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Equipping an extraterrestrial laboratory: Overview of open research questions and recommended instrumentation for the Moon

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Abstract

Humans are once again preparing to leave Earth and land on the surface of another planetary body. The two objects high on the list for permanent bases are the Moon and Mars. Both have been at the center of attention of many recent spaceflight activities, albeit these have so far been uncrewed. If humans indeed land on either one of them, science can potentially benefit tremendously.

In the past, most spaceflight missions have been implemented by adding scientific instruments after most of the engineering work is already finished. This has often limited scientific studies to relatively scattered, insular topics. However, if prepared appropriately, a research laboratory on either the Moon or Mars can help address scientific questions thoroughly and at a fundamental level.

In this paper we review the main scientific questions relating to the Moon that are still open and develop an overview of the instrumentation that would be necessary for a human astronaut inside a lunar laboratory to help answer these questions. Our primary focus is the Moon, however, we include an outlook to Mars, since we assume that the Moon not only provides a valuable testbed for many technologies to be used on Mars, but that both can be studied with the same habitat laboratory after some specific adaptations.

The research areas we focus on are related to (a) non-living matter (geophysics, geology, materials science), (b) extraterrestrial life (from chemistry of organic carbon compounds to astrobiology), and (c) life inside the human habitat (bioregenerative life-support systems, microbiomes, human physiology). We identify synergies between disciplines, in order to provide a list of priorities to mission planners, and provide a guideline of where further development of equipment would be desirable.

Keywords: human space exploration, Habitat laboratory, Moon, Mars

1. Introduction

The last time a human being set foot on the surface of the Moon was almost five decades ago, and it was for a total of just over 22 hours. Today, humanity is pushing for the Moon again, but this time to stay. Space agencies and companies alike strive for a permanent, sustainable human presence on the Moon (e.g., (NASA 2020, Musk 2016, Kriening 2018)). The plans do not stop there, but many actors envision the path to continue beyond the Moon and on to Mars (ISECG 2018, NASA 2020, Musk 2016).

From a scientific standpoint, sending humans to the Moon or Mars opens up many possibilities for investigations and analyses that would otherwise be impossible or at least impractical (Crawford et al. 2012). For example, the recent mishap of the Heat Flow and Physical Properties Package (HP^3) experiment of the InSight lander on Mars (Spohn et al. 2019) demonstrates that drilling into the subsurface still poses insurmountable challenges; the problems of the drill could likely have been overcome quite easily by a human tending to the issue. On the other hand, the Hubble Space Telescope, which has been serviced by 5 Space Shuttle crews, has been regarded as "the most productive of all astronomy space missions [for] many years" (Crawford et al. 2012). At the very least, a laboratory on the Moon would allow for faster and more efficient analyses than during the Apollo missions when all samples were brought to Earth for analysis.

Of course, such an extraterrestrial laboratory faces certain limiting factors like equipment mass and volume, energy supply, need for various consumables (e.g., gases, liquids), and staff qualifications. Nevertheless, several analytical instruments have been miniaturized successfully for use on board the International Space Station, and even on Earth the development often tends towards more portable, and multi-functional equipment. Thus, there is no reason to believe a scientific laboratory would not be feasible outside of planet Earth.

On the contrary, we believe that, if integrated properly from the very early draft of an interplanetary mission ("science first" approach), an extraterrestrial laboratory can serve three primary purposes: (1) conduct experiments utilizing the lunar gravity and prepare experiments to be placed outside the laboratory in the lunar environment, (2) conduct analyses of lunar rock and regolith in high volume, (3) perform preliminary analyses and screening of samples to be sent to Earth for more detailed, specialized analysis.

To discuss the options of having a laboratory on the lunar surface as part of a habitat, we have therefore assembled a team of scientists from different fields: geology, materials sciences, carbon chemistry, astrobiology, and human physiology.

We acknowledge that there are of course more disciplines that would benefit from a presence on the Moon and Mars. For example, astronomy would benefit from telescopes on the lunar surface; particularly a low-frequency radio telescope on the far side would enable the study of the Dark Ages of the universe, which can be achieved neither on Earth (due to the ionosphere) nor in space (lack of a stable surface for the km-range size of the telescope). Fundamental physics could benefit from placing a number of retroreflectors on the lunar surface for laser ranging experiments to test General Relativity (see e.g., (Crawford et al. 2012)). An extensive list of scientific questions that could be addressed on the Moon has been created by the Lunar Exploration Analysis Group (Lunar Exploration Analysis Group (LEAG) 2016). However, while such large-scale experiments would benefit from the infrastructure surrounding a lunar habitat, they would likely be outside of and at some distance from such habitat. Hence these disciplines would have only minimal interest in the proposed research laboratory.

The research areas we focus on instead would

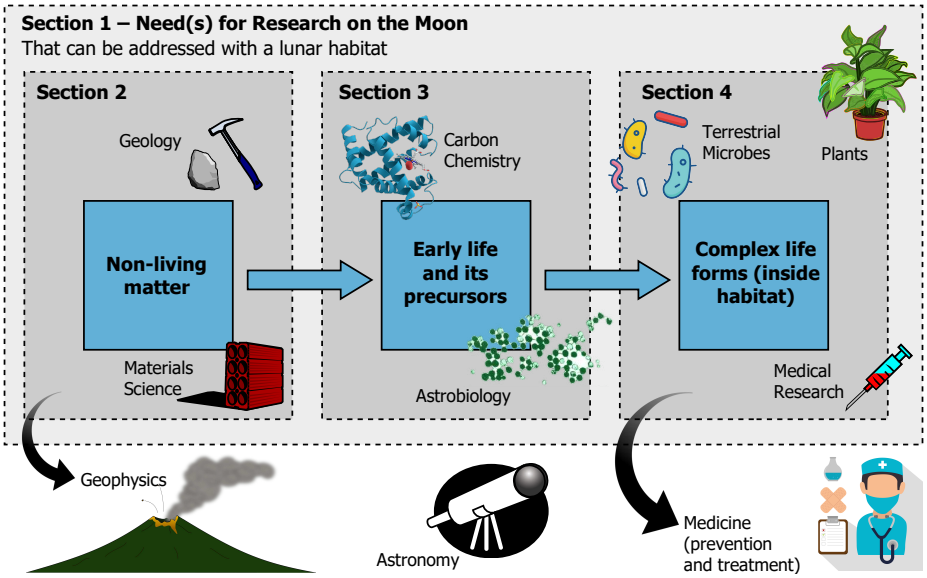

Figure 1: Graphical representation of the contents of this paper: We focus on disciplines and research areas that would benefit from a lunar habitat laboratory. The research areas include: (a) non-living matter (such as the lunar environment, lunar geology, and materials science), (b) early life-forms, their conditions and chemical precursors (in particular, carbon chemistry and astrobiology), and (c) complex life forms inside the habitat (plants, terrestrial microbes, medical research on humans). We explicitly exclude questions related to astronomy, geophysics, fundamental physics (which would largely be conducted outside a lunar habitat) and any question related to healthcare, prevention, or treatment of medical issues (which are not of direct scientific interest).

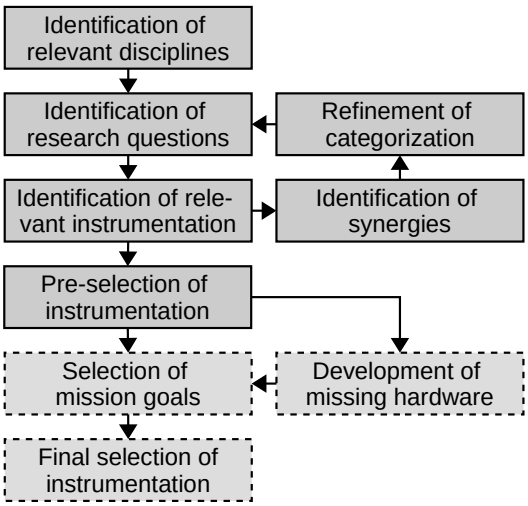

Figure 2: Flowchart of the selection process for the instruments presented here. After a first iteration of identifying relevant instrumentation, synergies were identified of several disciplines using the same instruments. These synergies lead to the categorization used in this paper (see fig. 1). Boxes with a dashed outline show how our instrument selection can be used in the future.

benefit greatly from a lunar habitat laboratory. We consider research areas related to (a) non-living matter (geology, materials science) in section 2, (b) the origin of life and the likelihood of its existence beyond Earth (carbon chemistry and astrobiology) in section 3, and (c) life inside the human habitat (biological life-support systems, microbiomes, medical research) in section 4 (see Fig. 1 for a graphical representation). We group these disciplines based on earlier work (Heinicke et al. 2018) where we found that methods and required instrumentation overlap significantly within these groups but not among groups. The selection of research questions and resulting instrumentation that we present here is the second iteration, improved after identifying synergies between related disciplines (Fig. 2). The order of how we present the research areas proceeds logically, starting with research on non-living matter, followed by matter with increasing chemical complexity up to living or-

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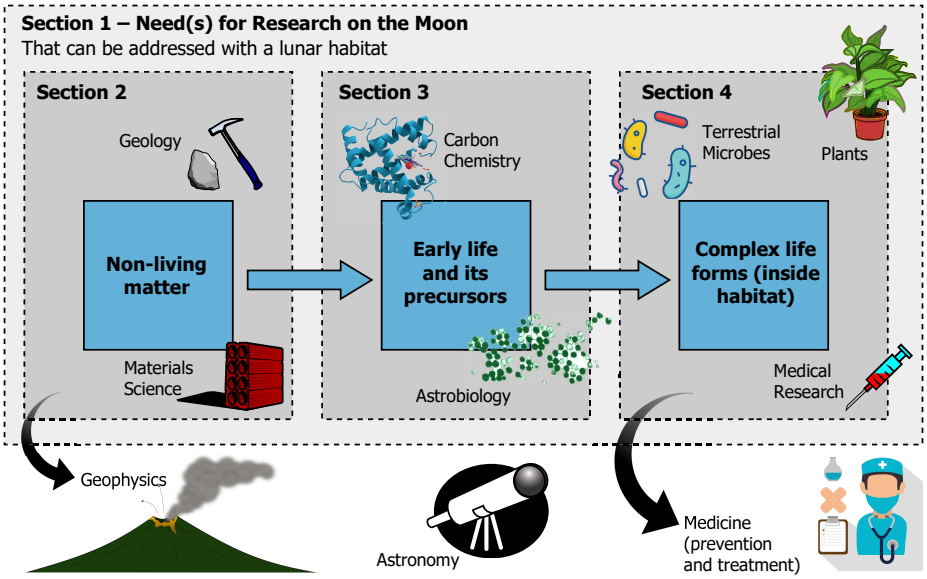

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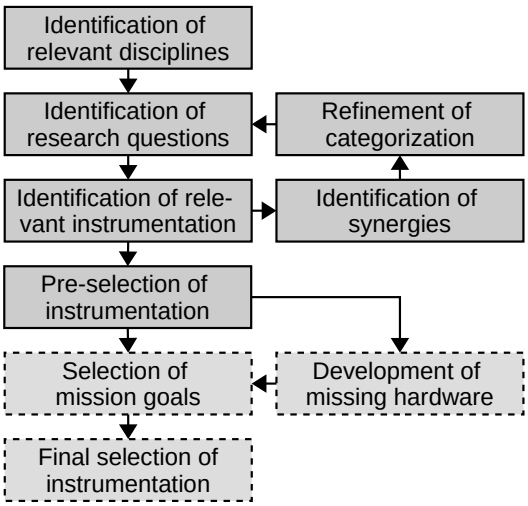

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ganisms, and ending with research on human occupants of the habitat.

Within each category we give an overview of (selected) open questions in the field relating to both the Moon and Mars. From these open questions we derive which instrumentation is necessary or desirable to have in an extraterrestrial research laboratory. Our primary focus is the Moon, however, we include an outlook to Mars, since we assume that the Moon not only provides a valuable testbed for technology to be used on Mars, but that both can be studied with the same habitat laboratory after only some adaptation.

Our instrumentation lists can be used by mission planners and engineers alike (see Fig. 2). The former may find inspiration as to how science could benefit from a human-occupied laboratory on the Moon and Mars; the latter are provided with a guideline of where further development of equipment would be desirable. It is important to note that our list is not and cannot be final. It is rather a proposition of which instruments should be considered for a laboratory; as Fig. 2 indicates, the final selection of equipment can only be made after the parameters of the mission are set and the boundary conditions of the laboratory determined. This is typically a multistage, iterative process (see for example Hörz et al. (2013), Groemer and Ozdemir (2020)). Similarly, while we tried to provide as much technical detail as possible, some technical parameters (e.g., frequency range of spectrometers, resolution and magnification, wavelength of light sources) depend on the exact scientific questions to be answered and samples to be studied and have therefore to remain open.

Finally, we end this paper with an outlook on operational aspects of scientific research on the Moon, how our recommended instrumentation can be tested in a complete laboratory as part of a habitat and how spacesuits and robots could support the astronauts' work both indoors and outdoors.

2. Investigations of non-living materials

In this section, we will discuss some open questions (section 2.1) related to lunar geology, geochemistry, in-situ resource utilization (ISRU), and materials science and how they could be addressed with the help of humans on the Moon. Open science themes around lunar geology range from the Moon's formation (2.1.1) and evolution, both in the subsurface (2.1.2) and at the surface (2.1.3), to what can be learned about the history of the Solar System (2.1.4). We briefly present research questions about resources in the lunar regolith (2.1.5), and material properties of the regolith (2.1.6) and of the materials brought from Earth (2.1.7) that need to be answered before any lunar outpost can be made permanent.

Following our discussion of open questions around geology and materials on the Moon, we will provide a brief outlook to Mars and how research on non-living matter on Mars could benefit from such research on the Moon (2.2). At the end of this section, we give a rough overview of the kind of equipment that would be useful for addressing open questions on the lunar surface (2.3).

We recognize that neighboring fields also have a strong scientific interest in the Moon. For example, geophysicists are interested in the remnants of the lunar magnetic field, the origin of moonquakes, outgassing, and the suggested existence of a liquid lunar core (e.g., (Jaumann et al. 2012)). However, besides sampling lunar rocks, geophysicists would probe the deep lunar interior with equipment that is typically placed on or below the lunar surface, such as seismometers (Latham et al. 1969, Lognonné 2005, Yamada et al. 2011), heat-flow probes (Langseth et al. 1972), magnetometers (Gordon and Brown 1972, Ness 1970) (further examples in (Allton 1989, Crawford and Joy 2014)). Such activities will take place outside the habitat laboratory and are thus outside the scope of this paper.

2.1. Open Questions of Lunar Research

2.1.1. Formation of the Earth-Moon system

The most accepted model for the lunar origin involves a giant impact between the earth and a large (Mars-sized) object (Canup 2012, Hartmann and Davis 1975). The exact nature of this impact, however, remains debated and there remains some discrepancy between the geophysical models and lunar geochemistry measurements (Lock et al. 2018). Particularly important is the observation that the Earth and the Moon are identical in oxygen and titanium isotope composition (Wiechert et al. 2001), and there has yet to be found any geochemical signature of the impactor. If the early Earth had indeed been hit by a proto-planet, the Moon's isotopic composition should be a mixture of the two, rather than matching the Earth's composition. A long-term lunar station and the ability to obtain and analyze samples from regions not sampled during Apollo would greatly help resolve this discrepancy.

2.1.2. The Moon's history as example for terrestrial planet evolution and differentiation

For the purposes of comparing planetary processes across the Solar System, Taylor and McLennan characterize three types of crust: primary, secondary, and tertiary (Taylor and McLennan 2008). This approach helps distinguish planetary bodies large enough to have undergone planet-wide differentiation, such as the Moon or Mercury, from undifferentiated bodies.

The notion of primary and secondary crusts on the Moon sets up a predicted chronology which has fed into models of the lunar magma ocean (LMO), which may have formed due to the large number of impacts during the early phases of lunar formation, and early differentiation. Models of the LMO (Elkins-Tanton et al. 2011) set up a predicted timeline where the anorthosites represent the last material to crystallize and a complement to the Mg-suite

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and ferroan anorthosites thought to be earlier crystallized cumulates. However, recent dating of Apollo samples and lunar meteorites (Borg et al. 2015) has shown an overlap in ages between the anorthosites and the Mg-suite, suggesting complications to the classical model of an LMO and that the anorthosites and Mg-suite either formed at the same time during differentiation or that they are unrelated to one another petrologically.

The lunar TiO_2 concentration is crucial for classifying the mare basalts and comprehending the geology and evolution of the lunar crust. The mare basalts are richer in TiO_2 than the highlands (<5 %); however the mare basalts are also divided into low-Ti (<7.5 %) and high-Ti (7.5−15 %) (Taylor et al. 1991, Giguere et al. 2000). It is still unclear what caused the high abundance of titanium on the Moon's surface and this distribution between the highland and mare basalts. The lunar mare basalts are samples of the interior composition of the Moon, thus their composition indicates the conditions of the Moon's formation and its mantle evolution.

One fundamental problem in lunar geology is the origin of the dichotomy of the lunar crust: the near side is low in elevation with a thin anorthositic crust and dominated by volcanic maria, whereas the farside is higher in elevation, has a much thicker crust and is heavily cratered. Possible explanations include large, possibly asymmetric impacts (e.g., Jutzi and Asphaug (2011)) and spatial variations in the Moon's internal composition or asymmetric convective processes (e.g., Miljković et al. (2013)). The ongoing Chang'e-4 mission **??** may help understand the origin of the dichotomy.

2.1.3. Impact cratering and formation of regolith

Since its formation 4.6 billion years ago, the Earth-Moon system has been subjected to meteorite bombardment. However, unlike on Earth where craters are eroded, buried, or transformed by tectonics over time, craters on the Moon have remained essentially unaltered, ranging in size from micrometer-size pits to few thousand-kilometer diameter impact basins. Besides the formation of craters, which will be discussed below, the bombardment with large and small meteoroids, micrometeoroids, solar charged particles and galactic cosmic rays (GCR) breaks down the surface rocks and creates the lunar regolith that covers almost the entire lunar surface (McKay et al. 1991). The average regolith thickness in the maria is 4-5 m, and in the older highlands possibly more than 10 m (McKay et al. 1991, Lucey et al. 2006).

Although the Apollo program caused the science of impact cratering to take a giant leap forward, many fundamental parts of the cratering process remain unresolved. Depending on gravity and, to some extent, target properties, the resulting craters from cosmic impacts see a change in final morphology with increasing size from bowl-shaped (a.k.a. 'simple') craters to wider, shallower structures with terraced rims and uplifted crater floors (a.k.a. 'complex' craters). On the Moon this transition occurs for craters with final diameters of 15-20 km. The crater center of smaller complex craters is characterized by a central peak, to great extent made up of material from deeper parts of the target that may be brought up to target surface level, or even overshoot it, similar to a water plume after dropping a pebble in water. At larger structures the central peak is replaced with a central peak ring, and for very large structures (basins) there may be several concentric rings.

For rock to obtain this plastic behavior, a temporary reduction in cohesive strength and internal friction is needed (Melosh 1977, McKinnon 1978), perhaps due to acoustic vibrations ('acoustic fluidization') remaining after the shock - and rarefaction waves induced by the impact - have passed (Melosh 1989). However, the weakening mechanisms are poorly un-

derstood for larger craters. On Earth, the only impact structure with a well-preserved and unequivocal peak ring to provide geological inputs to the numerical models used to analyze the process is the Chicxulub crater in Mexico, which is deeply buried and only accessible through drilling (see e.g., (Morgan 2016)). Direct sampling of lunar peak ring material is therefore fundamental for understanding the mechanisms involved in large impact crater formation. The results from the Chicxulub core drilling Expedition 364 (Morgan 2016) seem to support a model in which the peak ring forms due to the collapse of a greatly overshooting central peak (Murray 1980, Melosh 1989). However, material from other peak ring craters showing shock deformation and density reductions is needed to validate the model.

2.1.4. Regolith maturation and the archive of the Solar System

Surface regolith is continuously modified by (further) meteoroid impacts and radiation. Meteoritic impacts can generate enough heat to melt or partially vaporize dust particles, generate ejecta blankets, mix different generations of regolith together, as well as create new particles such as agglutinates, regolith breccia, and impact glass. In this way the regolith becomes a blend of rock fragments, mineral fragments, meteoritic components, glass, nanophase iron (Pieters et al. 2000), and radiation–implanted particles (Spray 2016). However, it is not fully understood how the regolith is consolidated into a coherent mass of breccia. Welding of deposits still hot from an impact is a possibility; another is shock lithification (Christiansen and Spilker 2018).

Studies of the effects of amorphous rinds on mineral grains, nanophase iron, and other alterations of mineral spectra are important in remote sensing observations of the lunar surface. Spallation may lead to cosmogenic nuclides (Crawford and Joy 2014) which can alter the isotope ratios of mineral elements affecting radiometric dating. On the up-side, the cosmogenic nuclides can be dated to calculate how long the regolith has been exposed to space radiation. It is of particular interest to compare with so-called paleoregolith that has been buried by lava flows and fresh ejecta (Fagents et al. 2010, Fa et al. 2015). Such paleoregoliths can hold an undisturbed record of composition and evolution of the Sun, samples of the Earth's early atmosphere and crust, asteroid populations, and probably interstellar dust particles (Crawford et al. 2013).

Today's lunar impact chronology is essentially based on calibration points that are between 3 and 3.85 Ga old (Stöffler et al. 2006), leaving room for debate whether the rate of impacts on the Moon has declined monotonically (with minor fluctuations (Kirchoff et al. 2013)), or whether there were periods of increased activity such as the suggested "cataclysm" between 3.8 and 4.1 Ga (Tera et al. 1974, Cohen et al. 2000). Sampling older craters will not only provide knowledge about the Moon, but more generally about the early history of the inner Solar System.

2.1.5. Resources in the regolith

The lunar regolith is a major source of chemical elements and compounds we may use to build structures, exploit resources, and support human missions. Compared to terrestrial basalts, lunar basalts contain greater concentrations of refractory elements (titanium, zirconium, and chromium), but lower concentrations of relatively volatile elements such as sodium and potassium (Haskin and Warren 1991) and no water.

Ilmenite ($FeTiO_3$) is a valuable source of titanium and iron, can be used for oxygen production, and has been detected widespread on the surface of the Moon. Ilmenite minerals trap solar wind hydrogen efficiently; therefore processing ilmenite will also produce hydrogen. Ilmenite may be an efficient trap for helium-3 with potential use as a fuel for fusion energy generation.

One of the most unusual terrains on the

Moon, which has been known since the Apollo era, is the Procellarum KREEP terrain, an area enriched in potassium, rare earth elements, and phosphorus.

Historically, the Moon was considered extremely volatile-depleted (Taylor and McLennan 2008), having water concentrations of less than 1 ppb (McCubbin et al. 2017). However, in 2007, a series of papers speculated that there may be more water in the lunar mantle (McCubbin 2007, Saal 2007, Saal et al. 2008, McCubbin 2010). Lunar Prospector found high concentrations of hydrogen at the lunar poles in 1998 (Feldman et al. 1998) suspected to belong to water. In 2009 Chandrayaan-1 confirmed the existence of surface water ice in some permanently shadowed polar craters (Pieters et al. 2009), and shortly after, the LCROSS impact experiment estimated the water content in the regolith to be 5.7 % by weight (Colaprete et al. 2010). Recently, SOFIA detected molecular water in the illuminated region of the Moon (Honniball et al. 2021). However, it is largely unknown how this water is contained within the rock and how it could be extracted efficiently.

2.1.6. Processing and material properties of regolith

The most ubiquitous and versatile resource on the Moon is the lunar regolith. It may be used as construction material for habitats and radiation shields (an artificial cave prepared from regolith would need to be ~ 0.5 m thick (Miller et al. 2009) or more (Jia and Lin 2010)), to pave or prepare surfaces in order to facilitate operations in the vicinity of the habitat, and it may be mined for its valuable components (see section 2.1.5. Plants or microorganisms could potentially derive nutrients from lunar regolith (Ferl and Paul 2010, Brown et al. 2008, Kozyrovska et al. 2006, Olsson-Francis and Cockell 2010) (see section 4.1.4).

The most commonly suggested processing method for regolith is Additive Manufacturing (AM) (Labeaga-Martínez et al. 2017). In some studies, regolith simulant was consolidated with the help of binders (e.g., (Cesaretti et al. 2014)), although they would add to the launch mass. The most promising techniques are sintering techniques using lasers (e.g., (Goulas et al. 2016, Abbondanti Sitta and Lavagna 2018, Xu et al. 2019, Fateri and Gebhardt 2015b)) and solar light (e.g., (Meurisse et al. 2018, Imhof et al. 2018, Fateri et al. 2019b)), or other heat sources (Khoshnevis et al. 2012, 2014, Taylor and Meek 2005b) and techniques (e.g., (Taylor et al. 2018)).

However, all these techniques have been developed and tested under terrestrial conditions (occasionally under vacuum, e.g., (Cesaretti et al. 2014)). To adapt them to lunar conditions, the following behaviors of regolith in lunar gravity must be understood: (1) sintering and melting behavior, (2) sedimentation of solid particles in a liquid phase and behavior of bubbles from outgassing, (3) wetting behavior of the heated regolith atop different substrates, (4) droplet shape variation of molten regolith at different heating rates, and (5) optimum energy source (laser, microwave, solar etc.) for specific applications.

Additively manufactured samples should be tested on site regarding their chemical and physical properties (strength, hardness, etc.), and, in the case of habitat structures, tested for long-term stability. A laboratory run by humans would help analyze material samples and adapt production parameters more rapidly compared to an alternative sample transfer to Earth.

2.1.7. Degradation of materials

There are multiple ways in which the lunar surface environment leads to the degradation of materials: the ionizing radiation mentioned above, UV radiation, ultra-high vacuum, micrometeoroids and debris, extreme temperature variations between illuminated and dark regions, and the lunar regolith itself. These environmental factors can lead to erosion, embrittlement, and optical property degradation,

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diminishing the performance and durability of hardware on the Moon.

Effects of vacuum could be investigated on the ISS (see e.g., (de Groh et al. 2018)), but the radiation environment of low Earth orbit (LEO) is not identical to that of the Moon (Sato et al. 2018), and LEO cannot represent the lunar dust environment.

Cosmic and solar radiation will degrade habitat and surface infrastructure materials, the crew's surface suits, and human tissue. Secondary radiation can damage critical hardware such as electrical control systems (Srour and McGarrity 1988), structural materials or coatings (Grossman and Gouzman 2003), and scientific hardware (e.g., (Heaney et al. 2000)), and cause radiation-related health issues (see section 4.1.6).

Polymer films can degrade from UV radiation and the extreme temperature cycles on the Moon to the point of cracking. Protective coatings may be scratched and do not protect against degradation from ionizing radiation (Dever et al. 2005). Furthermore, polymers may suffer from selective material outgassing in vacuum (Grossman and Gouzman 2003).

The combination of small dust particles (between 60 and 80 μm (McKay et al. 1991)), electric potentials (e.g., (Pirich et al. 2010)) plus micrometeorites can lead to lunar regolith being levitated (Grün et al. 2011, Horanyi et al. 2014), and levitation is likely to increase with human activity on the Moon. Levitated dust particles may settle and accumulate on hardware which may result in potential degradation of radiative heat transfer and optical components through the fouling of surfaces, visibility reduction during extravehicular activities (EVAs), dust contamination of equipment and prevention of effective sealing (Wagner 2006).

2.2. Outlook to research on Mars

Geologically, the biggest open questions on Mars—at least in terms of size—center around the hemispheric dichotomy: the relatively smooth surface of the Borealis basin covers most of the northern hemisphere, about one third of the entire planet. The southern hemisphere is heavily cratered, higher in elevation, and its crust is roughly twice as thick as the one in the north. There are two categories of hypotheses for the origin of this dichotomy: endogenic theories in which the northern crust was thinned by mantle convection, overturning, or other processes in the interior of Mars (Elkins-Tanton et al. 2005, Wise et al. 1979), and exogenic theories that are based on one or more large impacts in its early history (Wilhelms and Squyres 1984, Frey and Schultz 1988, Andrews-Hanna et al. 2008).

Mars is still seismically active today (Golombek et al. 2020, Banerdt et al. 2020), but the extent and origin of tectonic activity is poorly understood. Mars never had plate tectonics (Turcotte and Schubert 2002), however, there is evidence for recent (few tens of Ma) volcanic activity (Hauber et al. 2011), and the large canyons in the equator region are likely formed by extension of the crust due to magmatic uplift (Schultz 1998, Mège and Masson 1996) or crustal loading in the Tharsis region (Turcotte and Schubert 2002).

There is clear evidence of the presence of liquid water (Baker 2001) in the past. In addition to the observation of fluvial valleys and crater lakes, aqueous minerals and evaporites have been widely detected on the surface. Water has been detected on present-day Mars in various forms, as ice in the polar caps (Langevin et al. 2005, Titus et al. 2003), glaciers at lower latitudes (Neukum et al. 2004, Head et al. 2005, Forget et al. 2006), and subsurface permafrost (Farmer and Doms 1979) or ice deposits (Johnsson et al. 2014), liquid water under ice (Orosei et al. 2018), and as vapor in the atmosphere (Farmer et al. 1977, Jakosky and Farmer 1982, Smith 2002). Recurring slope lineae were thought to be created by brines (e.g., (Martínez and Renno 2013)), but there are arguments for a dry origin (Munaretto et al.

2019). In situ investigation of the surface and near surface material would help understand the history of liquid water on Mars, which has direct implications for the search for life on the red planet.

Perhaps the most intriguing field of study are the caves near the giant volcanoes. Geologically, they offer a stratigraphic window into the volcanic history of Mars and they might have been or might still be home to non-terrestrial life forms (Léveillé and Datta 2010), as well as to subsurface water and ice reservoirs (McKay and Stoker 1989).

2.3. Recommended instrumentation

2.3.1. Field equipment

Typical field equipment for geologists on Earth comprises a hammer, magnifying glasses or lenses, a note pad, camera, directional markers and scales, as well as sample containers. For specific tasks these can be complemented with certain portable spectrometers (e.g., portable Raman). Such situations may become more common on the Moon where there is less accumulated field experience on, for instance, the connection between visual appearance and composition of a rock than in terrestrial geology. Additionally, on the Moon, seemingly simple tasks require considerably more effort due to the limited mobility with the pressurized suit and the reduced gravity that led to a considerably large number of falls during the Apollo missions. Hence, Apollo astronauts used an additional set of equipment that facilitated their work on the surface. For example, it was nearly impossible to kneel down in the Apollo surface suits, so the astronauts used tongs and scoops with extended handles so they did not have to kneel or bend down to pick up samples.

Today, there are efforts to enhance previously used instruments (Anderson 2016) and devise new ones, such as equipment trolleys and caddies, or cuff controls (Budzyń et al. 2018, Young et al. 2013a, Brannan and Bradshaw 2011). In some cases, devices developed for terrestrial use might be adapted for space exploration (e.g., (Young et al. 2016, 2013b)). The development of tools has been modernized since the Apollo area, but the goal is still the same: to overcome the limitations of the suits on basic tasks with additional equipment. Apollo astronaut Schmitt, who is also the only geologist to have walked on the Moon, suggests a whole list of equipment that would be useful for surface exploration (e.g., helmet-mounted laser-ranging devices, or "hand-positioned, self-anchoring, portable geochemical sensors" (Schmitt et al. 2011)). In addition, there are strong arguments and promising developments for rovers (both autonomous and crew-controlled) (Spudis and Taylor 1988, Schmitt et al. 2011, Akin et al. 2011, Harrison et al. 2008, Wilcox et al. 2007), as well as spacesuit-integrated artificial intelligence systems (e.g., McGuire et al. 2014) supporting the crew's field work both physically and with the sample selection process.

2.3.2. Lab equipment

Although some optical and spectrometry instruments will be applied in portable format already during the fieldwork their resolution will not be sufficient for detailed studies. This will require instrumentation with specifications in par with terrestrial geoscience laboratories (e.g., visible + polarized optical microscope, Scanning Electron Microscope with Energy Dispersive X-ray spectroscopy (SEM-EDX), Raman microscope). These microscopy devices enable analysis of samples from both bedrock and regolith regarding its mineralogy, petrology, geometry, granulometry, chemical composition.

We envision instruments that combine elements of terrestrial lab based instruments and those which have previously flown on missions, primarily Mars missions. For example the Curiosity rover included the Mars Hand Lens Imager (MAHLI) instrument (Edgett et al. 2012) that was able to bridge the gap between lab-based microscopes and unaided viewing. Sim-

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ilarly, both Curiosity and the Perseverance Rover house Raman instruments (Rull et al. 2017, Beyssac 2020). Importantly, these rover-based instruments have disadvantages compared to lab-based tools (resolution, collimation etc.) and a lunar base lab would likely be able to resemble Earth-based labs more so than rover-based instruments.

Sample preparation and granulometry studies may require dry and/or wet sieving and sorting of the material into different particle sizes and distributions. Grain size classification is commonly done by using different mesh-sieves and a vibration and/or a centrifuge units (Martinez et al. 2012) as well as electrostatic-based particle sorter (e.g., (Adachi et al. 2017). Sieving could be implemented using a shaker at different frequencies. This shaker could be further applied for compacting/tapping the regolith to study the effect of lunar regolith compressibility and cohesion under reduced gravity. A penetrometer was employed during Apollo to measure porosity, density, cohesion, and internal friction of regolith in-situ (Houston and Namiq 1971, Mitchell et al. 1972). Determination of these properties after transport to Earth has been very limited, both due to the amount of samples brought to Earth and their alteration during transport.

Rock samples could need to be crushed using a jaw crusher or a ball mill device. Moreover, a lunar calibrated scale would be necessary in order to provide the mass fraction of particles and rocks. Many of these devices are difficult to miniaturize as they may depend upon human physiometry (e.g., optical microscope), requirements such as the need for sensor cooling in bottle of liquid nitrogen (i.e., SEM-EDX), or a minimum of applied mechanical force (i.e., sample splitter and crusher).

For handling clastic material, basic equipment from the chemical lab such as beakers and funnels are necessary. For studies of the possibilities to shape regolith into solid objects as well as its sintering/melting behavior on-site, an oven and corresponding molds (crucibles) are needed. This oven should reach temperatures above 1200 °C which is the melting temperature of regolith for the most studied areas on the Moon so far (Lofgren and Smith 1978) It should be noted that heating of regolith could also be accomplished by using lasers (Fateri and Gebhardt 2015a) and microwave radiation sources (Taylor and Meek 2005a). This would imply very high energy requirements.In these studies, a Differential Scanning Calorimeter (DSC), a viscometer and a contact angle analyzer device could provide more detailed information on the melting and wetting behavior of the regolith on-site. (Fateri et al. 2019a)

In order to shape regolith into a denser form, a press device is required before exposing the sample to heat. Furthermore, volume analysis of the formed geometries is required. This could be done using different methods such as envelope density measurement devices or 3D scanners.

Chemical analysis and crystal structure of the lunar regolith as well as the sintered/molten shaped products could be done using SEM-EDX and X-Ray Diffraction (XRD): XRD is already successfully applied on Mars (the CheMin instrument on the Curiosity rover (Bish et al. 2014), and SEM is being developed for use on the Moon for more than a decade (Campbell et al. 2010). Mechanical testing devices such as a compressive and flexural strength analyzer would be needed in order to evaluate the properties of the shaped products. Heat diffusivity of the processed regolith could also be measured using a Laser Flash Analyzer (LFA). Subsequently, knowing the heat capacity and density of the processed regolith, heat conductivity of the processed regolith could be calculated.

Hardness testing devices (e.g., Vickers testers for indentation hardness) would be required for evaluation of the final samples. Moreover, spectrometers which could deter-

mine the absorption, reflection, and transmission of regolith and the shaped products at different wavelengths would be needed. Targeting the volatile extraction aspect (especially after the proven evidence for accessible hydrogen and water at the lunar poles), a fully automated mobile miner is among the initial needs. The miner must be adaptable to the environment and the mechanical properties of the feedstock.

High temperature ovens and thermoelements capable of working under different gas pressures and types would be required beside the mobile miner. Gas analyzers as well as thermal cameras would also be required for having a closed loop controlled system for volatile extraction. The latter two are already in development for the Moon (e.g., (Szopa et al. 2018, Hager 2013). After conversion of the feedstock, the resource as well as the waste product must be preserved in a sealed reservoir and subsequently delivered for use (Carpenter et al. 2016).

Lastly, AM (3D printing) devices which enable on-site manufacturing of necessary lab equipment such as spare parts would be needed (Fateri et al. 2018).

2.3.3. Consumables

The consumables typically needed on Earth will be very similar on the Moon (and on Mars). They comprise sample containers in various sizes, with more or less controlled environments (for example, samples of ice need to be cooled if they are to be transferred into a human habitat), safety equipment (disposable gloves, including gloves for a glovebox required for working on dusty or outgassing samples), liquids and gases for maintenance of the above mentioned equipment (coolants, lubricants, etc.) as well as spare parts. For calibration, there will need to be reference or baseline targets, reference light sources, scales, etc. There should be cleaning materials and chemicals, and filters. Various instruments require a sample to be placed inside a special sample container or crucible, these should be available in adequate quantities, or re-usable. In the case of liquid samples, this is often done with a pipette; ideally, the corresponding pipette tips are re-usable, too. Generally, re-usability should be aimed for in all hardware, as well as inter-usability, i.e. various instruments should share the same consumables wherever feasible.

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	Instrument	Purpose	Special requirements	Readiness Level	Size
Field equipment	Sampling tools (hammer, scoops, tongs, markers, sample containers, magnifying glasses etc.)	sampling (2.1.1-2.1.5)		Used during Apollo	Hand-held portable.
	Recording tools (camera, sketch pad, etc.)	surveying, recording of geological context (2.1.1-2.1.5)		Used during Apollo	Hand-held portable.
	Spectrometers (UV-Vis-IR, Raman, EDX)	non-destructive sample analysis/screening (2.1.1-2.1.5)	XRF and Raman are better when measuring flat surfaces, so may be used in conjunction with small hand tools.	Partially flown to Mars (ExoMars Raman Laser Spectrometer (RLS), Mars Express OMEGA)	Hand-held portable.
	Gas analyzer, thermal camera	volatile extraction (2.1.6-2.1.7)		In development (e.g., Luna-Resurs Gas Analytical Complex experiment).	Hand-held portable.
Laboratory equipment	Microscopes (visible, polarized,SEM)	sample analysis/screening (2.1.1-2.1.5)	Vibration sensitive.	Microscopes are on ISS (e.g. Light Microscopy Module (LMM)), SEM for the Moon is in development	Bench top, not portable.
	Vibrational Spectroscopy instruments (UV-Vis-IR, Raman)	non-destructive samples' analysis/screening (2.1.1-2.1.5)	Some detectors may require being cooled (typically LN2). Raman instruments require additional laser(s).	Partially flown to Mars (ExoMars Raman Laser Spectrometer (RLS), Mars Express OMEGA). Laboratory Raman cannot be replaced by a portable field Raman (e.g., higher resolution).	Benchtop to desk sized. Can be coupled with a microscope.
	X-ray diffractometer (XRD), X-ray fluorescence spectrometer (XRF)	chemical and crystal structure analysis (2.1.1-2.1.7)	Requires compressed air or LN2.	In use on Mars (e.g., CheMin on MSL); in development for Moon (e.g., XTRA). Mars-XRD was supposed to fly on the Rosalind Franklin rover but was de-scoped.	Benchtop to desk sized.

	Instrument	Purpose	Special requirements	Readiness Level	Size
	Particle sorter (vibration unit/shaker, centrifuge, sieves/mesh units, fluidized bed)	grain size classification & sorting (2.1.1-2.1.6)		Partially in development.	Large floor or bench space required.
	Crusher (law crusher, ball mill), mobile miner and milling devices	sample preparation 2.1.4,2.1.6	Typically require a lot of energy.	For terrestrial application only.	Large floor or bench space required.
	Thin section production (rock cutter, polisher)	sample preparation (2.1.1-2.1.3)	Coolant needed.	Cutting discs for sectioning lunar samples available, but devices need to be modified for lunar gravity.	Benchtop, not portable.
	Press	sample preparation (2.1.6)		Only terrestrial application so far. Must be miniaturized.	Large desk size, not portable.
	Thermal oven (conventional, laser beam, microwave)	sample treatment (2.1.5-2.1.7)		Feasibility tests using microwave, lasers,... have been done for earth application. Modifications for lunar environment necessary.	Benchtop.
	Melting and wetting behavior analyzer (Differential Scanning Calorimeter, viscometer, contact angle)	material properties testing (2.1.6-2.1.7)		Only terrestrial application so far.	Benchtop.
	Density measurement device (envelope and skeletal density)	material properties testing (2.1.6-2.1.7)	Pycnometry requires displacement medium (e.g., helium).	Adaptation to lunar environment possible.	Benchtop.
	Mechanical testing devices (compressive strength, flexural strength, hardness)	material properties testing (2.1.6-2.1.7)		Lunar penetrometer used during Apollo. Rest for terrestrial application only.	Benchtop to desk size, not portable (must be miniaturized).
	Thermal property analyzer (laser flash (LFA), heat capacity, heat conductivity)	material properties testing (2.1.6-2.1.7)		Only terrestrial application so far.	Benchtop to desk size, not portable (must be miniaturized).
	3D scanner	volume analysis (2.1.6-2.1.7)			Little development needed for adaptation to Moon.
	Scales	Sample characterization (2.1.1-2.1.7)		Currently on ISS (SLAMMD, BMMD).	Lunar scales could use the same measurement principles used on Earth.

	Instrument	Purpose	Special requirements	Readiness Level	Size
Consumables	Basic lab containers (beakers, funnels, molds/crucibles, sealed reservoir)	sample storage for transport and/or analysis (2.1.1-2.1.7)	Materials of sample containers must not alter samples.		Some could be 3D printed.
	Basic safety equipment (disposable gloves, glovebox gloves, goggles, ...)	Personal protective gear (2.1.1-2.1.7)	Re-usable would be desirable.		Required by all disciplines.
	Coolants, lubricants, etc.	Maintenance (2.1.1-2.1.7)	Materials must be non-hazardous to humans and the LSS.		Highly dependent on specific equipment.
	Reference targets, reference light sources, etc.	Calibration (2.1.1-2.1.7)			
	Cleaning materials, filters	Cleaning (2.1.1-2.1.7)	Re-usable or recyclable.		Filters could be 3D printed.

Table 1: Summary of the lab equipment suggested for research within the category of non-living matter. The purpose column lists the sections where the open research questions are discussed that the respective instrument relates to.

3. Investigations of life and its precursors in extraterrestrial conditions

3.1. Open Questions of Lunar Research

The lunar surface presents conditions which are extremely harsh to life, biosignatures and prebiotic molecules (see Figure 3). Somewhat paradoxically, the Moon may have preserved traces of intermediates between simple chemistry and today's biological systems: it lacks an atmosphere and plate tectonics, has barely been contaminated by modern Earth, and is devoid of wind- or water-driven weathering.

Such an environment could help answer questions as fundamental as how life emerged from chemistry, where it could have existed and may still exist today, and how we could detect it. In the following sections, we expand on a selection of open research questions pertaining to lunar carbon chemistry (subsections 3.1.1-3.1.3) and astrobiology (subsections 3.1.4-3.1.7).

3.1.1. Lunar organic chemistry: rationale for study

The lunar rocks returned by the Apollo missions were analyzed in the 1970s for their carbon containing compounds (see Gibson and Moore 1972 for a review). In that time, it was rather difficult if not impossible to distinguish whether they were of exogenous or terrestrial origin. More recently the Apollo 17 samples have been revisited with new instrumentation and techniques (Brinton and Bada 1996, Thomas-Keprta et al. 2014). With the development of compound-specific isotopic measurements, it is now possible to distinguish with more accuracy between the different sources of organic compounds contained in the Apollo samples (Elsila et al. 2016).

Continued investigations into organic content of meteorites and comets (Cronin et al. 1988, Mumma et al. 1996) prompt the search for organic matter on the Moon with added fervor. The ongoing analysis of lunar regolith will help distinguish more precisely the origin of organic compound content, be it from (micro-)meteoritic infall, solar wind (thought to have delivered acid-hydrolysable precursors to amino acids; Harada et al. 1971), or terrestrial contamination.

Studying lunar samples on the Moon has the advantage of being less prone to contamination by terrestrial organic molecules. With scientists being involved in the entire process of sample collection, preparation, and analysis, the inevitable contamination history can be well documented and understood.

3.1.2. Lunar organic chemistry: the Moon as a test platform

Photolysis of organic carbon compounds induced by UV and cosmic radiation has been studied largely in the context of Mars. Since the Viking landers, there have been many laboratory studies concerning the degradation of organic molecules by radiation on simulated planetary surfaces (Oro and Holzer 1979, Ten Kate et al. 2006, Shkrob et al. 2010).

The surface of the Moon is subject to unhindered UV and high energy solar and galactic rays and solar wind sputtering, all of which can degrade organic molecules in the regolith and could be studied firsthand. A depth profile of organic carbon content could be created in a way which would be unfeasible with a meteorite or laboratory analogue, which are constrained in size, or on Earth, where a significant portion of ionizing radiation is attenuated.

Another advantage in studying photochemistry on the Moon is that any metal-catalyzed effects are easier to distinguish since much of the surface minerals are dehydrated. Whereas ice photochemistry has been extensively studied in laboratories on Earth (see Öberg 2016 for a review), dehydrated metal photochemistry and catalysis is understudied in this context and likely plays a significant role in the degradation of organic compounds on the Moon.

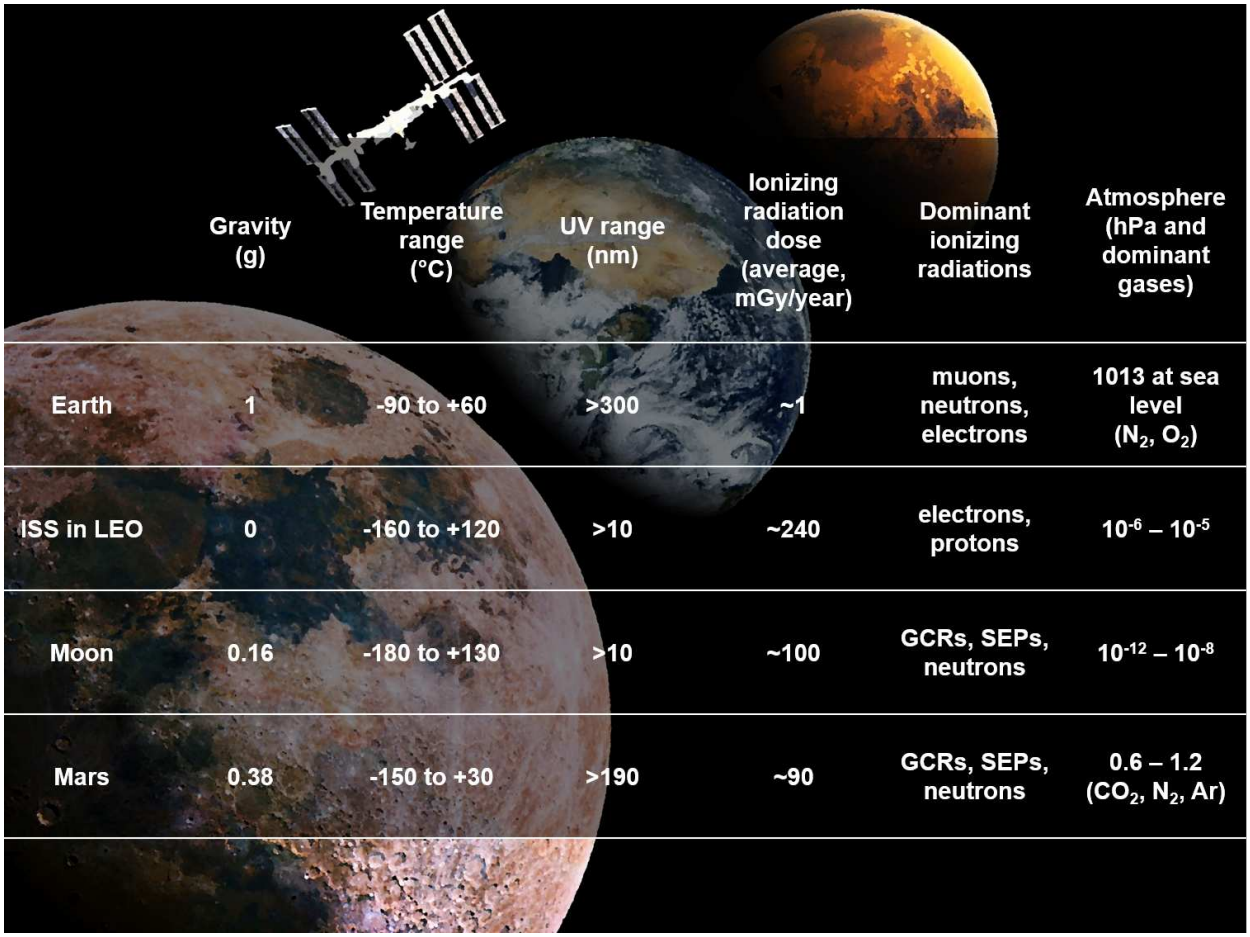

Figure 3: Comparison of some environmental factors on the surface of Earth, the Moon and Mars, and outside the ISS in low Earth orbit. Adapted from (Cottin et al. 2017) with additions from (Hassler et al. 2014, Reitz et al. 2012, Dachev et al. 2017, Rabbow et al. 2017).

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3.1.3. Accumulation and evolution of lunar organic carbon compounds

Interplanetary dust particles (IDPs) and (micro-)meteorites contain significant amounts of carbonaceous matter, which has been accumulating on the Moon since its formation. A lunar laboratory could determine the infall rate of organic material from these sources and establish an effective radius of accretion. Additionally, it would be interesting to compare the influx rate on the nearside versus that on the far side, to determine whether Earth displays any shielding effects on organic matter accretion.

Continued falls of meteorites offer the possibility to study the survival of organic molecules during impact, free of prior atmospheric heating and burning effects. The aforementioned recent studies of Apollo 17 regolith samples show evidence of organic compounds of meteoritic origin, suggesting they may survive impact events on the Moon, as may volatiles (Ong et al. 2010).

The influx rate, destruction mechanisms and lifetime of organic carbon compounds could be studied in great detail in a laboratory on the Moon. These results could be extrapolated to bodies like Mars where organic matter may have been important for potential past or extant life. A detailed understanding of the inventory and evolution of organic carbon is important when discussing to what extent complex chemistry could have evolved, the feasibility of life on Mars and the preservation of biosignatures.

3.1.4. Limits for life beyond Earth: rationale for study

Our growing knowledge of life's limits beyond Earth guides the search for extraterrestrial life: it helps determine which environments are the most likely to have hosted it (e.g., Schulze-Makuch et al. 2017). It also supports planetary protection, providing a basis for assessing the risk that accidentally released microorganisms could proliferate on site (e.g., Cortesão et al. 2019) or otherwise produce positive signals in search-for life assays.

An additional motivation for studying life's limits deals with the theory of lithopanspermia, according to which microorganisms might travel from one planet to another (e.g., from Mars to Earth) within rocks ejected by impacts. Experiments suggest that a fraction of rock-borne microorganisms could survive expulsion from Mars (Horneck 2008, Benardini et al. 2003, Mastrapa et al. 2001) but large uncertainties remain on how long they could survive in interplanetary space, even though rock-borne microorganisms can withstand months in low Earth orbit if protected from UV (Cottin et al. 2017, Olsson-Francis and Cockell 2010, de Vera et al. 2019). A better understanding of damage from vacuum, ionizing radiation and their combination would thus allow for more accurate assessments of lithopanspermia's likelihood.

Such investigations bear little relevance to the study of the Moon itself (which is unlikely to have ever harbored life) but a lunar base could greatly support them. This claim is justified in the following subsection.

3.1.5. Limits for life beyond Earth: the Moon as a test platform

Ground-based simulations of extraterrestrial conditions are highly limited in their fidelity (Cottin et al. 2017), notably when it comes to radiation. Simulations in low Earth orbit (LEO) are more realistic, but their flux of ionizing radiation flux is affected by the Earth's magnetic field. The Moon, on the other hand, has no magnetosphere and virtually no atmosphere, resulting in qualitatively unaltered fluxes of both ultraviolet and ionizing radiation (e.g., Reitz et al. 2012). This would be highly useful for assessing the effects of space radiation, in combination or not with vacuum (de Vera et al. 2012). Different extraterrestrial environments could be simulated by adding radiation filters (accounting, e.g., for Mars's atmosphere) and/or elements

of the simulated environment (e.g., atmosphere and/or regolith).

A laboratory on the Moon could solve other pitfalls of exposure experiments in LEO. First, preparing and analyzing (or stabilizing) samples on site would avoid long-term storage in non-optimal conditions. It would also limit damage from vibrations, shocks and accelerations during takeoff and landing, which can be hard to distinguish from damage caused by the environmental factors under study. Second, assembling hardware on site would enable both larger-scale experiments (sample number and size in are highly limited in LEO) and the use of more delicate equipment. Third, samples could be collected and hardware quickly re-used for follow-up (or independent) experiments.

In short, a lunar laboratory could address the major pitfalls of ground- and LEO-based studies on the limits for life in extraterrestrial environments.

3.1.6. Search for extra-terrestrial life

The Martian surface is likely uninhabitable, even to microorganisms (e.g., Schuerger et al. 2003), but is thought to have been more hospitable in the past (Carter et al. 2015, McKay 1997, Wynn-Williams and Edwards 2000). Survivable conditions may have persisted locally up to present day, most likely under the surface (Cockell 2014, Westall et al. 2013, Schirmack et al. 2014, de Vera et al. 2014).

Exposing organisms to simulated Martian conditions on the Moon (see subsection 3.1.5) can help determine which locations on Mars are most likely to have supported life. It can also help refine databases of biosignatures (detectable features which are typical of life; see Horneck et al. 2016) by assessing how they are being affected by the environments where they are being looked for (Horneck et al. 2016, de Vera et al. 2012, 2019).

In addition, Martian material found on the Moon (see section 3.1.7) could be analyzed for the presence of biosignatures, an approach—though likely less fruitful—more feasible in the middle term than doing so on Mars. Analyzing such samples on the Moon would lower the risk of contamination by terrestrial life.

Finally, the Moon could be a valuable testing ground for life-detection instruments and protocols, supporting their refinement in view of a Mars mission.

3.1.7. Origin and early development of life

Due to its lack of plate tectonics and wind or water-driven weathering, the lunar surface may have preserved fragments of the early Earth, Venus and Mars, landed there after impact ejection (JC et al. 2002, Matthewman et al. 2015). Their analysis may yield information on those planets' habitability through time. Samples may even harbor identifiable signs of terrestrial (or even Martian) life so early that all traces of them have been degraded beyond usefulness on their planet of origin, perhaps including intermediates between simple chemistry and complex life forms. Besides, prebiotic molecules—either indigenous or deposited by meteorites or IDPs—may be preserved in permanently shadowed ice (JA and DA 2009), which could shed light on the emergence of life (see subsection 3.1.3).

3.2. Outlook to Research on Mars

As described in section 3.1, the results from research carried out in a lunar base could direct the search for life on Mars: it could help assess where life may have existed, indicate where it is most likely preserved, identify areas where accidental contamination with imported microorganisms would be particularly problematic, and refine our abilities to detect and interpret biosignatures.

Further investigations on the Moon may help refine planetary protection rules. In order to ensure compliance to those rules within missions that may not make astrobiology an absolute priority, those rules should be highly pragmatic and evidence-based. Guidelines

have been proposed (e.g., Conley and Rummel 2010, COSPAR 2020) but specific requirements, technologies and operations remain to be defined. The Moon would be an interesting testing ground. On the one hand confinement (inside habitats, vehicles, EVA suits) and operations would be comparable to that expected on Mars, and imported microbial components should be clearly distinguishable from endogenous material. On the other hand, low levels of contamination would be unlikely to significantly affect future investigations, leaving room for experimentation.

3.3. Recommended Instrumentation

In this section, we discuss instrumentation that would enable a crew on the Moon to perform research pertaining to extraterrestrial life and to life's precursors. This instrumentation is summarized in Table 2. Further insights on how to equip an astrobiology laboratory on the Moon can be found in Gronstal et al. (2007).

3.3.1. Field Equipment

The search for early and/or extraterrestrial life, and possibly planetary protection-related studies, will require the collection and rough processing of samples from the lunar surface and subsurface. The required instrumentation can be used for non-biological samples as well and was described in section 2. The same is true for the identification of extra-lunar materials (from terrestrial, Venusian or Martian origin), which can be performed using spectrometers—infrared spectrometers, mostly, but also Raman spectrometers and laser-induced breakdown spectroscopy (LIBS) instruments—to assess both bulk and mineralogical compositions (Crawford et al. 2008). Spectrometers can also help detect organic matter in situ, although probably not directly on surface-exposed samples, and thus help in the selection of samples for further analyses. Since current rover missions to asteroids, planetesimals, and Mars are already carrying such instruments, their adaptation for a crewed lunar base is expected to be straightforward (e.g., Rull et al. 2017, Wiens et al. 2017). Spectral ranges should be as broad as possible (from UV to far infrared, for both reflectance and Raman spectroscopy).

Hardware for extravehicular exposure experiments can draw largely from exposure platforms in LEO (Cottin et al. 2017). However, they could be developed further to take advantage of the possibilities to prepare and analyze samples, and to deploy hardware, on site (see section 3.1.5). Platforms should feature an array of environmental sensors including thermometers, radiometers (for UV, visible, and ionizing radiation), hygrometers and vacuum sensors, to monitor exposure conditions. Those sensors could be similar to some already deployed in space, notably on the ISS. Real-time acquisition of data pertaining to the biological samples themselves (notably UV-VIS-IR and Raman spectrometry data)—a component often missing from ground- and LEO-based exposure (Cottin et al. 2017, de Vera et al. 2012)—is recommended. Spectrophotometer-carrying nanosatellites and cubesats have been flown, and the required development is not expected to be prohibitive ((Ehrenfreund et al. 2014, Nicholson et al. 2011, Shiroma et al. 2011)).

3.3.2. Lab Equipment

Current astrobiology experiments where exposure is performed beyond Earth tend to rely on samples prepared on the ground and analysed post-flight. While this saves crew time and payload mass, it comes at the cost of flexibility and sample integrity. Analytical capabilities and room for improvisation on the Moon would be beneficial; the laboratory equipment described below could enable both. As for all categories of equipment recommended here, this list is by no means definitive or exhaustive: mission parameters, specific research projects and upcoming technology development will have a large impact on the instruments eventually selected.

A critical asset for astrobiology research in

a lunar laboratory will be a sterilizable and contained workstation, used for handling samples which may be hazardous (solvents, Moon dust...) or sensitive to contamination (e.g., containing microorganisms or simpler organics). This workstation should offer the possibility to work under an atmosphere different from ambient (e.g., Mars-like, or composed of neutral gases to avoid oxidation/degradation) and accommodate the required instruments, possibly connected via optical fibres (e.g., for spectrometers). Likely workstations are glovebox systems: sealed areas accessible through built-in gloves, possibly with low inside pressure and an airlock. They have been used extensively in space to protect the user, the samples, or both; examples include the BioGlove-Box (Brinckmann 2003), the Clean Bench (Ishioka et al. 2004) and the Microgravity Science Glovebox (Spivey and Flores 2008). Sterilization of the inside of a glovebox (as well as instruments that need to be sterilized) can be achieved using UV LEDs or ozone. Adaptations to space-flown hardware may be desirable to facilitate complex operations requiring fine motor skills in aseptic conditions; flow cabinets and fume hoods (depending on applications) may be considered for samples that can be handled under ambient air.

To analyze (or screen) collected samples, microscopy will be the go-to technique. Microscope instruments should be as versatile as possible to cover different needs, combining for instance light, fluorescence, confocal, and electron microscopy in one to a few instruments. Various microscopes have been used in space, some including the aforementioned capabilities (e.g., De Vos et al. 2014, Meyer et al. 2015, Own et al. 2020). Other non-destructive life-detection instruments would complement (or be combined with) microscopes; particularly relevant are UV-VIS-IR and Raman spectroscopes with capabilities higher than the field instruments mentioned above. Once those have been used, samples can forego more powerful but destructive techniques such as mass spectrometry, PCR-based techniques, sequencing, microarray technologies or other "omics" platforms, which can rely on instruments needed for other biological investigations and described in section 4.3.

On-site sample preparation and culture maintenance will require basic microbiology hardware to grow, maintain, treat and separate the investigated organisms. A large part of that equipment could be drawn directly from the ISS, where a wide range of instruments such as a high-speed refrigerated centrifuge, spectrometers, cooling units, and plate readers, have been used (see, e.g., Buckley et al. 2017). Others (e.g., pipettes, pH meters, autoclaves or ozone sterilization devices, vortex mixers) could be transferred from Earth after little to no specific development.

For chemical analysis, as some larger kerogen-type molecules can be difficult to extract from a mineral matrix, an accelerated solvent extraction system would be required. While current instruments would in theory work on the Moon, development efforts are required to obtain more rugged and lightweight instruments.

Generally speaking, payload weight and volume, waste generation, and need for crew time could be reduced by miniaturization and automation. Considerations are given in section 4.3; for astrobiology specifically, miniaturized and sensitive instruments are being developed in the form of biosensor arrays (or biochips). Immunoassay testing platforms, for example, can provide a great versatility of detection (e.g., Moreno-Paz et al. 2018). Instruments which include some have been selected for missions to Mars and icy moons and are close to flight readiness (McKay et al. 2013, Fairén et al. 2020). However, these techniques (notably the associated biological reagents) have not been fully tested in the high radiation environments of the Moon or interplanetary space. Although ground-based and LEO experiments

have shown the resistance of selected target-binding reagents of biosensor arrays, such as antibodies or aptamers (e.g., Coussot et al. 2019), long-term testing on the Moon would definitely validate the techniques, for use there and within further exploration missions.

3.3.3. Consumables

Consumables needed for the above-mentioned astrobiology and carbon chemistry investigations are similar to those used on Earth for microbiology, molecular biology and organic chemistry but, given payload weight and waste disposal limitations, reusable and/or recyclable versions should be preferred for typically disposable resources (Petri dishes, reaction tubes, syringes, sample containers, pipettes, etc.), an approach often avoided on Earth to save time and reduce expenses. Glass could be considered (even heat-resistant nucleases—an argument against reusing items when working with nucleic acids—can be easily removed) but lighter, less breakable and less hazardous options may be available. One candidate is 3D-printable plastic: printing laboratory supplies could offer both a reduction of launch volume by packing material as a compact batch, and a much higher flexibility for a given mass than ordinary labware that has to be packed in advance. Besides, different pieces of labware can be printed from the same batch of raw material if printed material is returned to the printing feedstock, reducing the launch mass even further. The search for easy-to-print materials with chemical stability, biocompatibility, and/or the ability to withstand sterilisation conditions and/or extreme pH, has been giving encouraging results (e.g., Capel et al. 2018).

Radiation may significantly reduce the shelf life of some reagents such as, for instance, antibodies, fluorescent dyes and qPCR reagents (Carr et al. 2013, Baqué et al. 2017, Coussot et al. 2019). Future work could quantify this effect on critical reagents, so as to adequately determine the amounts to be brought.

	Instrument	Purpose	Special requirements	Readiness Level	Comments
Field equipment	Sampling equipment (e.g., hammers, core drill, scoops)	Sampling of regolith (3.1.1-3.1.7, planetary protection, ISRU for BLSS)	See section 2.3.		
	Portable spectrometers (UV-Vis-IR, Raman, LIBS)	Sample characterization and selection, in situ monitoring of exposed samples (3.1.1-3.1.7)	See section 2.3		
	Exposure platform	Exposure of biomolecules and organisms to lunar environment, and to simulations of other environments (3.1.1-3.1.7)	Exposure to lunar environment, and to simulated radiation & atmosphere of e.g., Mars. Real-time characterization of biological samples and environment.	Already in space (e.g., Expose)	Could be developed to take advantage of less stringent constraints on the Moon.
Laboratory equipment	Contained workstation (e.g., glovebox)	Handling hazardous and contamination-sensitive samples (3.1.1-3.1.7, 4.1.1-4.1.5)	Sterilizable. Protection of both sample and user.	Used in space (e.g., BGB, CB, MSG)	Other types of workstations used on Earth (e.g., flow cabinets) could be considered for comfort and dexterity, although with higher power consumption. Highly versatile (could be used for all fields).
	Microscopes	(3.1.1-3.1.7, 4.1.1-4.1.5)	Various functions (e.g., light, fluorescence, confocal and electron microscopy)	Already in space (e.g., CSM, Nanoracks Microscope, Mochii, LMM, light microscope in the CB)	Highly versatile; would benefit other investigations, such as biomedical and geological research.
	Spectrometers (UV-Vis-IR, Raman, LIBS)	Non-destructive sample screening and analysis (3.1.1-3.1.7, ISRU for BLSS)	See section 2.3.		
	High-speed centrifuge	Use in various microbiology and molecular biology protocols (3.1.4-3.1.7, 4.1.1-4.1.5)	Sample volume: 0.2-50 ml. Acceleration: 500-15 kG. Cooling: down to 4°C	Already in space (e.g., Refrigerated Centrifuge of HRF-2)	For the least demanding operations, can be substituted with palm-sized devices (e.g., a 3D printed rotor that can be mounted on a drill)
	Freezers	Storage of biological samples (3.1.4-3.1.7, 4.1.1-4.1.5)	Down to -80°C required; cryogenic desirable.	Already in space (e.g., GLACIER, MERLIN, MELFI).	Would benefit other investigations such as biomedical research.
	Plant growth units	All plant growth experiments, e.g., germination, seed to seed, gas exchange analysis, gravitropism (4.1.1-4.1.3)	Power needed for lighting, cooling, ventilation, environmental control.	Already in space (e.g., Lada, Veggie, APH), biggest growth area 0.19 m^2.	Scale-up development likely needed for long-duration studies, larger walk-in growth units available in laboratories on Earth.
	Environmental monitoring sensors for aerial and root zones	Environmental monitoring and control (4.1.2)	Should enable monitoring of air and water temperature, relative humidity, airflow, dissolved O_2, pH, EC.	Integrated in current plant growth units on ISS	

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	Instrument	Purpose	Special requirements	Readiness Level	Comments
	Low-speed centrifuges	Simulating higher gravity (3.1.4-3.1.7, 4.1.1-4.1.3)	Various sizes (from seeds and microbes to grown plants). Acceleration up to 2 G.	Small centrifuges on ISS (e.g., MVP, and rotors in EMCS and BioLab)	Larger centrifuges used on Earth, which could be adapted to the Moon.
	Incubators	Microbial growth and incubation of various other samples (3.1.4-3.1.7, 4.1.1-4.1.5)	Control of temperature and, based on applications, other parameters (e.g., atmospheric conditions, lighting).	Already in space (e.g., Kubik, Merlin, CBEF).	Highly versatile; would benefit other investigations such as biomedical research
	Bioreactors	Vigorous microbial growth (3.1.4-3.1.7, 4.1.1-4.1.4)	Accurate control of growth-relevant parameters (e.g., temperature, aeration, stirring, pH, lighting). Long-term cultivation with minimum intervention. Capacity from sub-ml to tens of liters.	Already in space (e.g., MOBIAS, Bioculture System, Arthrospira-B photobioreator)	Could also benefit biomedical research (e.g., for cell culture).
	Flow cytometer	Characterization of microbial populations (4.1.1-4.1.4)	Should be highly versatile.	Already in space (Guava, Microflow1) but for highly limited range of applications.	Development expected to be easier for lunar gravity. More versatile instruments deployed in remote stations (e.g., Antarctica). Could also benefit biomedical research (e.g., within immunological studies).
	Nucleic acid sequencer (likely nanopore-based)	Genomics and transcriptomics (3.1.4-3.1.7, 4.1.1-4.1.5)	Should enable both DNA and RNA sequencing.	Already in space (MinION).	Accuracy relatively low for space-proven devices, but rapidly increasing.
	Thermocyler	DNA detection and amplification, transcriptomics (3.1.4-3.1.7, 4.1.1-4.1.5)	Should enable both basic PCR and RT-PCR.	Already in space (miniPCR, Cepheid SmartCycler, RAZOR EX).	
	Mass spectrometry platform	Characterization of a wide variety of samples (3.1.1-3.1.7, 4.1.1-4.1.5).	Should be highly versatile (from gas analyses to omics).	Already in space, but with low performances. No miniaturized, ruggedized system with suitable performances available today.	Could be substituted with other, easier-to-deploy platforms, but not to full capabilities. Highly versatile; could benefit other research fields (e.g., laser-based mass spectrometer in development (CRATER) for study of regolith.
	Basic microbiology/ molecular biology hardware.	Various microbiology and molecular biology operations (3.1.4-3.1.7, 4.1.1-4.1.5)	Should enable routine microbiology/molecular biology operations.	Some has flown; more could be transferred from Earth with little to no modifications.	Part of it may be made redundant by automation and microfluidics as technology progresses.

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	Instrument	Purpose	Special requirements	Readiness Level	Comments
	Sample preparation platforms	Sample preparation for analysis (3.1.4-3.1.7, 4.1.1-4.1.5).	Should be compatible with various assays, notably for omics.	Processes like RNA extraction already performed in space. Kits used on Earth expected to work in lunar gravity, but need more automation and less waste. Some being developed for space (e.g., for small satellites) or could be adapted from emerging tools (e.g., Voltrax, microfluidic platforms).	Largely overlap with other entries (e.g., basic microbiology/molecular biology hardware). Could also benefit biomedical research.
	IR, multi, hyper spectral cameras	Plant health monitoring (4.1.1-4.1.3).		IR sensor currently in plant growth unit on ISS (APH)	Need to be miniaturized compared to the ones used in Earth laboratories
	Accelerated solvent extraction system	Extraction of organic compounds from a mineral matrix (3.1.1-3.1.3).	Microwave system for high throughput.		Development needed to ruggedize Earth-based systems.
	Biosensor arrays (e.g., immunoassays)	Biomarker analysis (3.1.4-3.1.7, planetary protection).	Can be palm-sized or smaller.		Earth-based systems could likely be used, and related systems have been flown (e.g., BioChip SpaceLab), but studies on long-term stability under lunar radiation are desirable.
	DNA microarrays	Genomics and transcriptomics (3.1.4-3.1.7, 4.1.1-4.1.5).	Probes depend on application.	Direct transfer from Earth technologies expected to be possible. Reader should be miniaturized and ruggedized.	May be redundant with RT-PCR (can monitor more genes, but less reliable) and sequencing (may be more convenient to use, but requires prior knowledge of target sequences).
	Automated biology platforms	Implementation of routine microbiology and molecular biology protocols (3.1.4-3.1.7, 4.1.1-4.1.5).	Ideally modular (e.g., instruments could be mixed and matched for complex protocols), and allowing for high protocol flexibility. Should generate little waste.	Some processes have been automated in space, but far from the capacities of biology robots on Earth. Extensive work needed to have flight-ready, highly autonomous and flexible platforms.	Could make some of the other entries redundant. Rapidly evolving technologies (e.g., as acoustic liquid handling, microfluidics) could greatly reduce waste generation and lead to highly miniaturized platforms. Could also benefit biomedical research.

	Instrument	Purpose	Special requirements	Readiness Level	Comments
	Random positioning machines, rotating wall vessels, clinostats, and/or magnetic levitation devices	Simulating microgravity (3.1.4-3.1.7, 4.1.1-4.1.3).		Could be adapted from Earth-based systems with little to no modifications.	
	Plant composition sensors: chlorophyll, anthocyanin meters, electronic tongues	Food quality monitoring, plant health assessment (4.1.1-4.1.3).		Could be adapted from Earth-based systems with little to no modifications	
	Geology equipment (e.g., particle sorter, crusher, XRD).	Regolith preprocessing and characterization, esp. organism-mineral interactions (ISRU for BLSS).	See section 2.3.		
	DNA synthesizer	Generation of DNA units designed on Earth during the mission (4.1.5)	Capacity to synthesize long fragments	Quickly improving on Earth; no fundamental obstacle to use in Moon base but development needed for Moon-readiness (e.g., ruggedization and miniaturization).	
	Leaf area meters	Assessments of plant biomass production (4.1.1-4.1.3).		Could be adapted from Earth-based systems little to no modifications.	Portable and hand-held device available
Consumables	Reagents associated with aforementioned instrumentation	Preparing and storing samples for later analysis (3.1.4-3.1.7, 4.1.1-4.1.5).			Highly dependent on technologies. Consumption and hazard should be minimized.
	Microbial stocks, seeds, etc.	(Re-)starting cultures (3.1.4-3.1.7, 4.1.1-4.1.4).			
	Nutrients and fertilizer, plant growth substrate	Plant nutrition, microbial media (4.1.1-4.1.3).			Growth technique dependent

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	Instrument	Purpose	Special requirements	Readiness Level	Comments
	Routine microbiology / molecular biology / chemistry laboratory consumables (e.g., distilled water, pipettes, filters, gloves, containers, salts, enzymes, gases, organic solvents and other chemicals, ...).	Miscellaneous laboratory work (3.1.1-3.1.7, 4.1.1-4.1.5)			Reusable, recyclable, and/or 3D-printable preferred. Quantity and nature largely depend on specific protocols, and levels of automation and miniaturization. The stability of some reagents may be affected by radiation.
	Fixation / stabilization solutions, filter paper and paper bags.	Preparing and storing samples for later analysis (3.1.4-3.1.7, 4.1.1-4.1.5).			
	DNA units	Assembly and use of artificial genetic constructs (4.1.4).			A wide range could be stored in palm-sized (or smaller) repositories.
	Microbiome sampling kits	Sampling microorganisms on surfaces, in air and in water (4.1.5).			

Table 2: Summary of the equipment suggested for biological investigations (biomedical studies excluded) on the Moon. The open questions relate to carbon chemistry (sections 3.1.1-3.1.3) and astrobiology (3.1.4-3.1.7), BLSS (4.1.1-4.1.3), bio-engineering (4.1.4) and microbiomes (4.1.5).

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4. Investigations of in-habitat biology

Although the first crewed missions to the Moon of this century (expected to start with NASA's Artemis 3 landing in 2024) will likely be of short duration and draw heavily from ISS systems, longer missions will call for the development of life-support systems (LSS) which are less dependent on resupplies from Earth, for a careful management of microbiomes, and for a deep understanding of (as well as countermeasures against) the impacts on health of the lunar environment. Biological investigations must be performed on site as some factors there (e.g., gravity, radiation, and regolith) cannot be simulated accurately on Earth, let alone their combinations over the long term.

This section, which focuses on open questions in the fields of bioregenerative life support, habitat microbiomes, and health, does not aim at presenting bioregenerative LSS (BLSS) as will be used on the Moon; neither does it suggest microbiome management strategies or describe medical treatments and countermeasures. It rather outlines research that could be performed on site to develop and characterize such systems (4.1). As in previous sections, we also provide a brief outlook to research into these topics on Mars (4.2) and discuss equipment categories (4.3) that would help address our selected research questions. A summary of our recommended equipment is given in tables 2 (non-human research) and 3 (human research).

4.1. Open research questions

BLSS components and processes should be characterized on the Moon, with particular focus on loop closure, recycling efficiencies, yields (notably of direct metabolic products), plant and microbial responses to the lunar environments, use of in-situ resources, bio-engineering, cultivation hardware, and operational and logistical aspects.

Microbiome research should help determine the long-term evolution of the habitat microbial flora, accounting for changes in microbial loads, population dynamics, and microbial physiology (e.g., emergence of drug resistance or heightened virulence). This information should help determine risks to crew health and equipment, and inform countermeasures.

Finally, the long-term psychological and physiological effects of the lunar environment should be assessed. Of particular concern are the reduced gravity, ionizing radiation, disruption of circadian rhythms, isolation, confinement, and possibly hypoxia (Dietlein 1977, Buckey 2006, Demontis et al. 2017). Countermeasures should be developed and tested on site.

4.1.1. Overall considerations for bioregenerative life support systems (BLSS)

BLSS subsystems to be tested on the Moon include (but are not limited to) those involved in food production—which can be coupled to other functions, such as water and air recycling (Gros et al. 2003, Wheeler 2003)—; waste recovery and recycling in waste processing reactors (Meier et al. 2019); water recovery and recycling using bio-physicochemical urine treatment (Lindeboom et al. 2016); atmosphere revitalization, based for instance on ESA's Advanced Closed Loop Systems (ACLS), cyanobacteria, eukaryotic microalgae, and/or plants; automation (greenhouse operations, for instance, can be extremely time-consuming; see Zeidler et al. 2017, Zabel et al. 2019); and ISRU technologies relying on local regolith. Efforts in biological engineering aimed at adding or improving functions performed by biological systems (e.g., Langhoff et al. 2011, Menezes et al. 2014, Verseux et al. 2016) could also be considered on site, both to obtain rapid feedback and to take advantage of local conditions for directed evolution. Beyond its subsystems, the entire BLSS loop will require extensive characterization and fine-tuning on site. In the following paragraphs, we focus on the cultivation of plants and microorganisms as they are likely

to be the most represented; we do acknowledge, however, that other organisms may be included.

4.1.2. Investigating plants within a bioregenerative LSS

Plants grown on the Moon will be subject to constant stress due to reduced gravity and high radiation levels, as well as a possibly hypobaric environment (Rygalov et al. 2002, Rajapakse et al. 2009). They may also grow in modules where environmental conditions — temperature, relative humidity, ventilation, and light quality, intensity and photoperiod — might not be tailored to each species (Anderson et al. 2017) and where ventilation might not be homogeneous, which, combined to lower buoyancy-driven convection on the Moon, may lead to suboptimal plant growth (Kitaya et al. 2001, 2003). Besides, insufficient ventilation in space associated with high humidity leads to the development of micro-organisms which can be detrimental to plant development (Khodadad et al. 2020; see also 4.1.5). Basic research on plant growth and development in these non-standard conditions for a wide range of species will bring a better understanding of their behaviour for future long-duration lunar, and more remote, exploration missions (Poulet et al. 2016). Combined to plant growth mechanistic and knowledge models, this will enable finer assessments of the intricate and combined physical, biochemical, and morphological phenomena involved, which is necessary to accurately control and predict plant growth in BLSS (Poulet et al. 2020).

Finally, technological demonstration for nutrient delivery (less challenging in lunar gravity than in weightlessness; Zeidler et al. 2017), lighting (using sunlight could spare mass and energy; Zeidler et al. 2017, Bugbee et al. 2020), autonomous sowing and harvesting, plant health monitoring, and the autonomous deployment of greenhouse modules and their subsystems could be tested on the Moon.

4.1.3. Investigating micro-organisms within a bioregenerative LSS

Next to plants, microorganisms are expected to be central components of BLSS. Direct applications range from the production and processing of food to the purification of water, the revitalization of air and the processing of waste (e.g., Godia et al. 2002, Hendrickx and Mergeay 2007). Microorganisms could also enhance the sustainability of BLSS by facilitating the use of lunar regolith as a nutrient source (e.g., Cockell 2010, Zaets et al. 2011).

Extensive characterization is necessary on site for some factors can hardly be simulated on Earth. Microorganisms are often found to behave differently in microgravity than in unit gravity: observed effects have included altered growth dynamics, altered production rates of some metabolites, modified gene expression, increased virulence, tendency to form biofilms, and changes in differentiation (e.g., Horneck et al. 2010). Several plausible explanations have been proposed (e.g., the lack of gravity-driven convection, of sedimentation and/or of shear stress) but neither the mechanisms nor their consequences have been ascertained, leaving doubts on the effects of long-term exposure to lunar gravity and on whether simple hardware features could counteract them. Data on radiation-induced mutation in metabolically active microorganisms in space is scarce and contradictory (Harada et al. 1997, Takahashi et al. 2002, Fukuda et al. 2000, Weng et al. 1999), and the Moon's incident radiation may affect the long-term stability of microbial modules. Assays with local resources would best be performed on site given the low availability of lunar regolith (especially unweathered) on Earth and the costs of returning samples. Operational constraints, from limited crew training to a possibly hypobaric atmosphere in the habitat (Norcross et al. 2013) that may affect microorganisms (Niederwieser et al. 2018, Verseux 2020), should be accounted for.

Mechanisms of acclimation and adaptation

should be understood over the long term (in conjunction with several iterations of cultivation hardware), both for axenic populations, for more complex communities microbial communities, and for plant-interacting microorganisms.

4.1.4. Bio-engineering for BLSS and other bioprocesses

Bio-engineering could greatly improve the efficiency of BLSS on the Moon. In particular, plants and microorganisms could be engineered for higher abilities to rely on local resources (e.g., the lunar regolith) or intermediate products, to better withstand the environment they would be exposed to on the Moon, and to carry their targeted functions at higher rates (Cumbers and Rothchild 2010, Montague et al. 2012, Verseux et al. 2016, Llorente et al. 2018).

Organisms could also be conferred new functions of interest, within and beyond BLSS: suggested applications to space exploration pertain to (among others) the production or processing of food, materials, drugs, fuels and other chemicals, waste recovery, microbial support to plant growth, biomining, optimization of the astronauts' microflora, and biosensing (Cumbers and Rothchild 2010, Langhoff et al. 2011, Cockell 2011, Montague et al. 2012, Menezes et al. 2014, 2015, Verseux et al. 2016, Rothschild 2016, Llorente et al. 2018, Berliner et al. 2020, Nangle et al. 2020, McNulty et al. 2020).

While organisms could be engineered on Earth and sent to the Moon, bio-engineering is typically a trial-and error process; having the ability to iteratively test and refine genetic constructs on site would be highly valuable. Besides, tools that rely directly on the application of stress factors (chiefly, directed evolution) would best be performed in the operational environment. The implementation of such work in plants may be limited by their generation times and the space required for their cultivation, but may be extensive for microorganisms even in early bases. Finally, wherever their components are engineered, bioprocesses involving modified organisms should, even more so than those involving natural organisms only, be characterized on site over the long term.

4.1.5. Microbiome evolution and containment

Human-borne microorganisms will be unavoidable in lunar habitats. Risks ensue to crewmembers' health and to the integrity of the equipment (e.g., Mora et al. 2016).

Health risks are posed by the potential emergence of pathogens, opportunistic or not. Though no life-threatening infection has been reported so far, pathogens have caused tens of incidents in space (see Mermel 2013, Fajardo-Cavazos and Nicholson 2016). The threat will increase with mission duration and the difficulty of short-term returns. The second category of risks—to the equipment—comes, first, from technophiles: microorganisms that can colonize and degrade industrial materials (see (Gu 2007)). Some were found in both the Mir station (Alekhova et al. 2005, Novikova 2004) and the ISS (Novikova et al. 2006, Ott et al. 2014). Second, microbial contaminants could affect BLSS (Sun et al. 2016; see subsection 4.1.3).

Efforts are being made to characterize microbial populations in the ISS (e.g., Mhatre et al. 2020, Avila-Herrera et al. 2020, Sielaff et al. 2019), as well as within missions analogous to a stay on the Moon or Mars (Mayer et al. 2016, Schwendner et al. 2017, Sun et al. 2016, Van Houdt et al. 2009, Mahnert et al. 2021), but none of those settings gathers all factors of a lunar base that may significantly impact microorganisms' behavior. Long-term monitoring of microbial communities should thus be performed on site.

4.1.6. Human physiological and psychological changes on the Moon

A major obstacle to a long-term presence on the Moon and beyond lies in the physiological and psychological risks faced in habitats deployed beyond Earth. Addressing it will re-

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quire, first, a deep understanding of the involved mechanisms; and second, the development and assessment of countermeasures and mitigation strategies. However, most of the data available on a human body's response to spaceflight were collected in LEO: beyond it, data is limited to the Apollo missions (Pinsky et al. 1974, Delp et al. 2016). Some of the key challenges are summarized below.

Starting from approximately two days of exposure, fluid shifts caused by microgravity can lead to neurovestibular deconditioning (Katkov and Chestukhin 1980, Clément et al. 1992), decreases in the volume of grey matter (Van Ombergen et al. 2017), increases in intracranial pressure, and the so-called spaceflight associated neuro-ocular syndrome (Lee et al. 2020). Over the long term, microgravity induces alterations in the musculoskeletal system, most noticeably a decrease in bone density (which can cause the formation of renal stones) and in muscle mass (Rittweger et al. 2018, Vico and Hargens 2018), cardiovascular deconditioning (Fritsch-Yelle et al. 1996, Verheyden et al. 2009) and increased risks of venous thrombosis. The lunar gravity will presumably have similar, albeit attenuated, effects. Countermeasures exist—they include regular resistance exercise, and the use of antiresorptive drugs and nutrition supplements (Smith et al. 2012, Leblanc et al. 2013)—but are not fully effective (Vico and Hargens 2018).

Exposure to high doses of ionizing radiation can lead to a wide panel of deleterious effects such as cataracts, cardiovascular and central nervous system diseases, acute exposure syndromes, cancers, dysfunction in the vascular endothelial cells (Kennedy 2014, Chancellor et al. 2014, Cucinotta et al. 2013, Donnelly et al. 2010, Vico and Hargens 2018, Delp et al. 2016, Hughson et al. 2018). Other issues observed in space, affecting for instance the musculoskeletal and immune systems, may be aggravated by radiation (e.g., Crucian et al. 2016).

Experience in ICE (Isolated, Confined, Extreme) environments — which includes space stations, submarines, Antarctic stations, and space analogue missions — shows that isolation and promiscuity can pose severe psychological problems (Nelson et al. 2015, Kanas and Fedderson 1971, Palinkas 2001, Gushin et al. 2012, Anderson et al. 2016), which can be worsened by other mission-specific stresses such as changes in circadian rhythms (Monk et al. 1985, Matsangas et al. 2017).

The combined effects of reduced gravity, high radiation levels, and intense psychological stressors (and possibly of other factors, such a potentially hypoxic atmosphere in crewed quarters; see Norcross et al. 2013) will need to be investigated thoroughly and over the long term. This cannot be achieved on Earth only. Reduced gravity, for instance, cannot be simulated over the long term (though some specific effects may be, for instance with bed-rest studies), and reproducing the complex radiation flux reaching the lunar surface (see Figure 3)—let alone the secondary radiation resulting from interactions with EVA suits and the habitat—is beyond today's capabilities. Biomedical research on the Moon would consequently be highly valuable to the preparation of future crewed missions.

4.2. Outlook to Research on Mars: the Moon as a Martian analog

The Moon could serve as a testbed for Martian BLSS, in a setup from which crewmembers can be evacuated promptly and to which supplies from Earth can be delivered faster and at lower costs. BLSS will serve similar functions on the Moon and Mars, and at both locations will have to meet stringent mass, volume, operational and energy requirements, as well as provide a high degree of closure (aside from ISRU). Differences can be attenuated for higher simulation fidelity, for instance with centrifuges, solar filters, or gas-tight growth systems recreating atmospheric conditions expected for out-

door BLSS modules on Mars (see, e.g., Murukesan et al. 2016, Verseux et al. 2021).

On Mars, terrestrial microorganisms could interfere with the search for endogenous life (COSPAR 2020, Horneck 2008; see subsections 3.1.4 and 3.1.6). A lunar base would enable studies on microbiome dynamics inside a Mars base-like setup, but also outside: the load of dispersed microbial contaminants, as well as their origin (e.g., from BLSS or the crew's biota), could be determined in an environment where planetary protection constraints are mild and where contamination would be less critical than on Mars.

Health-relevant parameters of the lunar and Martian environments—e.g., reduced gravity, radiation, dust, isolation—largely overlap; biomedical studies on the Moon will help develop medical care and countermeasures for long-duration missions to Mars.

4.3. Recommended Instrumentation

A detailed list of equipment to be brought for the areas of research addressed in this section would be too tentative, as specific experiments and protocols remain to be selected. Even with specific research questions, equipment strongly depends on mission design. Besides, a lunar laboratory on the Moon may be equipped with instruments beyond today's state-of-the-art; miniaturized, automated, and/or high-throughput processes will be particularly relevant. Nevertheless, we attempt a list of desired research instrumentation (see table 2), which should not be mistaken as exhaustive or definitive.

4.3.1. Lab Equipment for non-human studies

If optimizing for mass, crew time and training needs, most analyses could be performed on Earth and on-site operations be limited to simple, predetermined actions using pre-loaded systems. This, however, would delay or prevent followup experiments, and could affect the integrity of sensitive samples. The allocation of more crew training and time, coupled with higher investments in instrumentation, would enable more ambitious programs. On-site analytical capabilities and room for improvisation would greatly accelerate the trial-and error processes which characterize innovative biology research. Below, we assume that the latter strategy is being favored when possible. In some cases, however (e.g., when results will not affect followup experiments, do not involve sensitive samples, and require heavy instrumentation), further analyses would best be performed after return. Samples could then be stored until mission completion, using chemical fixation (commonly done in space) and/or cold storage (various fridges and freezers have been flown; those on the ISS include -80°C and cryogenic freezers).

For research on food production and fundamental biology experiments with plants, environmentally controlled chambers will be needed, as they can be designed to allow monitoring and control of all environmental parameters in the shoot zone (e.g., air temperature, relative humidity, CO_2 levels, air flow) and in the root zone (e.g., pH, dissolved O_2, electrical-conductivity (EC), specific ion concentrations (Bamsey et al. 2012, Monje et al. 2020)). Because of size and volume constraints for launch, it is unlikely that the first plants on the Moon will grow in walk-in environmentally controlled chambers; rather, small, reach-in chambers, similar in size to the APH (Massa et al. 2016, Monje et al. 2020) are expected to be the first plant growth modules. In the mid- to long-term, they could become larger and be used to test autonomous deployment (Zeidler et al. 2017). If sealed enough they could allow photosynthetic, transpiration and respiratory rates measurements (Corey and Wheeler, 1992; Bugbee and Monje 1992), which are useful for performance and stress assessment in plants. This technique has been used in the past in the Biomass Production system on the ISS (Stutte et al. 2005) and is currently used in the Advanced Plant Habitat (APH)

on the ISS to measure gas exchange (Monje et al. 2020). Instruments used on Earth for gas exchange measurements include infra-red gas analyzers (IRGA) (Douthe et al. 2018), often coupled to fluorescence measurements, and they could be down-scaled and adapted for a lunar utilization. Alternatively, porometers could be used to measure the boundary layer above the leaves and compute gas exchange from this measurement, however that would be much more time intensive. To monitor plant health and development, imaging techniques could be used (Li et al. 2014, Tucker et al. 2020, Monje et al. 2020) and would allow for more automation on the experiments and thus free some crew time. Optical cameras and infra-red (IR) sensors are currently used within the APH on the ISS (Monje et al. 2020); dual wavelength spectral imagers are currently being used and demonstrated in relevant operation environment at the German Neumayer Station within the EDEN-ISS facility (Zeidler et al. 2019, Tucker et al. 2020). These cameras and sensors would require some miniaturization (roughly, from tens of cm to a few cm) before being implemented in a laboratory on the Moon. Plant pigment measurements, such as chlorophyll and anthocyanin, are routinely performed in laboratories on Earth, with small size instruments (typically 15 by 5 by 2 cm) and could be used on the lunar surface with no necessary modification. Element analyses of plant compounds are often performed to assess taste of plants and fruits (sugar and acid contents) and nutritional composition with methods requiring heavy sample preparation (e.g., inductively coupled plasma optical emission spectrometry (ICP-OES) (Mickens et al. 2019), high-pressure liquid chromatography (HPLC), or gas chromatography (GC)). For plants grown in space, these analyses are currently performed on Earth from samples brought from the ISS (Khodadad et al. 2020). In a lunar laboratory, electronic tongues could be used instead, for a basic in-situ analysis of taste-related compounds (Beullens et al. 2008), which may be followed by more thorough analyses on Earth if needed. Plant morphology measurements can be achieved with a ruler and a small leaf area meter or with a camera and image-analysis software. Leaf area meters are routinely used in laboratories on Earth and there are handheld versions of these instruments, which could be used as is on the Moon. However, this might be too time-consuming for a crew of astronaut and image analysis may become the preferred method. Biomass measurements (for plants but also microorganisms) require analytical scales (calibrated for lunar gravity) and a drying setup (e.g., desiccator or low-temperature oven), which would require little to no development from Earth or ISS-based systems.

Investigation on plant and microorganisms under a range of gravity levels (e.g., for 1-G or microgravity controls, or to simulate Martian gravity) will require additional instruments, able to accommodate samples of various sizes (from microbial cultures and germinating seeds to whole plant throughout their life cycle). Low-speed centrifuges have been used extensively in space for such purposes (Brinckmann 2012). Devices simulating a lower gravity level, such as random positioning machines, rotating wall vessels, clinostats and magnetic levitation systems (Huang et al. 2018, Kiss et al. 2019) can be directly adapted from those used on Earth.

The use of local resources would induce a need for further equipment; using regolith would for instance require the characterization of input mineral samples (composition, surface area, grain distribution, etc.) and possibly its processing (e.g., adjusting grain size with a ball mill and sieves), using geology equipment (see section 2). If an ICP-OES device is used for assessments of plant biomass composition (see above), it could find opportunistic uses here as well, for instance to determine on site the effects of microbial activity on the rates of ele-

mental release from the regolith.

Microorganisms would be grown in incubators and bioreactors providing accurate monitoring of, and control over, cultivation-relevant parameters. The experimental growth of microorganisms have been performed in microgravity since the late 1950s (Zhukov-Verezhnikov et al. 1962); since then, a wide range of cell and microbial culture systems have been flown on board satellites, shuttles and space stations. Modern hardware (e.g., Hoehn et al. 2004, Fossum et al. 2005, Levine et al. 2009, Schuber et al. 2013, Blaber et al. 2014, Detrell et al. 2019, Poughon et al. 2020) can provide accurate control of temperature, light, pH, aeration, humidity and gas phase, among others, and routine operations (e.g., sampling and liquid injection) can be automated. Microbial cultivation systems can draw directly from this extensive experience in space, though engineering challenges will be lowered by the lunar gravity.

For manual operations, a contained workstation and basic microbiology hardware will be required; they is similar to that which would used for astrobiology investigations and are described in section 3.3.2.

Automated flow cytometry devices could be run regularly for quick assessments of, for instance, contamination, population dynamics, and growth rates. Flow cytometers have been deployed in remote locations such as, for instance, a winterovering base in Antarctica (Feuerecker et al. 2019). However, regular models rely on gravity-driven fluid flows and are consequently not usable in microgravity, generate large amounts of hazardous liquid waste, and require extensive training. Efforts were made to develop spaceflight-compatible models, some of which have been used in the ISS (Dubeau-Laramée et al. 2014, Xun et al. 2018), but these remain limited in their range of applications. Further development is needed toward devices compatible with a Moon laboratory and with capabilities close to modern, Earth-based models. The lunar gravity should greatly facilitate this development.

A large part of the characterization of biological systems (be they part of BLSS, microbiomes, or biomedical studies) would best rely on "omics" technologies: high-throughput equipment to, notably, amplify and sequence DNA (genomics), and quantify specific RNA transcripts (transcriptomics), proteins (proteomics) and metabolites (metabolomics). Considerations follow; a more substantial perspective on the use of omics technologies in space can be found in work by Karouia et al. (2017).

Nucleic acid sequencing will be highly versatile: it can be a tool to detect mutations (resulting in, e.g., adaptation or undesired properties), assess contamination, and document population dynamics of non-axenic cultures in BLSS, help check the correct manufacturing and insertion of engineered genetic constructs, and be used to document the nature and dynamics of microbiomes. Recently developed sequencing instruments (see for instance Slatko et al. 2018) tend to be much more compact than their predecessors. Devices based on nanopore sequencing technologies are particularly interesting due to their simplicity of use, lack of sensitive instrumentation, low power consumption, and high miniaturization. Among the most advanced is the palm-sized MinION, which has been used extensively in remote locations on Earth (e.g., Johnson et al. 2017, Goordial et al. 2017, Pomerantz et al. 2018) and tested on the ISS to sequence DNA (Castro-Wallace et al. 2017, Burton et al. 2020, Stahl-Rommel et al. 2021). DNA microarrays could also be used for applications where prior knowledge of the sequences of interest is available, for instance to study the structure and dynamics of microbial populations (e.g., non-axenic BLSS modules or microbiomes).

Gene expression can be monitored through nucleic acid (cDNA or RNA) sequencing, and RNA has been sequenced in the ISS using the

MinION. The expression of a moderate number of genes can be documented by RT-PCR, which has also been performed in space (Parra et al. 2017, Montague et al. 2018). Another element in the transcriptomics toolbox could be DNA microarrays: those can help assess the expression levels of a large number of genes simultaneously, are amenable to miniaturization and automation, and would require little to no re-engineering for use on the Moon. However, the set of genes that can be studied in a given microarray is predetermined and, due to various other limitations (e.g., the non-linear relationship between nucleic acid abundance and signal strength), identified genes must often be confirmed using RT-PCR. Which among those three methods is most relevant depends on application and, while their capabilities overlap, access to each would be beneficial.

Transcriptomics are not enough to characterize the production of active proteins: various phenomena happen at the post-translational level that alter their structure and regulate their concentration. Further down the process, metabolomics (though less developed at the moment) may give the most accurate picture of the cell's state and activity. Mass spectrometry-based platforms (MS) are central to both proteomics and metabolomics, allowing for the identification, characterization and quantification of macromolecules over a wide range of concentrations, in complex samples and with a high throughput. One major limitation to the use of MS on the Moon is their dimensions (standard instruments typically weigh around 100–200 kgs), as well as the required level of skills. MS have been used in space for decades, serving a wide range of purposes thanks to high ruggedness and remarkably low size, weight, and power requirements (Arevalo Jr et al. 2020). Those advantages, however, were traded for analytical performances: instruments flown so far would be unsuitable for omics studies. Although progress is being made at a fast pace (Mielczarek et al. 2020), miniaturized and easy-to-use MS with suitable performances are not available today. Alternatives (or complements) exist for proteomics (e.g., protein microarrays) and metabolomics (e.g., nuclear magnetic resonance), which could likely be made suitable for a Moon base faster than MS, but the latter remain highly desirable.

Preparing samples for omics assays is a difficult task in microgravity; it would be easier under lunar gravity. Commercial kits used on Earth (e.g., for solid-phase nucleic acid extraction) could be considered, in spite of possibly unsuitable waste production, time consumption and error risks. Besides, technologies are emerging which are expected to simplify sample preparation in space and on the Moon. For example, the MinION's manufacturer, Oxford Nanopore Technologies, recently released an automated sample preparation module called VolTRAX. NASA developed a suite of molecular biology laboratory tools, reagents, and methods, which was used in space for RNA extraction; RNA could then be used as a template for RT-qPCR or sequencing (Parra et al. 2017, Stahl-Rommel et al. 2021). Spaceflight-compatible automated platform for DNA extraction (Urbaniak et al. 2020), or even for entire microarray-based gene expression protocols, from cell lysis to data analysis (Peyvan et al. 2019), have shown promising results on the ground. Various advances aimed at facilitating sample preparation on Earth could benefit Moon operations much more directly than they would operations in microgravity.

Bio-engineering operations are highly varied and rapidly evolving; we focus in the next paragraphs on common operations relying on versatile equipment. Strategies can be grouped into rational design and directed evolution. The former typically relies on iterations of a design, build, test sequence (design can be performed remotely, on Earth), the latter on iterative rounds of genetic diversification and either screening or selection.

The testing of rationally designed constructs, and the selection or screening within directed evolution, could rely for the most part on material already described: a workstation preventing contamination, routine microbiology hardware, and omics platforms.

The building blocks of rationally designed gene constructs, as well as the starting materials for sequence-specific (as opposed to whole-organism) directed evolution, are DNA units (plasmids, coding sequences, regulatory elements, etc.). A large variety could be sent from Earth in palm-sized (or smaller) repositories and amplified as needed by the crew. Amplification can rely on a thermocycler, some versions of which have been used in space (Boguraev et al. 2017, Khodadad et al. 2017, Montague et al. 2018). Genetic parts which could not be designed pre-flight (e.g., accounting for results from previous design-build-test iterations) could be synthesized on site. No DNA synthesizer has been used in space, however, and efforts are needed to develop lightweight, easy-to-use, sturdy systems, possibly based on microfluidics and acoustic liquid handling (see below).

Steps following DNA synthesis or amplification usually require various chemical (mainly, enzymatic) reactions, purification steps, and transformation into a host organism. All can be performed using reagent kits and benchtop molecular biology hardware (e.g., pipettes, thermocycler, electroporator, tabletop centrifuges) which largely overlap with microbiology hardware and can be adapted easily from Earth- or ISS-based devices. However, processes could be miniaturized and automatized to reduce the payload's weight and volume, resource consumption, and waste production. Automation could be based on sample-handling robots: some on Earth are optimized for directed evolution (e.g., Zhong et al. 2020, Marlière et al. 2011), others can perform a wide range of tasks traditionally performed by hand such as liquid and plate handling, colony picking, and screening. Contactless, gravity-independent systems (based, for instance, on acoustic liquid handling; see Olechno et al. 2016) could greatly reduce the generation of waste associated with pipette tip-based robots, and help miniaturize processes (reaction volumes could be brought down to micro- or nanoliters). An alternative (or complementary) strategy for both miniaturization and automation lies in microfluidics. Proofs-of-concept have been shown for the most common synthetic biology operations, from DNA synthesis to directed evolution, and more complex and automated workflows are emerging (Linshiz et al. 2016, Shih et al. 2015, Gach et al. 2017, Zhang et al. 2020). Although microgravity can introduce some challenges, such as bubble management in the absence of buoyancy (see Nelson 2011), automated microfluidic systems have been used in the ISS and small satellites (e.g., Padgen et al. 2020, Hawkins et al. 2020). The Moon's reduced gravity should not oppose the use of Earth-proven microfluidics: at this scale, fluid transport is dominated by gravity-independent forces such as friction and surface tension. Microfluidic devices and part of the supporting hardware could be 3D-printed (e.g., Patrick et al. 2015, Nielsen et al. 2020) for higher flexibility.

Sampling equipment for microbiome studies would best be provided as kits (see subsection on consumables below). On-site microbial monitoring facilities are desirable, not only for research but also for health and safety (Yamaguchi et al. 2014), which could rely on equipment described above (e.g., based on microbial cultivation, PCR, microarrays, and/or sequencing).

4.3.2. Lab Equipment for studies on human physiology

Studying the effects of the lunar environment on human physiology requires relatively specific equipment. We would like to stress here that we restrict ourselves to specific research questions; a more complete overview of neces-

sary medical capabilities, albeit at much less detail, can be found for example in a position paper by space medics and NASA flight surgeons (of Members of the Space Medicine Association and the Society of NASA Flight Surgeons 2008).

To investigate the effects of fluid shifts in lunar gravity, core body temperature profiles, blood and urine sample analyses, long-term measurements of head and trunk acceleration, vestibule-ocular tests for measuring eyes displacement and body alignment with the gravity vector, as well as questionnaires will be needed. Blood and urine sample kits, thermometers, accelerometers, and cameras are equipment already routinely used on ISS (Buckley et al. 2017). The CSA Bio-Analyzer now allows for real-time sample analysis on the ISS (Cohen 2017) and could be used on the Moon. Advanced magnetic resonance imaging (MRI) techniques would need to be employed to investigate lunar gravity effects on the brain and cardiovascular activity — blood flow, anatomical and morphological characterization of the heart and its relative geometry while operating, cardiac strain and contractility. Miniaturised space-adapted Magnetic Resonance Imaging (MRI) using a technique called Transmit Array Spatial Encoding (TRASE), which uses a novel radio wave timing technique that requires much smaller magnets, is currently under development and soon to be tested on the ISS (Sarty et al. 2012, Sarty and Obenaus 2012, Sarty et al. 2014). Electroencephalogram (EEG) studies, which have been performed on the ISS for years (Van Ombergen et al. 2017), could be performed on the Moon with similar devices to investigate brain activity in lunar gravity.

Heart dynamics are routinely studied on ISS and several techniques, which have been or are currently being investigated could be used on the Moon such as ballistocardiography (Migeotte et al. 2011), seismocardiography (Di Rienzo et al. 2017), ultrasound imaging (Sargsyan et al. 2005), pneumography, as well as impedance and electro cardiography (Baevsky et al. 2007, BAE 2009). The measurement of exhaled nitric oxide (NO) has been tested in microgravity (Karlsson et al. 2009) and low gas density (Linnarsson et al. 2013) to assess lung function and particularly airway inflammation. Spirometry could also be used to diagnose airway inflammations (Miller et al. 2005) in a lunar environment.

Bone and muscle mass are typically monitored through specifically designed exercise machines, used in combination with electromyography and electrical stimulation both at rest and under stress (Buckley et al. 2017). Additional tests could be, among others, MRI, blood samples, muscle biopsy and measurements with ultrasound, X-Ray techniques such as peripheral quantitative computed tomography (pQCT) — routinely used post-flight (Vico et al. 2017) but such device has never been flown to date — or dual-energy X-ray absorptiometry (DEXA) — also used post-flight (JD et al. 2015) and flown to the ISS for mice (Laboratory 2017) —, or positron emission tomography (PET).

Studying the effects of space stressors on the immune system might include blood, hair, saliva, breath, urine, and stool sampling, electrocardiograms, MRI to monitor (patho-) physiological stress-responses and stress-dependent immune changes, as well as actigraphy and pulse oximetry, which are already available on ISS (Buckley et al. 2017).

Radiation monitoring within the ISS and on single crewmembers is currently achieved by passive dosimeter payloads Matryoshka, PADLES, and DOSIS 3D (Buckley et al. 2017, Sihver and Berger 2017); similar instruments could be used on the Moon.

Finally, biomedical studies beyond Earth often rely on biological models such as eukaryotic cell cultures (e.g., Lu et al. 2017, An et al. 2019) and animals. While the largest among animals flown so far (see Hariom et al. 2020)

are unlikely to be brought to an early Moon base, others can be considered: examples include rodents (e.g, Roberts 2014, Horie et al. 2019), fruit flies (e.g., Marcu et al. 2011, Ma et al. 2015, Kamyshev et al. 2020), fish (e.g., Anken et al. 2016), amphibians (e.g., Horn and Gabriel 2011) and meiofauna (e.g., Ishioka and Higashibata 2019). Culture systems for those different models have been flown (e.g., Ishioka et al. 2004, Huin-Schohn et al. 2013, Moyer et al. 2016, Walls et al. 2020). Data collection at the molecular level would largely rely on instruments described above for "omics" studies.

Regarding psychological studies, these are mostly conducted via crew questionnaires and surveys, which require crew members to have personal electronic devices such as tablets or laptops.

4.3.3. Consumables

Nutrients and fertilizer to grow plants will be necessary consumables. Growth substrate and media will depend on the growth technique — e.g., hydroponics, aeroponics, soil. Currently on ISS, plants grow on arcelite with fertilizer pellets to which water in added via porous tubes (APH) or manually using syringes (Veggie) (Massa et al. 2016, Monje et al. 2020). Seeds for starting new crop cultivation cycles also constitute consumables for plant growth experiments; seed quantity needed from Earth may decrease in the future, when in situ seed production becomes feasible. Dry weight analyses may require drying bags and filter paper. All containers used to store samples would need to be washable and reusable. Instruments listed in section 4.3.1 have dedicated consumables (e.g., desiccant and CO_2 scrubber for the infra-red gas analyzer (IRGA); calibration solutions for pH and EC meters). Finally, spare parts for lighting and watering systems can be considered as consumables as well.

Consumables for research related to BLSS microbial modules and bio-engineering include those associated with the equipment mentioned above and, depending on the level of automation, consumables routinely used for microbiology and molecular biology (see subsection 3.3.3). Microbial stocks (e.g., cryostocks and/or lyophilized samples) are likely to be brought, if only for initiating, and possibly resetting (e.g., after contamination or widespread mutations), cultures.

Molecular biology reagents used for BLSS characterization and bio-engineering (enzymes, DNA repositories, etc.) may, as those used for astrobiology research, be affected by radiation (see subsection 3.3.3). Their shelf life on site should be determined. Lyophilized reagents could be considered for facilitating storage (Parra et al. 2017).

Reagents specific to microbiome studies may be best organized as kits: surface sampling kits (e.g., swabs, wipes and/or contact slides, with wetting agents and storage solutions included), air sampling kits (the air sampler itself is not a consumable, but the associated filters, storage solution and tubes), and water sampling kits (e.g., based on sterile syringes and Teflon bags). Microbiome studies pertaining to planetary protection could rely on additional regolith sampling kits (based, e.g., on sterile scoops, tubes and bags).

Consumables for human and animal research include sampling kits for biological samples collection (e.g., blood, urine, hair), as well as the necessary protective gear to collect them (e.g., gloves, coats, goggles). Rapid analysis devices such as dipsticks would also be in the realm of consumables for human physiological research.

	Instrument	Purpose	Readiness Level	Size	Comments
Field equipment	Passive dosimeters	Radiation monitoring during EVAs	Flown to ISS	Wearable devices	
Laboratory equipment	Basic physiological monitoring devices (thermometers, accelerometers, actigraphy, pulse oximetry)	Monitoring of basic physiological function, especially for the study of fluids shift and the effects of space stressors	Currently on ISS	Very small and light.	Can be used both as laboratory equipment or field equipment during EVAs.
	ECG, ICG, seismocardiography	Heart dynamics monitoring	Currently on ISS	Wearable devices.	Could be used as is on the Moon
	Electroencephalography (EEG)	Electrical brain activity monitoring	Currently on ISS	Wearable device (bulky helmet-like)	Could be used as is on the Moon.
	Electromyography and electrical stimulation	Assessment of bone and muscle mass	Currently on ISS	Similar to ESA Percutaneous Electrical Muscle Stimulator (PEMS)	
	Physical exercise equipment (e.g. treadmill, stationary bike, leg press)	Assessment of human physiology to lunar gravity, development of physiological countermeasures.	Currently on ISS	Similar to current ISS equipment	Design may vary to transition from microgravity to lunar gravity
	Ultrasound	Assessment of bone and muscle mass	Currently on ISS	Similar to NASA Ultrasound 2	
	Breath analyzer systems (exhaled NO)	Lung function and airway inflammation assessment	Flown to ISS		
	Active/passive dosimeters	Radiation exposure monitoring	Currently on ISS	Small size, can be placed on a wall	
	Incubators and bioreactors for cells and tissues	Experiments relying on cell and tissue models.	Currently on ISS (e.g., MOBIAS, Bioculture System, CBEF).		Could be combined with bacterial cultivation systems (see Table 2)
	Culture systems for animal models (e.g., rodents, fruit flies, fish, amphibians, mesofauna).	Experiments relying on animal models.	Used in space (e.g., MHU, Fruit Fly Lab, AQH, ABS).	Dependent on species; most can fit in racks.	Could be used in non-biomedical studies as well (e.g., investigations on animal BLSS modules).
	Fridges, freezers, incubation chambers	Human sample storage	see Table 2		
	Personal electronic devices	Psychology studies - questionnaires	Currently on ISS	Tablet or laptop size	
	X-ray techniques (e.g., pQCT, DEXA)	Assessment of bone and muscle mass	Routinely used post-flight. A DEXA device for mice flown to ISS.	Lunar version will need to be miniaturized	
	Magnetic resonance imaging (MRI)	Morphological data on cardiovascular system, brain, bone and muscle mass	Wrist-sized MRI currently designed for ISS	As little as 50kg if superconductor replaced with permanent magnets	No issues on MRI contrast in LEO, may not be the case in Lunar Environment
	Positron emission tomography (PET)	Functional mapping of cardiovascular system, brain, bone and muscle mass.	Never flown before, available in Earth hospitals	Needs to be miniaturized	Use of radioactive tracer to find tumor cells. Major re-design needed to be flown to space.

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	Instrument	Purpose	Readiness Level	Size	Comments
Consumables	Sampling kits for blood, hair, saliva, breath, urine, stool	General health monitoring, stress research, immune system	Currently on ISS	Palm-size or smaller	
	Protective gear (e.g., gloves, coats, sanitizer, goggles)	Basic hygiene measures	Currently on ISS	Size dependent on equipment, can be compactly stored / packed	
	Rapid analysis devices (e.g., dipsticks)	Measure of different compounds in blood and urine (e.g., pH, protein, glucose, bilirubin content in urine, white blood cells in blood)	Some already on ISS	Small	

Table 3: Summary of the equipment suggested for investigating human physiological and psychological changes on the Moon (4.1.6).

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5. Summary and Outlook

The Moon is a stepping stone for ventures deeper into our Solar System and possibly beyond. This is true logistically, as the Moon provides various resources that could facilitate the journey to Mars (see section 2.1.5). It is also true scientifically, since the Moon allows us to broaden our Earth-centric view to understand the history and evolution of our home, the Earth-Moon system, and its broader context, the Solar System. Returning to the Moon for longer periods will help us understand how living organisms—including humans—respond to different environmental conditions, and help us prepare for the more perilous journey to Mars.

It is true that some of the questions we outlined above may eventually be carried out in-situ directly by rovers. However, for some tasks (such as deep core-drilling, recognition of meteoritic samples), it seems illusory to hope for sufficient technological advancement in the next few years to conduct these robotically. Besides, the vast majority of research questions would benefit from a human-operated laboratory on the Moon, where more delicate experiments can be undertaken that require the experimenter to respond to unforeseen issues and results.

The task for astronauts to work on the Moon is not an easy one. The only experience humankind has with exploration of extraterrestrial surfaces is more than five decades old. The Apollo astronauts encountered various dangerous situations that were caused by their cumbersome pressurized suits and the unfamiliar low gravity environment. Harrison Schmitt, the Apollo geologist astronaut, pointed out that astronauts should have been trained specifically to avoid hand and forearm fatigue Schmitt et al. (2011). One would think that fifty years of development could have vastly improved pressurized suits, but in reality suit development was not only directed towards orbit, where requirements are vastly different from a surface suit, but also no substantial changes have been made in the past 30 years (Jordan et al. 2006). Only relatively recently have new suit concepts emerged that promise to facilitate the astronauts' mobility on the lunar surface (Kothakonda et al. 2019, Ross et al. 2014, Lee 2016).

More conservative designs are developed in parallel, which are perhaps more likely to feed into the first generation of surface exploration suits. Some suits and suit analogs are tested in operational and field environments (e.g., (Abercromby et al. 2012, Akin 2018, Weiss et al. 2014, Groemer et al. 2016)), albeit often with the focus on studying and improving the interaction between astronauts and ground support, rather than the suit itself.

Much work is left to be done before the first take-off to a long mission on the Moon, in order to understand which tasks are better performed by rovers and where humans even in their unwieldy suits offer an advantage over rovers. The general consensus seems to be that reconnaissance and repetitive precision tasks are easier to conduct by rovers, whereas humans excel at mobility, improvisation and reacting to unforeseen tasks and events (Fong et al. 2010, Spudis 1999, Crawford et al. 2012, Leidner et al. 2015). Yet, it remains to be explored where the dividing line should be drawn in the broad range between these two extremes.

If samples were to be sent to Earth, they need to be curated, packaged, and transported to Earth, for which tools and protocols need to be developed (Lunar Exploration Analysis Group (LEAG) 2016). Some researchers doubt that we have appropriate facilities on Earth to deal with environmentally sensitive samples (like ice from the south pole craters) (Lunar Exploration Analysis Group (LEAG) 2016).

Finally, even though there is an ever-increasing number of analog habitats around the world which are often dedicated to science (first) and (then) outreach, relatively little attention is paid to the outfitting according to

scientific needs, or the laboratory and scientific instruments are limited to one specific research area (see e.g., (Thiel et al. 2011, HI-SEAS 2017, IBMP, C. Heinicke 2020)). A notable exception is the Habitat Demonstration Unit (Howe et al. 09102013) that was equipped with a workstation for geological and medical operations and used during field campaigns (Howard 2018). However, the equipment was rather rudimentary and the laboratory is re-purposed today as the HERA isolation facility (NASA 2019).

A more recent proposal for a habitat laboratory was devised as part of the MaMBA project (Heinicke et al. 2020) that made an attempt to incorporate scientific recommendations, engineering constraints, and architectural suggestions into a holistic laboratory design. A mock-up of the laboratory was successfully tested in 2019 (Heinicke 2019). However, the duration of the test runs was much shorter than a mission to the Moon is expected to last, and the number of experiments that were conducted was somewhat limited.

Consequently, one major gap that remains open is the entire process chain from sampling to laboratory analysis, including sample storage, transfer into the habitat laboratory, and concrete safety measures that would ensure planetary protection.

All these gaps and issues need to be addressed in the coming years. With this paper, we hope to provide useful input for habitat designers and mission planners that facilitates the incorporation of scientific requirements and desires into a lunar habitat laboratory. This laboratory would open up pathways way beyond the Moon, and humankind would be ideally equipped to draw a wealth of scientific results from a mission to Mars.

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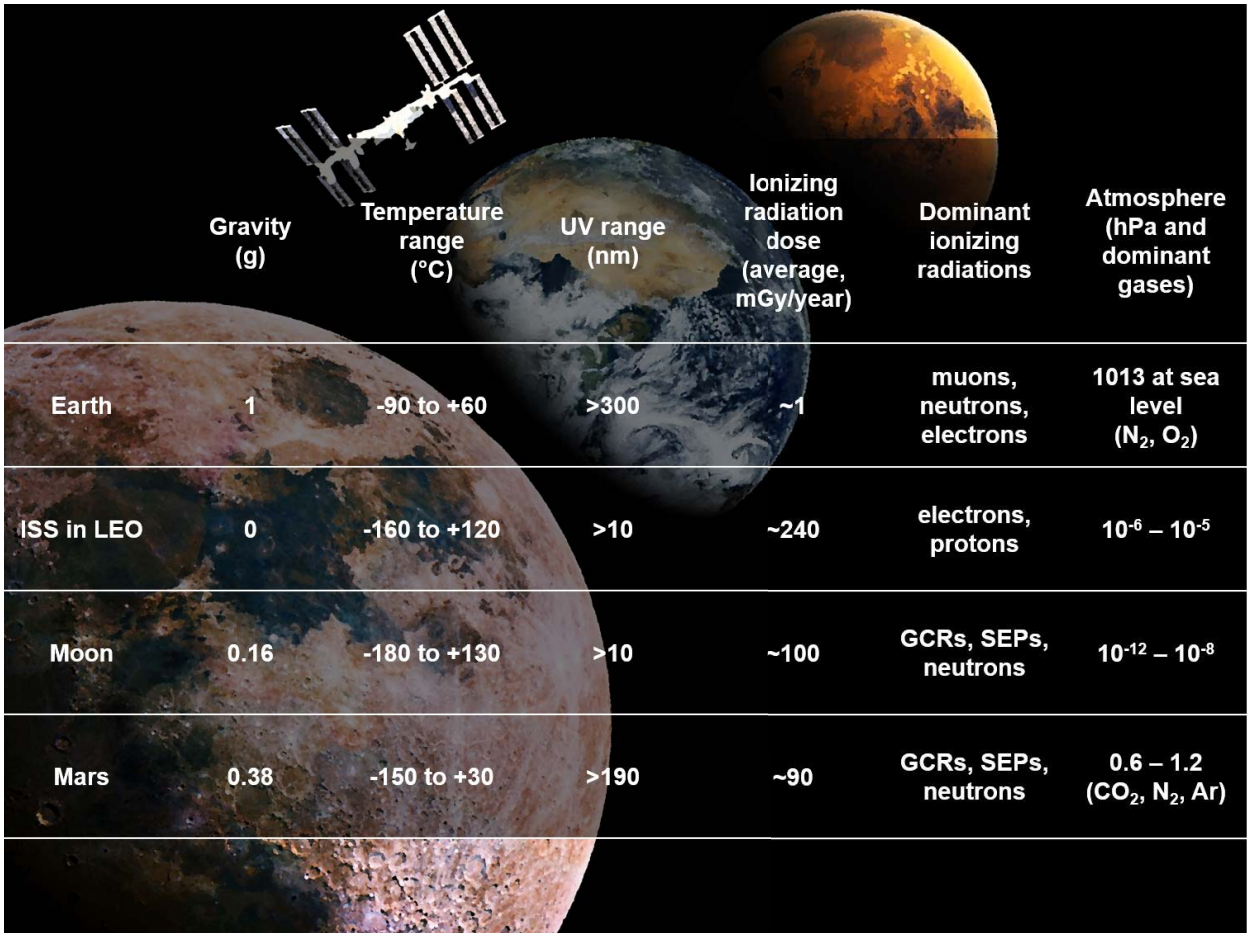

Figure 3: Comparison of some environmental factors on the surface of Earth, the Moon and Mars, and outside the ISS in low Earth orbit. Adapted from (Cottin et al. 2017) with additions from (Hassler et al. 2014, Reitz et al. 2012, Dachev et al. 2017, Rabbow et al. 2017).

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