trapped as ice or gas in the subsurface (e.g. CH_4, SO_2) including perhaps in clathrates, remains speculative for lack of evidence and existing experiments to search for them. Use of atmospheric CO_2 for oxygen production or other purposes will be pioneered by MOXIE on Mars2020, which experience will likely feed refined strategies for future CO_2 capture. Prospective studies are warranted which include Mars analogue chambers on Earth.

Radiation damage to biological tissue is a major health hazard for long duration missions to Mars. The RAD instrument on board MSL was able to monitor the dosage for a subset of the incoming radiation and at a local Mars environment (Gale crater floor). More monitoring stations will be required that include a comprehensive view of radiation, including all particles and over a wide energy spectrum. Of particular interest would be a comparison of the dosage at, just below and above the surface. That knowledge would likely govern the future shielding strategy and habitat location at Mars (e.g. in lava tubes versus suspended above the surface). Little knowledge currently exists on the hazards posed by the surface environment of Mars based on its mechanical and chemical properties. What level of toxicity would the oxidative, chlorinated surface of Mars trigger? What damage to mechanical parts and to the human respiratory system would the abrasive Martian dust cause, especially when mixed with water? Amongst the other mechanical properties, the resistance of the Mars regolith to heavy loads must be tested: where can we safely land a multi-metric ton spacecraft and rove a heavy rover? In conclusion, the chemical, mechanical and radiation environment of Mars need to be better modelled, simulated in Mars chambers or in space (for radiation), and likely also tested at Mars through dedicated experiments in its atmosphere and surface.

2.2.3 Technological capabilities required

The following items are clearly desirable from the scientific ideas presented above. These items provide infrastructure support to the various scientific objectives that we have at Mars.

- Maintenance and improvement of rover capability
- Accurate landing capability over that currently seen in the ExoMars programme (sub-km accuracy); this is critical for delivering multiple elements to a base or mission.
- Atmospheric flight (e.g. helicopters and/or drones) to provide intermediate scale mobility
- Concepts for polar landers (thermal control, etc.)
- Coring and drilling capability in hard substrates (e.g. water ice)
- Improvement of (cryogenic) sampling handling systems
- Instrument development studies (many items)

2.2.4 Priorities for the HRE SciSpacE Programme

The list of scientifically interesting elements shown above is extensive. The European Space Agency and its optional HRE (Human and Robotic Exploration) programme is unlikely to be large enough to be able to address all these elements. Hence, some form of priority either has to arise from the developments or needs to be set. As in the discussion of priorities for the Moon, we will not discuss prioritization of science questions, given that the questions to be addressed strongly depend on the mission opportunity. Said opportunities are however strongly dependent on necessary collective impulses from the European science community. However, we would make the following observations.

Our view is that Europe is well placed to contribute to orbital remote sensing in several fields such as imaging and imaging spectroscopy at optical to infrared wavelengths and radar sounding. Similarly, the ExoMars programme and strong European contributions to NASA rovers (MSL, Mars2020) have illustrated that development of scientific instruments for rover based missions is at an advanced state in Europe. Given the diversity of the science associated with Mars at global and local scales coupled with the interest in both these scales in the European community, we recommend that the Programme seeks to maintain activity in both areas.

A number of outstanding science questions can only be tackled through analyses of samples returned to laboratories on Earth. Consequently, Mars Sample Return is a priority. This also suggests however that investment in laboratory efforts prior to the completion of MSR is warranted. Such investment would prepare the laboratories scientifically and technically for the tasks ahead. It is hence likely of strategic importance for Europe to anticipate the need and then develop curation facilities, in an era of increasing sample return missions from Mars and elsewhere.

It seems improbable that samples from many sites can be collected and returned to Earth. The costs are likely to be prohibitive – at least in the medium term. The need for sampling a variety of terrains at Mars requires landed platforms with enhanced mobility compared to current platforms. Almost all science cases described above require in-situ investigations, which is clearly the future of Mars exploration. The unquestionable benefit of one sample return mission should therefore not be at the cost of in-situ exploration, for which there is currently a dearth of planned missions in the mid-term.

Studying the possibilities for intermediate scale science (i.e. over ranges > 20 km) using mobile platforms may therefore be beneficial for future activities. ESA has funded numerous start-ups for drone technology on Earth for example but the application to tasks on other planets such as Mars does not yet appear to be a priority. This may limit the ability of ESA to increase the range of scientific investigations in the medium term. Hence, there is a good case for studying methods of increasing mobility so that in situ sampling and analysis of a wide range of terrains can be achieved.

There is also a case for the construction of networks of static landers on the surface designed to study geological and atmospheric activity both at mid-latitudes and towards the poles. The scientific priority for such a network should be left open at this point, but there are a large number of tasks that would provide enormously useful information on the behaviour of Mars as a dynamical system.

Given the resources required, the timing of a push towards human exploration of Mars is likely to be a political decision. However, the preparation of such a mission demands that we establish the environment as accurately as possible in the coming years. ESA member state teams are more than capable of contributing to these questions and could place themselves in a scientifically strong position to play a leading role in the missions when they arise.

As the number of Mars-faring countries grow, multilateral and bilateral collaborations between ESA member states and those countries should continue to be promoted. While continued international collaboration both on instrumentation and science should and will continue unabated, ESA should consider reducing its reliance on other countries for critical capabilities to deliver payloads to the surface of Mars, such as landing systems or non-solar power generation.

2.2.5 Recommendations in short, middle and long term

There are several missions to Mars upcoming within the Mars Sample Return programme. These missions may be able to carry additional payload. These payloads should be selected through a standard Announcement of Opportunity process and we do not want to prejudice that process by giving a detailed priority list. However, we can identify certain objectives that would be beneficial to enhancing the whole programme without exact specification.

2.2.5.1 Short-term

- Support European exploitation of existing Mars data sets, including of the martian moons to support the upcoming JAXA-led MMX mission
- Support laboratory investigations that prepare skills for analysing samples from Mars Sample Return
- Preparation (including selection) of contributions to scientific payload in the fields of orbital remote sensing and in situ analysis

Exploitation of data sets from the current missions needs to be re-emphasized. There is significant science that can be extracted from the on-going Mars mission data while there are limited resources for scientific studies in the national programmes. ESA’s involvement in upcoming Mars missions, including the ExoMars Rover and JAXA-led MMX mission, will increase the need for resources in the coming years for exploitation of science data.

Laboratory studies remain important in a more general sense, but the need to enhance and improve our capabilities in preparation for Mars Sample Return also suggests that short-term investment in this area can pay off for European scientists. It is observed that at least in some ESA member states, the flow of information is not good between scientists working directly in space missions and those conducting laboratory work. A collective effort should be carried out, perhaps with help from ESA, to better bridge these two approaches. The outcome would be mutually beneficial, as more laboratory work would help better refine observables that space instruments should look for, optimizing their design, and in turn, up-to-date observables from Mars instruments should be factored in the design of the laboratory experiments reproducing Mars present/past conditions.

From orbital remote sensing, we see that some of the missions currently orbiting Mars (e.g. Mars Express and Mars Reconnaissance Orbiter) will be reaching the end of their useful lives (despite the fact that they have survived well beyond their design lifetimes). Replacement with improved technology and capability is clearly necessary on short timescales. Hence, instrument development for European contributions to forthcoming missions should be emphasized.

2.2.5.2 Medium-term

- Development of instrumentation for MSR both as scientific payload and in the laboratory
- Development of a plan for exploitation for scientific purposes of sensor data from the MSR Earth Return Orbiter and Sample Fetch Rover (SFR), as well as a plan to operate SFR on a potential mission of opportunity after its primary sample delivery mission is complete, and assuming its survival (including of the Mars Ascent Vehicle launch event).

In the medium term, it is now apparent that Mars Sample Return will occur and it is mandatory that ESA plays a significant role. Samples might be returned to Earth in the first half of the next decade, possibly earlier. Consequently, implementation of accompanying remote sensing and surface science payload will become a priority within the next 5 years. Similarly, laboratories in Europe need to be readied for reception (curation) if they are to play a role in the analyses. This includes studies of the security and safety aspects.

- Technology maturation

Work should be carried out in the meantime to enhance the capabilities of ESA member states to study the Martian surface in-situ, and to anticipate the next generation of instruments.

2.2.5.3 Long-term

- Maintenance of remote sensing of the Martian system from orbit
- Deployment of surface networks for atmospheric and/or geological studies
- Development and possible deployment of mobile platforms for detailed environmental assessment over longer ranges
- Assessment of threats to human health
- Identification and extraction techniques of required resources (e.g. water)

Beyond MSR, we can envisage preparations for human exploration intensifying by establishing clearly the environment into which the future astronauts will go. These would include studies of atmospheric dynamics (countering the dangers of dust storms and weather), geological dynamics (countering any threat from geological events), surface and sub-surface composition and particle size (countering potential chemical and particulate threats), and radiation effects (also countering potential threats to human health). The need to guarantee that resources can be usefully extracted from the local materials will also require dedicated missions and payload.

One final, important point: Industrial knowhow and experience does not reside in companies, but on the people that work in those companies. A space mission takes on the order of fifteen to twenty years to realise. Through the effort of engineers and scientists over this period, key capabilities are developed and exercised. Unless the momentum is sustained, knowledge does not endure: people retire, or move on, and so does their *savoir faire.* To counteract this erosion of competence, we propose that maintaining and improving on our hard-won science and technology achievements should be an important objective. As a possible example for how to build on the ExoMars experience, Europe should have a landed mission every ten years.

The science to be addressed and the emphasis of the technologies (*e.g.,* improved landing accuracy) to be implemented on each mission may differ, but it is anchored in an exploration programme having a strong science and technology backbone able to provide the necessary continuity for industry and science to flex their muscle that Solar System exploration in Europe will be best served.

Open fundamental scientific question	Future HRE SciSpace experiments and suitable environment (LEO, Moon, Mars, BLEO)	Space relevance (importance of microgravity and/or relevance for space exploration)	Timeline (short, medium, long)
A. Sequence of events on early Mars What was the timeline of events that modified the geological make-up of Mars's ancient upper crust, surface, and atmosphere? Were the processes mostly global or local in scale? Did some of the environments created during these events result in habitable conditions over long timescales? Can an absolute Mars chronology be determined and how will it relate to the evolution of other Solar System objects, including its moonlets?	1. Orbital/aerial compositional and structural analysis of rocks in their stratigraphy, globally and locally at high resolution. 2. In-situ sampling / returned samples for absolute dating of select geomorphic units and individual strata. 3. In-situ sampling / returned samples of host rocks sequestering the early atmospheric record 4. Orbital measurement of the remnant early crustal magnetic field correlated with dated geomorphic units 5. Continued in-situ sampling / returned samples from Mars moonlets post-MMX, to further understand their co-evolution with Mars and as a host for ancient Mars meteorites	Optimization of the search for strata of potential biological significance. The search for various surface lithologies can lead to the identification of potential valuable mineral deposits for ISRU	(S) Continued exploitation of the existing data sets from European (TGO, Mars Express) and US (MRO, InSight, Curiosity) spacecraft (S) IR spectral imager at ~1 m px^{-1} from onboard a Mars orbiting platform. (M) Mass and X-ray spectrometry (or other technique) for radioisotopic dating of individual units from a mobile surface element (rover, etc.). (M) Landers sampling different surficial terrains of various ages, with the capability to extract and detect trace/noble/isotopic elements in the trapped gas phase (S) Support analysis of MMX data and (L) Depending on findings from MMX, subsequent landers sampling Phobos and/or Deimos rocks in search for Martian components: analysis of their composition and age

Open fundamental scientific question	Future HRE SciSpace experiments and suitable environment (LEO, Moon, Mars, BLEO)	Space relevance (importance of microgravity and/or relevance for space exploration)	Timeline (short, medium, long)
B. The fate of volatiles and water on Mars What were the reservoirs of volatiles (including water) on early Mars and where did they go? How much water ice is present today on Mars and where is it located? What is the current hydrologic cycle, particularly towards polar latitudes? What were the source-to-sink cycles of other volatiles, and could they have contributed to a warmer paleoclimate?	1. Sub-surface sounding of ices/large salty deposits 2. Sub-surface sounding and surface in-situ investigations of volatile concentrations 3. Thermo-mechanical studies of the (near) surface layers 4. Reconnaissance compositional sounding from orbit or the ground of the hosts phases for volatiles: ices and salts 5. Continued sounding of trace gases at Mars, from orbit or from the Earth (ground-based and space platforms)	Water is of course necessary for human exploration. Source localization is critical. Understanding the present water cycle might provide a guide to water distribution. Volatiles in general are valuable resources to harness for ISRU.	Continued search and monitoring of traces gases: (M) from orbit (further exploiting TGO), through (L) Direct sampling of the trace atmospheric gases at different altitudes (e.g. from balloon-like or other flying platforms), or (S) from the Earth using high resolution spectroscopy across a broad spectral bandwidth (S) Orbital IR spectral imager at ~1 m px^{-1} from onboard a Mars orbiting platform (M) High resolution radar sounding (M) Drilling and/or coring to expose the water composition with depth at multiple sites (equatorial and polar) (M) GPR onboard a mobile element and dielectric spectroscopy (M) High resolution (<10 km) from orbit and in-situ reconnaissance of surface/shallow depth elemental chemistry (various methods)

Open fundamental scientific question	Future HRE SciSpace experiments and suitable environment (LEO, Moon, Mars, BLEO)	Space relevance (importance of microgravity and/or relevance for space exploration)	Timeline (short, medium, long)
C. The recent to current dust cycle and climate evolution What is the dust cycle in the Martian atmosphere and how much deposition occurs at the poles? How has the climate on Mars changed over the past 10s Myr to the present day? Does seasonal transient flow of liquid water exist on Mars?	1. Monitoring local, regional and global-scale weather from orbit 2. Measurements of dust deposition rates at the poles using mobile or static platforms/networks. 3. In situ studies of Mars polar layered terrains 4. Cap wide high spatial resolution radar sounding 5. Direct sampling of the RSL areas.	Better understanding of weather and possibly dust storms as potential dangers to human exploration. Better knowledge of influences on Martian climate evolution in the future for longer-term exploration. Water is of course necessary for human exploration and RSL may be of current biological significance.	(S) Radar sounding, LiDAR, and IR radiometer from orbit onboard a Mars orbiting platform. (L) Polar lander(s) with mobile studies of the polar stratigraphy (L) Polar network with atmospheric stations. (L) Mobile surface element determining the water content and imaging the source of RSL at a specific site (e.g. Newton crater)
D. The origin of carbonates and the presence of organic matter Why are carbonates so rare at Mars, were they chemically inhibited or destroyed? Are there large reservoirs of carbonates deeply buried today?	1. Further global investigation of carbonate deposits at high spatial resolution 2. Direct sampling / return sample of carbonate rich sites 3. Direct sampling / return sample of rocks susceptible to sequester	Carbon compound degradation in the Mars environment is a serious issue for the erection of structures on the surface. Conversely, the presence of useable	(S) High resolution spectroscopic sensing of putative organic matter-rich strata (S) Generalized experiments on analogue organic matter in a Mars chamber or in space, within various host rocks and realistic current/past environmental conditions

Open fundamental scientific question	Future HRE SciSpace experiments and suitable environment (LEO, Moon, Mars, BLEO)	Space relevance (importance of microgravity and/or relevance for space exploration)	Timeline (short, medium, long)
What is the source of carbon in carbonates: atmospheric or from geology/biology? Did Mars sequester and preserve past organic matter, both exogenous or endogenous? If so, where is it? Could Mars have preserved specifically biotic organic matter? Can we find "bio-signatures"?	large amounts and diverse organic matter 4. Direct sampling / return sample of preserved local geological features that may have been a habitat for microbial life	carbon as a resource may be of interest.	(M) Landing on a carbonate-rich site (L) Roving and digging in sediments, returning samples (L) Use a mass spectrometer to study how identical samples changes with age in Mars conditions (L) Direct maturation experiment of terrestrial organic matter brought to a landed platform on Mars
E. Is Mars geologically active (driven by internal processes) today and what is the current structure of the Martian interior? How recently was Mars geologically active? When were the last major changes to the Martian surface and why have these changes stopped? How thick are the crust and mantle?	1. Seismological and thermal heat probe networks. 2. Higher resolution orbital thermal sensing of thermal anomalies 3. High resolution gravity measurements to study the shape and interior of Mars 4. High resolution measurements of the remnant magnetic field	Determination of the present danger from geological activity and where on the surface that might be relevant.	(M) Further attempts to obtain thermal heat probe measurements post-InSight (M) Higher resolution thermal mapping from orbit with strong scientific effort to identify temperature anomalies. (M) GRAIL-type mission to study the gravity field of Mars (M) Landing of simple corner cubes on the surface to be hit by lasers from orbit.

Open fundamental scientific question	Future HRE SciSpace experiments and suitable environment (LEO, Moon, Mars, BLEO)	Space relevance (importance of microgravity and/or relevance for space exploration)	Timeline (short, medium, long)
What was and is the state of the core? How and how much heat is transported from the interior to the surface?			(L) Low altitude scanning of the magnetic field in the southern highlands. (L) Networks of seismometers on static landers.
F. Is Mars suitable for long-term human exploration? What is the radiation environment at/near the surface and where can it be mitigated? Is water available as ice in the (near) surface, non-polar regions? How extractable are volatiles and water in the Martian rocks: how much is there and how much energy would it cost to extract? Can the materials available be used to provide shelter? Are specific geological formations capable of providing shelter?	1. In-situ radiation monitoring on the mobile platforms at several tentative landing sites 2. In-situ wet chemistry laboratory of biologically relevant compounds 3. Material strength test of the regolith in the Martian environment 4. Atmospheric/surface analysis of the mechanical properties of the Martian dust for their harmfulness 5. Subsurface ice sounding at the metres depth and at < 10 km resolution for landing site definition	Evaluation of the environment in terms of the danger to humans.	(S) Experiments on analogue material in a Mars chamber on Earth or in space (L) Multiple atmospheric measurements, surface measurements and experiments onboard mobile surface elements (L) Direct maturation experiment of biologically-relevant or human-rated material brought to the Mars surface on a landed platform

Open fundamental scientific question	Future HRE SciSpace experiments and suitable environment (LEO, Moon, Mars, BLEO)	Space relevance (importance of microgravity and/or relevance for space exploration)	Timeline (short, medium, long)
How dangerous are the atmospheric and surface materials to human-rated machinery? What is the effect of Martian surface chemicals and dust on the human health? How suitable is the Martian regolith to support landing then roving of heavy payloads? What are the properties of the atmospheric boundary layer and would they influence manned missions? Can Martian soil be used as a basis to grow crops?	6. Quantitative estimates of the volatile content in Martian rocks, and their extraction cost in energy 7. Experiments with analogue Mars dust and chemical compounds		

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2.3 Asteroids

2.3.1 Introduction

Several thousand tons of extraterrestrial material penetrate the Earth's atmosphere every year. Much of this incoming flux of "meteoroids" is cometary dust. If the Earth encounters meteoroids traveling in swarms and streams, such meteors may be directly linked with their parent comet and thus can reveal compositional and dynamic properties of their source objects. However, the "meteoroid flux" also includes a significant portion of larger meter-size objects (termed "meteorites" if recovered on the ground), presumably representing fragments from asteroids.

The Moon is an efficient meteoroid detector, as is attested by the large inventory of craters and the substantial number of impacts recorded by the Apollo seismic station network (Dorman et al., 1974; Oberst and Nakamura, 1991). From the temporal/spatial distribution of impact events, constraints can be obtained on the meteoroid approach trajectories, velocities, and shower memberships.

Only as late as 1999 it was successfully demonstrated that meteoroids produce short (approx. 10-100 ms) "flashes" upon impact, which can be detected by sensitive camera equipment. During the peak of the Leonid meteor shower, at least 6 impact flashes were recorded on the Moon, at estimated magnitudes between +3 and +7 on a single night (Dunham et al., 2000). Today, observatories worldwide are engaged in the observation of these flashes. A unique very large impact flash (m=2.9) was detected on September 11, 2013 (Madiedo et al., 2014). A fresh crater presumably related to the event was later found in Lunar Reconnaissance Orbiter (LRO) images, which enabled unique studies of ejecta emplacement and the phenomenon of secondary impacts (Robinson et al., 2015).

2.3.2 Key knowledge gaps

Unfortunately, there is still much uncertainty about the origin, temporal/spatial distribution and physical characteristics of the objects in the size range in question, which are too small to be directly tracked by telescopes but can only be studied by their interaction with planetary surfaces or atmospheres (Mimoun et al. 2011). In fact, most of our knowledge on the meteoroid environment is based on the observations of the "meteors" observed from terrestrial ground (Ceplecha et al., 1998, Bouquet et al. 2014), which is limited by biases in the statistics and atmospheric opacity. Practically nothing is known about the current meteoroid flux in other parts of the Solar System, e.g., near Mars. Also, while the impact flash phenomenon is of high interest, there is considerable uncertainty about the physics of flashes, as systematic observations involving high temporal and spectral resolution data are missing.

2.3.3 Benefit for Earth and industrial relevance

The monitoring for meteors or impacts will provide a direct assessment of the danger to human assets in Earth orbit or humans on and near the Moon.

2.3.4 Priorities for the HRE SciSpacE Programme

We propose monitoring of the Earth's upper atmosphere for meteors using dedicated optical sensors, either from the ISS or from small cubesats. We foresee instrument assemblies similar to those realized on the ASIM (Atmosphere–Space Interactions Monitor) currently operating on ISS (Neubert et al., 2019), which however, is focused on observations of transient luminous events related to thunder storms and only marginally concerned with meteors. Observations from two or more cubesats flying in formation may enable stereo viewing, which supports identification of events and reconstruction of meteor trajectories. We benefit from clear viewing and observations of meteors above the cloud deck and from observations in wavelength ranges (e.g., IR) not feasible from the ground.

More directly, impact detectors may be employed for studies of the micrometeorite (sub-millimeter) population. These may also be used for identification of man-made debris, which contaminates the natural meteoroid complex. An appropriate technology development has been demonstrated on the ISS by NASA (Anz-Meador et al., 2019).

We propose monitoring of the lunar surface for impact flashes and other transient events from the Deep Space Gateway. Such new data on impact flashes, which benefit from the lack of atmospheric stray light and Earth-shine (on the Lunar farside), may shed light on the relationships between lunar crater statistics, seismic detections of impacts (Güldemeister and Wünnemann, 2017), and terrestrial meteor rates. Flash detections from the Gateway may be complemented by monitoring the surface for fresh craters and by inspection of these craters by high-resolution cameras.

Precise impact locations and impact times may also represent critical support to lunar seismic experiments (if available on the lunar surface). The impacts create useful seismic energy signals for the sounding of the deep lunar interior. The typical inversions of seismic data taken from three or more stations must solve for seismic event time and place. However, in the case of simultaneous orbital observations, time and place of the impact will be known. Thus, more seismic data will be available to solve for parameters of interior structure.

We also recommend the use of new seismic stations for monitoring of the impact flux. New instruments, more sensitive and more widely distributed than was possible during the Apollo era, may complement the observations from space and greatly improve our statistics and our knowledge on the characteristics of the lunar global present-day impact flux.

Open fundamental scientific question	Future HRE SciSpace experiments and suitable environment (LEO, Moon, Mars, BLEO)	Space relevance (importance of microgravity and/or relevance for space exploration)	Timeline (short, medium, long)
Determine overall flux of meteoroids in the Earth-Moon system, including spatial/temporal variations and characteristics of the objects	Monitoring Earth's atmosphere for meteors (from LEO) Direct measurements of the micrometeoroid flux using impact detectors (from LEO and from Lunar orbit)	Relevance for space exploration: meteoroid hazard	Short
	Monitoring of the lunar surface for impacts. Determine time, place, and magnitude of seismic events (on lunar surface) and impact flashes (from Lunar orbit)		Medium
Study the physics of high-velocity	Observations of lunar impact flashes with high temporal and	Understanding physics of high-velocity impacts	Medium

impacts on the lunar surface	spectral resolution (from Lunar orbit); comparison with characteristics of seismic events		
Characterize meteoroid environment near Mars	Monitoring Mars for impacts or Mars' atmosphere for meteors (from Mars orbit or from ground)	Relevance for space exploration: meteoroid hazard; characterizing the solar system environment	Long
Determine lunar interior structure	Monitor lunar surface for impacts. Determine time, place, and magnitudes of impact flashes. Use data to support inversion of seismic data (from Lunar orbit)	Relevance for space exploration: characterizing planetary interiors	Long

2.3.5 References (Asteroids)

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