ASTROBIOLOGY
Volume 7, Number 5, 2007

DOI: 10.1089/ast.2006.0082

Special Review

Lunar Astrobiology: A Review and Suggested Laboratory Equipment

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ABSTRACT

In October of 2005, the European Space Agency (ESA) and Alcatel Alenia Spazio released a "call to academia for innovative concepts and technologies for lunar exploration." In recent years, interest in lunar exploration has increased in numerous space programs around the globe, and the purpose of our study, in response to the ESA call, was to draw on the expertise of researchers and university students to examine science questions and technologies that could support human astrobiology activity on the Moon. In this mini review, we discuss astrobiology science questions of importance for a human presence on the surface of the Moon and we provide a summary of key instrumentation requirements to support a lunar astrobiology laboratory. **Keywords: Lunar astrobiology—Human lunar exploration—Instrumentation—Microbiology—Planetary protection.** Astrobiology 7, 767–782.

INTRODUCTION

The Moon is not expected to harbor indigenous life, yet human explorers and their robotic precursors will likely carry out a range of important astrobiology studies on the lunar surface that include the search for ancient meteorites, the testing of planetary protection protocols, and the monitoring of crew life-support systems. In addition to offering important insights in their own right, astrobiology investigations on the Moon would provide experience that could be applied in similarly hostile planetary environments, such as Mars, and even in extreme environments on Earth (Mendell, 2005). Therefore, defining the scientific objectives of lunar astrobiology and the suite of instruments necessary to accomplish them is an important objective of planetary science.

In this review paper, we discuss the primary research questions for lunar astrobiology. Based on a three-month design study for a lunar astro-

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biology laboratory conducted at the Open University in the United Kingdom (performed in response to a call for innovative concepts and technologies released by the European Space Agency (ESA) and Alcatel Alenia Spazio Italia*), our research also provides definition of the instrumentation that human explorers could use to conduct experiments in these scientific areas.

LUNAR ASTROBIOLOGY: KEY SCIENTIFIC QUESTIONS

In recent years, interest in lunar missions has increased immensely in space agencies around the world. In 2004, NASA released the President's Vision for Space Exploration, which includes specific goals for returning humans to the Moon (NASA, 2004). The European Space Agency completed its first dedicated lunar mission, SMART-1, in September of 2006 and is currently examining options for participating in lunar explorations that go beyond robotics (Messina and Vennemann, 2005; Laurance, 1996; Horneck *et al*., 2001). As interest in human missions to the Moon grows, it is important to look at the scientific reasons for returning there and, in particular, the reasons that warrant the establishment of a more permanent presence than that achieved during the Apollo era.

In this review, we examine astrobiology questions specifically of interest to human researchers on the lunar surface. Human settlement would provide a means by which to conduct novel science that cannot be performed on Earth. As well as consulting the primary literature, we carried out a survey of numerous researchers in fields related to astrobiology with the intent to define the scientific goals that will be pursued during future human missions to the Moon. What resulted was a list that ranged from the abiotic studies of geology and meteoritics to more biology-oriented areas of human physiology and planetary protection. Specific topics within each area of study are discussed.

Geology/Meteoritics

Meteorites on the Moon will be of great interest to astrobiology researchers and will yield geological information about Earth, Mars, and other planets or celestial bodies whose material may have been deposited on the Moon (Taylor, 2005; Korotev, 2005). During the Late Heavy Bombardment, a great deal of material was ejected from Earth, some of which would have been caught by the gravity well of the Moon and, consequently, deposited on the lunar surface (Koeberl, 2003; Armstrong *et al*., 2002). It is unknown how much of this material is present on the Moon, though some estimates indicate that as much as 200 kg km^{-2} of terrestrial material ejected from Earth during the period of 3.9 to 3.8 Gyr could be exposed at the surface today (Armstrong *et al*., 2002; Crawford, 2006). In addition, robotic remote sensing missions prior to human exploration could aid in narrowing down the search for meteorites by taking advantage of the differences in absorption spectra seen between the hydrated silicates and carbonates of Earth rocks and lunar rocks, which contain no water or carbonates (Crawford, 2006). These rocks would likely yield information about the bombardment history of Earth and improve our understanding as to the rate of impact and the size of impactors. A fuller understanding of conditions on Earth during the Hadean will help to answer key questions as to how the habitability of Earth evolved (Chyba, 1993; Ryder, 2002). Plate tectonics and surface weathering processes have wiped away most of the evidence of past impacts on our planet. The Moon, however, with its lack of plate tectonics and lack of aeolian and aqueous weathering processes, could be described as a "witness plate" of what Earth has experienced throughout its history (Spudis, 2001). The chemical and physical features of lunar material subjected to melting and brecciation during heavy bombardment reveal details about the nature of impacts during this early critical phase of terrestrial evolution (Petro and Pieters, 2004; Gomes *et al*., 2005) and the possible scenario within which life emerged (Arrhenius and Lepland, 2000).

The analysis of meteorites from other planetary bodies, such as Mercury, Mars, and Venus, would also contribute to our understanding of the geological history of these planets. If rocks from Venus, for example, have been transported to the Moon and currently reside there, they would be the only existing evidence of Venus's early geology (Armstrong *et al*., 2002). The identification of such meteorites on the Moon would contribute to the study of the exchange rate of material be-

*In 2007, Alcatel Alenia Spazio became Thales Alenia Space Italia.

tween bodies in our Solar System. This information could also be used to validate computer models of exchange rates within the Solar System (Gladman *et al*., 1996).

The geology of the Moon itself will be an important area of future study. It is thought that the Moon was likely formed when a large Sun-orbiting object or planetesimal struck Earth and jettisoned debris into orbit that later coalesced (Hartmann, 1986; Stevenson, 1987; Shearer *et al*., 2006). The orbital evolution of the Moon subsequent to its formation remains an intriguing mystery (Garrick-Bethell *et al*., 2006). Study of the geology of the Moon, along with a substantial addition to the diversity of samples from different locations on the Moon, would help to elucidate this geological and astronomical history (*e.g.*, Kleine *et al*., 2005). Although the Apollo program provided us with lunar surface samples from which much of our understanding of the Moon's composition and structure has been gained, remote sensing missions such as Clementine and Lunar Prospector have shown that there is a great deal of variation in materials at the lunar surface (Shearer *et al*., 2006; Wieczorek *et al*., 2006). Obviously, the knowledge drawn from Apollo samples with regard to the origin and geologic evolution of the Moon is incomplete (Crawford, 2004, 2006; Okada *et al*., 2006). Studying the history of geological processes such as volcanism and crust deformation would not only reveal information about the Moon's history but also further our understanding of how these processes work on other rocky bodies in the Solar System (Spudis, 2001; Crawford, 2004, 2006).

The Moon is thought to play a role in maintaining the habitability of Earth today; its history is, therefore, of direct interest to astrobiology in terms of defining the characteristics of habitable planets. It is known, for example, that the obliquity of Earth has been influenced by the presence of a moon (Touma and Wisdom, 1994; Waltham, 2004). Specifically, the obliquity of Earth has been postulated to be moon-stabilized (Laskar *et al*., 1993; Waltham, 2004), with the Moon exerting a torque that prevents the planet from entering chaotic zones of obliquity changes between 60° and 90°. Without the Moon, it is supposed that Earth would have been subject to much more frequent changes in climate, at least over geologic time periods; and this would, of course, have influenced the nature of biological evolution. Although investigations on the Moon cannot directly address these types of questions, a refined knowledge of lunar history, brought about by an analysis of an improved sample set, can help to constrain the early history of the Earth-Moon system and, thus, the role of the Moon in influencing the habitability of Earth.

Prebiotic chemistry

The Moon may not support indigenous life, but it is possible that chemicals native to its surface could provide important information about how life develops. Two important concerns with regard to astrobiology on the Moon are the extent of ice deposits or hydrated minerals in the polar shadows (Seife, 2004; Vasavada *et al*., 1999) and whether ices preserved in these regions could contain evidence of prebiotic chemistry. When the Apollo astronauts returned samples of the lunar regolith to Earth, no evidence of organics was discovered in the samples. All of the Apollo samples, however, were taken from the equatorial regions; other areas of the Moon support vastly different conditions.

Both indigenous and exogenous organics could be sought:

1) Indigenous: It has been proposed that prebiotic materials, such as amino acids, may have formed from inorganic molecules in volcanic conditions on the early Moon and may remain preserved to this day in permanently shadowed ice (Lucey, 2000). Careful examination of polar ice from the Moon would allow researchers to identify organic molecules, if such components were ever synthesized on the Moon (*e.g.*, Schulze-Makuch *et al*., 2005).

2) Exogenous: Organics have certainly been delivered to the Moon in the form of carbonaceous chondrites and interstellar dust particles. The search for, and possible characterization of, these materials may yield insights into the inventory of organics delivered to the surface of the early Earth and help to discern their chemical diversity as well.

The lunar environment and life: general aspects

Astrobiology can contribute to lunar exploration by providing a better understanding of how Earth life adapts to conditions on the Moon. The Moon environment, of course, will not support life as we know it; and Earth life forms, whether human or microbial, would require artificial habitats to survive (Tamponnet, 1996; Horneck *et al*., 2003). In the case of long-duration missions, these habitats would likely implement some form of bioregenerative life-support systems. These systems would utilize organisms, including bacteria and plants, to process waste and produce important elements for life such as oxygen and food (Sadeh and Sadeh, 1997; Horneck, 1996; Bluem and Paris, 2001). The lunar habitats would then become self-contained artificial ecosystems.

Even with the aid of such habitats, however, life would be exposed to adverse conditions unique to the lunar surface, including gravity that is one sixth that of Earth, fine dust particles that could harm respiratory systems, and high levels of cosmic and solar radiation (Horneck, 1996). During the Apollo missions, for instance, astronauts suffered radiation doses at the skin ranging from 0.0016–0.0114 Gy even with the protection of Apollo spacecraft and suits (Joules per kilogram of tissue; Armstrong *et al.*, 1975). More recent estimates of worst-case scenario radiation exposure, which includes solar events as well as galactic cosmic rays, for astronauts on the lunar surface under the protection of a space suit has been estimated at around 86.90 Sv (dose equivalent) at the skin, 33.40 Sv for the lens of the eye, and 1.89 Sv for blood-forming organs (Horneck *et al.*, 2003). This is well above the respective limits for exposure as recommended by the National Council on Radiation Protection and Measurement in the USA, which recommends a per mission whole-body dose equivalent for males and females at age 35 to be only 1 Sv and 0.6 Sv, respectively (Horneck *et al.*, 2003). The recommendations for exposures over the course of one year are only 3.0 Sv at the skin, 2.0 Sv for the lens of the eye, and 0.5 Sv for blood-forming organs, (Horneck *et al.*, 2003). These high exposure rates to radiation will require constant monitoring of astronaut health, which, in turn, will aid in our understanding of the deleterious effects of exposure and aid in the development of appropriate countermeasures to ensure astronaut safety.

The Moon provides a unique laboratory in which to study life's response to these conditions, many of which cannot be accurately simulated on Earth. Long-term habitation of the Moon would provide important multi-generational observations of all types of organisms and contribute to our understanding of the long-term effects of lunar conditions. Table 1 provides a comparison of the primary physical factors that must be addressed for habitation on the Moon.

Long-term settlement of the Moon and safety of human explorers will vitally depend on the behavior and adaptation of organisms under lunar conditions. Radiation can cause damage to DNA and result in mutation and the development of harmful conditions, such as cancer, in multicellular organisms (Saffary *et al.*, 2002; Horneck and Comet, 2006). Reduced gravity can result in bone demineralization and muscle atrophy (McCarthy, 2005; Zayzafoon *et al.*, 2005). Through observation of organisms that range from plants to hu-

TABLE 1. CONDITIONS AT THE LUNAR SURFACE RELEVANT TO ASTROBIOLOGY AS COMPARED TO CONDITIONS ON EARTH[a]

	Moon	*Earth*
Cosmic ionizing radiation	~0.3 Sv/a	1–2 mSv/a
Solar particle radiation	Up to 0.4–0.6 Sv/h	Not applicable
Solar UV radiation	Unfiltered spectrum	$\lambda \geq 290$ nm
Length of day	29.53 d	24 hours
Gravity	0.166 g	1 g
Atmosphere	No significant atmosphere or indigenous water	78.1% N_2 20.9% O_2 0.03% CO_2
Shielding	None	1000 g/cm^2
Pressure	3×10^{-12} mbar	1000 mbar
Diurnal temperature range[b]	≥173°C to <127°C	10°C to 20°C
Other factors	Fine lunar surface dust No significant atmosphere to protect from micrometeorite impacts	

[a]Adapted from Horneck *et al.* (2001).
[b]Williams (2006).

mans in ground-based studies and on short-duration space missions, it is already known that the ill effects of space travel on organisms are cumulative (Blakely, 2000; Brenner *et al*., 2003; Giusti *et al*., 1998; Horneck *et al*., 2003; Stein and Leskiw, 2000; Zayzafoon *et al*., 2005). The ill effects of long-term exposure are not entirely understood, and the lunar surface would be a unique theater in which to monitor these effects on organisms over the course of long-duration missions.

Microbiology

Microorganisms are the simplest and most abundant form of life on Earth. Single-celled organisms have inhabited our planet for at least 3.5 billion years and have evolved to survive in the harshest environments (Ehrlich, 1996). Therefore, they are thought to be the best-suited form of life as we know it for survival in space or on other planets.

Although microorganisms could not actively grow under the harsh conditions on the surface of the Moon, some microorganisms might be able to survive for a time on the lunar surface as dormant, inactive spores or in similar desiccation-resistant resting states. Though highly disputed, this may have been evidenced after the Apollo 12 mission when components of NASA's Surveyor 3 lander were returned to Earth after thirty-one months on the Moon and cells of the common *Streptococcus mitis* were isolated from a sample of foam from the lander's television camera (Mitchell and Ellis, 1971, 1972; Taylor, 1974, 1977; Jones, 2005). The initial claim that the bacteria were deposited on the camera before launch of the spacecraft and, subsequently, survived after thirty-one months on the Moon was made in the official 1972 NASA report, *Analysis of Surveyor 3 Material and Photographs Returned by Apollo 12*, in which arguments against contamination during various phases of the Surveyor 3 retrieval, transport, and analysis were made (Mitchell and Ellis, 1971, 1972). Today, there is a continued debate as to whether these spores were transported to the Moon or were simply the result of contamination following the return of the Surveyor 3 camera to Earth (Rummel, 2004). The Surveyor 3 mission was not designed with the intention of returning components to Earth, and the retrieval arose only because the Apollo 12 mission managed to land close enough to the Surveyor 3 spacecraft to allow astronauts access to the site. The opportunistic nature of the experiment meant that proper controls were not present, and a thorough analysis of the Surveyor 3 equipment to catalog the microorganisms present after pre-flight decontamination prior to launch was not conducted (Mitchell and Ellis, 1971). Many questions still surround the claims made concerning the Surveyor 3 study results, and a return to the Moon could yield answers by providing lunar explorers with the opportunity to conduct dedicated studies on the survival of soil- and human-derived microorganisms. Researchers could study microorganisms taken to the Moon and examine additional equipment left on the surface during the Apollo era. *In situ* studies of these objects would help to validate or disprove the results of the Surveyor 3 data by ruling out contamination occurring during the process of sample return to Earth (Glavin *et al*., 2004).

Studies that focus on the ability of Earth microorganisms to survive in dormant states during direct exposure to the space environment and conditions at the lunar surface could help to determine the viability of the panspermia theory, which is the idea that microorganisms can be transported from one celestial body to another aboard material ejected from planets by way of asteroid and comet impacts (Clark *et al*., 1999; Horneck *et al*., 2001; Mastrapa *et al*., 2001; Burchell, 2004; Cockell *et al*., 2007; Nicholson *et al*., 2006). The Moon would provide a platform on which to study microorganisms exposed to a wide range of conditions, including severe ionizing and UV doses, desiccation, and low temperatures. These studies would constrain the likelihood of the interplanetary transfer of material and the factors that limit transfer (Mileikowsky *et al*. 2000; Clark, 2001), particularly during the interplanetary transit phase of transfer.

In addition, it would be valuable to study components of past missions that were not designed to land "softly" on the Moon, namely the Saturn V stage four boosters and Lunar Excursion Module ascent stages that impacted with the lunar surface. It would be important to see how the impact of these materials affected microorganism spores they may have carried with them and to collect information concerning their ability (or inability) to survive the stresses of impact with a planetary surface. This information would also be valuable in understanding the potential for contamination and its distribution on the Moon, Mars, and other bodies following spacecraft impacts (Glavin *et al*., 2004).

In cases where microorganisms cannot withstand the harsh conditions of space travel and exposure to lunar conditions, it would still be valuable to examine whether we are able to detect any biomolecular signatures they may have left behind (Glavin *et al.*, 2004). It would be invaluable to see whether organic signatures from microorganisms carried aboard equipment on missions such as Surveyor, Ranger, Apollo and even the recent SMART-1 can still be identified today after their exposure to extreme lunar conditions. This would assist in the development of effective methods to detect biological signatures at low concentrations on other locations like Mars and reveal the fate of biological contaminants on the Moon (see *Planetary protection* below).

Microbiological investigations could also include the study of meteorites. Meteorites are not only important for the geological information they yield with regard to their locations of origin, but there is also a possibility that they could contain biologically important signatures (McKay *et al.*, 1996). Given the questions surrounding the validity of morphological biosignatures (Cady *et al.*, 2003), examination of material ejected from the Archean Earth during the time of life's early development would be of great interest, and any Earth meteorites discovered on the Moon might contribute to our understanding of the origin of life on our planet (Armstrong *et al.*, 2002). Likewise, rocks from Mars and other locations could provide extra material for assessing the likelihood of life or conditions conducive to life on the surface of these planets during earlier periods of their history.

Microbiologic research on the Moon could help to answer questions about the potential for current Earth life to adapt to new conditions beyond our planet. The survivability of microorganisms has been previously tested in a number of simulations for locations such as Mars. Microorganism survival has also been studied on rockets, satellites, and space stations (Shilov, 1970; Bücker, 1975; Schuerger *et al.*, 2006; Taylor, 1975; Mastrapa *et al.*, 2001; Nicholson and Schuerger, 2005; Horneck, 1993; Saffary *et al.*, 2002; Schuerger and Nicholson, 2005; Cockell *et al.*, 2007; Nicholson *et al.*, 2006). However, the lunar environment has been mostly overlooked as an environment in which to monitor microbial survival. Microorganisms from Earth could be brought to the Moon on future missions with the intent to examine their behavior and survivability under the unique conditions that the lunar surface presents in terms of gravity, atmospheric pressure, and radiation regimes. Attempts to culture microorganisms in lunar soil, for instance, could help to determine whether lunar regolith contains elements that microorganisms can utilize in biological life-support systems. Spores could be tested for survivability on the Moon in specific experiments over varied lengths of time and degrees of exposure to the lunar environment. While studies on plant growth in analog lunar regolith have been conducted, including the use of bacterial communities to aid in releasing nutrients for plant roots, research purely focused on the survivability of microorganisms in lunar regolith is currently lacking (Kozyrovska *et al.*, 2006). A small number of studies were conducted in the 1970s in which microbial communities were exposed to lunar materials returned to Earth by the Apollo missions (Taylor *et al.*, 1975). However, these tests focused mainly on proving that indigenous bacteria were not present on the Moon, understanding the potential for contamination of the Moon during lunar missions, and determining whether lunar soil was toxic to Earth microbes (Taylor *et al.*, 1975). This line of research was terminated subsequent to Apollo 14, when it had been sufficiently shown that the materials returned by lunar missions posed no threat to life on Earth (Taylor *et al.*, 1975).

The habitats used to support humans on the Moon would provide a laboratory in which to study microorganisms as they live, grow, and reproduce. Examination of these microorganisms would not only yield clues as to how life adapts to the Moon, but may also prove vital in maintaining the safety of human explorers. Human habitats, such as space stations, are known to support diverse microbial flora (Novikova *et al.*, 2001; Castro *et al.*, 2004). Human habitats will require the use of advanced life-support systems that would likely include organisms such as plants and microorganisms used to produce components such as oxygen that are required for human survival (Mitchell, 1994; Hendrickx *et al.*, 2006; Wang *et al.*, 2006). Study of microorganisms included in these systems would be a vital part of maintaining a safe living environment for human explorers. For instance, if the behavior of important bacteria is adversely affected by conditions (such as lunar gravity) and only produce a fraction of the oxygen they typically produce on Earth, this would have to be taken into account when developing the requirements of life-support systems. In addition to providing information about the behavior and adaptation of the most ubiquitous forms of life on Earth, many of these experiments—which would help us understand the role of various physical and chemical stressors on microbial growth, genetics, and physiology—could be used to test methods and technologies designed to aid in the search for and identification of life on Mars and at other locations.

Plant biology

The Moon is a relatively close destination, yet it is unlikely that essential components, such as oxygen and water, would be constantly re-supplied from Earth as is the case for the International Space Station. This means that efficient ways of generating these components *in situ* must be developed for lunar bases (*e.g.*, Ming and Henninger, 1994; Horneck, *et al.*, 2003; Foing *et al.*, 2006), and a likely option is to use regenerative biological life-support systems that utilize plants and other living organisms to help generate the essentials for life (Kozyrovska *et al.*, 2006). Such systems are vital if human beings are to expand to more distant locations such as Mars, and the Moon could prove to be an ideal test bed for their implementation. In addition, the creation of these self-contained, artificial ecosystems would help us understand our own ecosystem on Earth (Horneck, 1996).

While plants would be an important component of life-support systems on the Moon, a side benefit of their presence would be the study of their behavior and adaptation to the lunar environment (*e.g.*, Venketes *et al.*, 1970; Ming and Henninger, 1994). For instance, the efficiency and effectiveness of life-support systems could very well rely on our understanding of how plants react to extremely low gravity, particularly with regard to growth and productivity. During the Apollo era, a limited number of experiments were performed whereby plants were exposed to lunar materials (Taylor *et al.*, 1975). A primary aim of these studies was to determine whether lunar material contained any agents that were toxic for terrestrial plants. Some tests, however, showed that lunar materials could act as a source of nutrients for some plants (Taylor *et al.*, 1975). More recently, studies have been conducted on Earth to simulate plant growth in a lunar greenhouse (Kozyrovska *et al.*, 2006). In these experiments, the ornamental plant, *Tagetes patula*, was successfully grown in lunar anorthosite soil simulant with bacteria. Testing these technologies *in situ* on the Moon would provide an idea of the accuracy of Earth-based analog simulations. These studies would be relevant to assessment of the effects of gravity on life and would improve our understanding as to whether long-term responses to gravity are linear or whether there are critical gravitational thresholds of biological effects (Garshnek 1994a, 1994b).

Human biology

The presence of humans on the Moon would be the ultimate test for biological life-support systems and would offer the unique opportunity to observe how yet another Earth-based organism adapts to the lunar environment. Human biology is obviously far more complicated than that of microorganisms or plants, yet there are some simple observational and medical experiments that could be performed. Numerous studies on human biological response to space exploration have already been undertaken in Earth-based simulations and during numerous space missions (Taylor, 1974; Nicogossian and Pober, 2001). However, the Moon presents its own unique set of conditions, including radiation regimes that cannot be wholly simulated on Earth (Horneck, 1996). The Apollo missions provided a unique opportunity to study the response of humans before, during, and after short-term exposure to conditions at the lunar surface (Alexander *et al.*, 1975). However, it will be our understanding of how humans respond to long-duration exposure to elements of the lunar environment, such as extremely low gravity and high radiation, that will determine the future of human exploration in space beyond low-Earth orbit.

The one-sixth gravity environment of the Moon will likely cause certain physiological responses in calcium turnover, oxygen metabolism, blood formation, and cardiovascular activity as the body adapts to the new environment (Di Prampero and Narici, 2003; Horneck, 1996). In addition, the uptake of pharmaceuticals into the blood may be affected, and care must be taken when considering medical response measures to illness (Horneck, 1996). Radiation in space causes numerous problems, which include damage to elements in blood, to the reproductive system, and to the lens of the eye (Bailey, 1975). In addition, radiation exposure can cause a high rate of DNA damage and mutation and result in tumors or reduced life expectancy (Cucinotta *et al*., 2001). Continually monitoring the health of human explorers will, therefore, be of utmost importance in human lunar missions. Effective countermeasures and medical techniques for future Mars exploration will be developed by studying the effects of lunar habitation on human health.

Planetary protection

Another main goal of astrobiology on the Moon will be to develop and test effective strategies for planetary protection in preparation for future missions to Mars. The Moon is thought to be biologically inactive, and as it cannot support life as we know it, biological contamination is not considered to be of high concern (Rummel and Billings, 2004). When samples are returned from Mars for study, there will be some concern that unknown biological contaminants could be transported back to Earth (Rummel, 2001; Rummel and Billings, 2004). Because of this, the Moon may be a safe midpoint where these samples could be analyzed before risking their delivery to Earth. It must be noted, however, that return of some planetary samples to the Moon is still restricted under Category V of the COSPAR Planetary Protection Policy (Rummel *et al*., 2002). Category V states that "the Moon must be protected from back contamination to retain freedom from planetary protection requirements on Earth-Moon travel," which means that the Moon must remain free of contamination from distant locations as a safe-guard to the Earth-Moon system (Rummel *et al*., 2002). For instance, it is required that material brought to the Moon from Mars in no way affects the lunar surface, and any unsterilized samples must be suitably contained before transfer to Earth.

In addition, the inadvertant transport and dispersal of contaminants from Earth, such as bacterial spores, by robotic missions and human inhabitants on the Moon would be an important case study for future missions to Mars. If Mars does sustain indigenous life, it is important that missions to that planet do not transport microorganisms that could harm a martian ecology (Mancinelli, 2003; Debus, 2005). By quantifying the rate at which organisms disperse to the surrounding environment from a lunar base, which would be determined by such things as physical conditions (*e.g.*, vacuum, UV and cosmic irradiation, low temperatures), rates of extra vehicular activity, and surface soil churning, we gain generalized insights into contamination issues that can be applied elsewhere. Equipment for the rapid monitoring of these microbial movements can be optimized. Regardless of whether there is no indigenous life on Mars, it is still important to understand the spread of contaminants so that microorganisms or organics originating from Earth are not falsely identified as martian. Techniques for monitoring the delivery and spread of biological contaminants from a human settlement would be valuable in this respect. Beyond the possible natural spread of contaminants from human settlements, intentional contamination of specific sites could be undertaken to understand the rate at which organisms die off. This could be important in determining whether landing sites for past missions on the Moon and Mars can be considered sterile today.

The presence of human explorers raises issues in terms of preserving the pristine environment of the Moon (*e.g.*, Williamson, 2003; Spennemann, 2004; Lester *et al*., 2004). Human activities may alter the natural environment of the lunar surface over time, and it will be important to monitor any changes that occur. Although the Moon does not have any native ecology, there are specific sites on the Moon that may warrant special protective measures due to their scientific value. The landing sites of previous lunar missions, such as Apollo, are a valuable and limited resource for conducting studies on the effects of humankind's initial contact with the Moon (Rogers, 2004; Spennemann, 2004). Other locations, like the permanently shadowed craters at the Moon's south pole, may contain water ice or hydrated minerals and other valuable scientific and physical resources. If, for instance, these sites contain ice with signs of prebiotic chemistry, one can envision the establishment of organic special regions to protect these native lunar organics for careful scientific study. In addition, the Moon is currently classified as a Category I location under the COSPAR Planetary Protection Policy (Rummel *et al*., 2002). Is it possible that the presence of native organics could require an upgrade in its status to Category II? Finally, the Moon is an excellent location from which to conduct radio-wave astronomy due to unique lunar conditions, such as the absence of an atmosphere, a slow rotation rate, and very low temperatures (Horneck, 1996). Astronomy would not be a direct scientific goal for a lunar astrobiology laboratory designed to handle biological samples, but the scientific benefits of astronomy on the Moon might require that certain aspects of the pristine lunar environment are protected for the purposes of astronomy when designing habitats and laboratories (Horneck *et al*., 2001).

Conclusion to science questions

The surface of the Moon offers answers to a diversity of important questions in astrobiology. Table 2 summarizes the key research points we have identified in the areas of interest for lunar astrobiology, including technology developments that will affect future missions to locations like Mars.

LUNAR ASTROBIOLOGY INSTRUMENTATION

Many questions in lunar astrobiology will be answered by large-scale, dedicated missions,

TABLE 2. KEY AREAS FOR LUNAR ASTROBIOLOGY

Discipline/area	*Key Scientific Question*
1. Geology and Meteoritics	a. Study meteorites from the Earth to yield information about the geological history of our planet
	b. Study meteorites from other locations, such as Mars and Venus, in order to understand more about their geological histories and the history of the Solar System
	c. Study the history of the Moon and the lunar environment
	d. Examine the impact history of the Moon in order to understand more about the impact history of Earth and exchange rates of material within the Solar System over time
2. Prebiotic Chemistry	a. Examine ice deposits on the Moon for evidence of prebiotic organic molecules formed during early periods of volcanism on the Moon or delivered to the surface by carbonaceous meteorites
3. Microbiology	a. Understand adaptation of Earth life to the lunar environment
	b. Examine past Apollo equipment to determine presence of spores and levels of sterility today
	c. Determine viability of microorganisms transported to the lunar surface, both currently and during past missions, in order to test theories of Panspermia
	d. Search for and analyze meteorites from early Earth for clues to ancient microbiology
	e. Search for and analyze meteorites from other locations like Mars and look for evidence of microbiology
4. Plant Biology	a. Study adaptation of plants to the lunar environment
	b. Develop biological life-support systems for continued human presence on the Moon
5. Human Biology	a. Study the adaptation of humans to the lunar environment
	b. Understand the effectiveness of regenerative life-support systems in sustaining humans
6. Planetary Protection	a. Test strategies for minimizing microbial loads on spacecrafts sent to planetary surfaces
	b. Test methods for minimizing and monitoring contamination when searching for life on other planets
	c. Monitor the spread of biological contaminants in terms of rate and scale outside of human habitats
	d. Monitor contamination from previous lunar missions and equipment previously delivered to the surface
	e. Examine remnants of previous missions that impacted with the lunar surface to understand survivability of microorganisms and spores
	f. Use the Moon as a safe and sterile location to study materials returned from other locations such as Mars
7. Technology Development	a. Test methods for identifying life on other locations such as Mars
	b. Test methods for closed bioregenerative life support systems for future use on more distant locations such as Mars where resupply of essentials will be more difficult or costly
	c. Gain understanding of the Earth ecosystem through development of bioregenerative life support systems
	d. Understand long-term effects of exposure to low gravity on plants, humans and microorganisms to determine the potential for long-term habitation of Mars or other locations
	e. Understand contamination issues, such as the spread of biological contaminants from human habitats, before going to Mars or other locations that may harbor indigenous life

Table 3. Suggested Instrument Requirements for Conducting Lunar Astrobiology

Instrument	*Relevant for Key Scientific Question*	*Considerations*	*Current estimated mass*	*Estimated power*	*Estimated size*
Light microscope fitted with camera and UV epifluorescence	1a–b, 2a, 3a–e, 4a, 5a, 6a–f	Miniaturization for portability needed Potential for combining functions with other microscopes in the instrument suite Capability for multiple filters required	6.44 kg	100 W	Variable
Petrographic microscope	1	Miniaturization for portability needed Potential for combining functions with other microscopes in the instrument suite	6 kg	100 W	Variable
DIC light microscope setup	1	Miniaturization for portability needed Potential for combining functions with other microscopes in the instrument suite	6.44 kg	100 W	Variable
Confocal microscope	1	Although smaller than other microscopes, miniaturization is still required	25 kg	Power requirements for miniaturized instruments unknown	Potential size of miniaturized instruments unknown
SEM microscope and electron microprobe	1	Space agencies are already looking ways of miniaturizing this equipment[a]	Estimated mass not provided for instrumentation currently being developed	Estimated power requirements not provided	3 cm × 3 cm × 3 cm
Rock saw	1	Miniaturization for increased portability possible	1.6 kg[b]	1 W[b]	Variable
Digital camera/ imager	1–6	Private sector is already producing small components	0.026 kg	0.5 W	Variable
Handheld or laptop computer with basic database and image capture/ manipulation capabilities	1–6	Private sector is already producing small components	0.175 kg	5 W	11 cm × 7 cm × 26 cm
Distilled water source (micropore filter)	1–6	Needed for sterilizing liquids Filter setups are already quite small	Variable	None	Variable
Microcentrifuge	1–6	Needed for separation of substances Some need for miniaturization, although small versions do exist	7.5 kg	100 W	23 cm × 23 cm × 33 cm
PCR machine/ qPCR machine and sequencing	3a, 3c, 4a, 5a	Miniaturization required	7 kg	400 W	18 cm × 32 cm × 33 cm
Incubator	3–5	Miniaturization required	Variable	50 W	Variable
Hot or cold water bath	3–5	Easily adaptable for size requirements	Variable	400 W	Variable
Freezers	3–5	Habitats will likely include these large pieces of equipment, so there would be no need to include them in a portable laboratory suite	Variable	50 W	Variable
Mass spectrometer/ chromatograph	1	Miniaturization required Some miniaturized components already being developed for space missions	34 kg	180 W	38 cm × 58 cm × 38 cm
ICP-QMS	1–5	Miniaturization required	175 kg	Estimated power requirements unknown	64 cm × 110 cm × 60 cm
IR spectrometer	1	Miniaturization required	14.5 kg	Estimated power requirements unknown	Variable

TABLE 3. SUGGESTED INSTRUMENT REQUIREMENTS FOR CONDUCTING LUNAR ASTROBIOLOGY (CONT'D)

Instrument	*Relevant for Key Scientific Question*	*Considerations*	*Current estimated mass*	*Estimated power*	*Estimated size*
Raman spectrometer	1–5	Miniaturization required Some miniaturized components already being developed for space missions[c]	2.5 kg	Estimated power for instruments being developed not provided	Estimated size for instruments being developed not provided
Autoclave	1–6	Needed for sterilization Miniaturization required	Variable	180 W	Variable
Balance	1–6	Easily adaptable for size requirements	Variable	6 W	Variable
Vented fumehood	1–6	Workspace for many experiments Miniaturization or small-scale alternatives needed	Variable	Variable	Variable
Sterile working space	3–5	Workspace for many experiments Miniaturization or small-scale alternatives needed	Variable	Variable	Variable
Glove box	3–5	Workspace for many experiments Miniaturization or small-scale alternatives needed	Variable	Variable	Variable
pH meter	3–5	Easily adaptable for size requirements	0.070 kg	3 W	1.5 cm × 3.2 cm × 17 cm
Thermometer	3–5	Easily adaptable for size requirements	0.050 kg	None	Variable
Various forms of environmental sensors (for humidity, radiation, etc.)	3–5	Easily adaptable for size requirements	Variable	Variable	Variable
Biosensor arrays	3, 4a, 5a	For use in monitoring organism health based on biomolecules	0.01 kg	None	1 cm × 4 cm × 3 mm (each)
Lab on a chip	3–5	Miniaturized molecules biology test suites, such as Gene chips, etc.	0.01 kg	None	1 cm × 1 cm × 1 cm (each)

[a]Callas (1999); [b]Udomkesmalee (2005); [c]Wang *et al*. (2003).

such as deep drilling projects, which have been studied previously by ESA and NASA (Putz, 2000). For these projects, dedicated instrumentation will be required. In this study, it has been our objective to define the minimum equipped astrobiology laboratory that could be used to address the questions we outline above. However, it is important that a portable lunar laboratory provide a suite of instruments human explorers can use to take advantage of opportunistic science that may arise during human exploratory missions.

In Table 3, we review preliminary suggestions for the ideal equipment to be included in a laboratory for use by human explorers on the lunar surface. Many of the instruments have special considerations, such as large mass requirements or delicate hardware, all of which must be taken into account before they can be included in such missions. Others could potentially be combined into single pieces of equipment that could accomplish similar tasks as multiple instruments. It is vital to reduce mass and size requirements for every piece of equipment to reduce the costs involved with transportation to the Moon. Currently, the average launch cost for heavy launch vehicles in western countries into geosynchronous orbit alone is roughly $37,550 per kilogram of payload (Futron, 2002). Costs for launching a kilogram of equipment to the Moon will be even greater; therefore, minimizing the mass of instruments is a necessity. Examples of the primary considerations identified during the study for each instrument are provided.

This portable laboratory should be adaptable enough to perform opportunistic experiments that will undoubtedly arise for researchers as more knowledge is gained about the lunar environment. This would ensure that human explorers gain the full potential of lunar studies.

The initial list we proposed was based on dis-

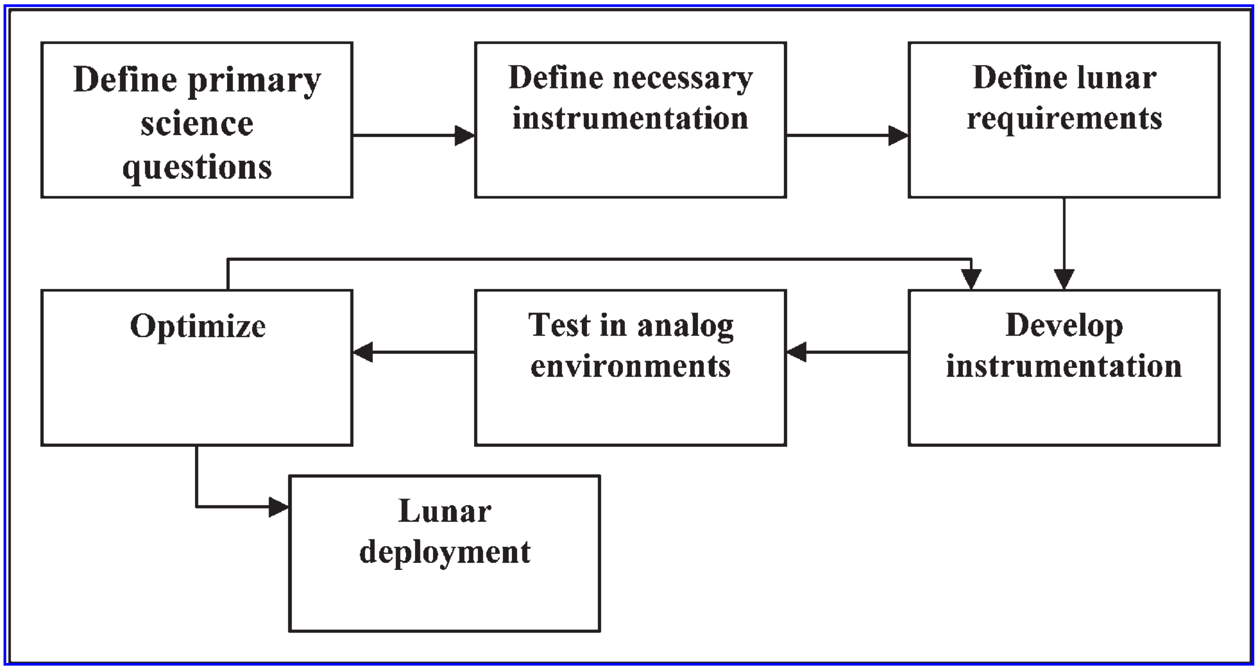

FIG. 1. A Roadmap for development of a lunar astrobiology laboratory. The information contained in this review falls under the initial step of defining the primary science questions relevant to lunar astrobiology.

cussions with researchers as well as equipment requirements for each of the outlined areas above. We have not listed many items that would be required in a laboratory such as pipettes, beakers, and the diversity of consumables associated with many areas such as molecular biology. This list is intended to cover major laboratory items, and through identification of critical areas of technological development and miniaturization, it could lead to a roadmap for lunar astrobiology technology development in support of human lunar missions (Fig. 1).

CONCLUSION

Though it is expected that the Moon does not harbor indigenous life, astrobiology has a profound role to play in areas of lunar science and human lunar exploration. This mini review provides discussion of the key scientific questions in astrobiology that will be addressed by future human missions. Many of these areas of study have common instrumentation requirements, and we have identified these synergies and presented a preliminary roadmap for further development to support a lunar astrobiology laboratory.

Human explorers, if equipped with the appropriate scientific tools, could take advantage of the unique environmental conditions at the lunar surface to conduct novel science in the areas of geology and meteoritics, prebiotic chemistry, molecular biology, plant biology, human biology, and planetary protection (Cockell, 2005).

ACKNOWLEDGMENTS

This paper emerged from a three-month preliminary design study for the International Lunar Astrobiology Laboratory, which was funded and supported by the European Space Agency and Thales Alenia Space Italia in Torino, Italy. The study was conducted at the Open University in the United Kingdom.

ABBREVIATIONS

COSPAR, Committee on Space Research; ESA, European Space Agency.

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1. Tomas Hode . 2007. Astrobiology Up NorthAstrobiology Up North. *Astrobiology* **7**:5, 723-724. [Citation] [PDF] [PDF Plus]