Human Planetary and Astrobiology Exploration: How Will Radiation, Low Gravity, and Isolated and Confined Conditions Affect Our Health?

Jancy C. McPhee, Ph.D., Research Scientist, The Aerospace Corporation
281-684-6307, jancy.mcphee@aero.org

John B. Charles, Ph.D., NASA, retired
281-546-7763, jbcharle@gmail.com

I. In situ Scientists Can Best Answer Some Planetary Science and Astrobiology Questions

In this section, we discuss the need for direct human explorers to answer key planetary science and astrobiology questions.

A. What is the interplay of planetary science, astrobiology, and human exploration science?

As humanity explores further into our solar system in the next 10-year period, we need to answer many key scientific questions related to planetary science, astrobiology, and the effects of long-term occupation of planetary bodies on human health. Robotic exploration can address many of the planetary and astrobiological scientific questions previously outlined in the *2013-2022 Vision and Voyages Decadal Survey* (National Research Council, 2011), but many of the questions for the coming decade (2023-2032) will be best answered through in person inquiry. Thus, we need to address additional scientific questions related to the health of the humans carrying out the research to answer these key planetary and astrobiological questions.

B. What planetary and astrobiological science questions will benefit most from in person human exploration?

Human exploration for the coming decade (2023-2032) will focus primarily on the Moon and Mars. Even initial short human missions will inform subsequent longer missions. For the purposes of this white paper, we will thus focus primarily on discussing the benefits of human-operated planetary science and astrobiological research at those two destinations. We recognize that an extravehicular activity (EVA)-intensive human exploration mission to a Near Earth Object, like an asteroid, or Phobos or Deimos could be possible in that time frame as well, but we will not cover it specifically, because many of the human health considerations are similar to those relevant to International Space Station (ISS), lunar and Martian missions.

The *2013-2022 Vision and Voyages Decadal Survey* outlined three cross-cutting themes of scientific questions (building new worlds, planetary habitats, and workings of solar systems) that multiple research missions involving the Moon and Mars can address. The importance of that research will still be significant in the next 10-year period. Under the cross-cutting theme of “planetary habitats,” for example, questions about the origins, evolution, distribution, and future of life are a high scientific priority. Analysis of samples from Mars may help answer these questions, and Mars is a destination for long-term human exploration.

The Moon is NASA’s priority for the next 10 years for human exploration. The current presidential administration has committed to return to the Moon by 2024 and to establish a permanent lunar surface base and develop technologies to take American astronauts to Mars (NASA, 2019). Many other countries and associated agencies plan to build villages or long-term development sites on the Moon as well, either collaboratively with the United States or independently, like the European Space Agency, Canada, Japan, China, Russia, and others. Multiple commercial companies, like SpaceX and Blue Origin, also have plans to land humans on the Moon.

Human missions to Mars will not likely occur until after the end of the next 10-year period; however, much like how current ISS work informs future deep space missions, coordinated planetary, astrobiological and exploration science conducted on the Moon will help inform future surface missions to Mars and beyond. The Moon is not a perfect analog for Mars, as it differs in surface gravity, lack of an atmosphere, circadian cycle, temperature, dust characteristics and the location of key resources (Koren, 2020). Still, we can establish a baseline of experience about

human exploration on the Moon to inform our scientific experimentation and operational practice on Mars.

C. What are the benefits of in-person geology vs. robotic geology?

Effective sample selection, equipment placement, and maintenance are the key benefits of in-person human planetary science and astrobiology exploration. The *2013-2022 Vision and Voyages Decadal Survey* noted that “Finding and collecting the most scientifically valuable samples for return to Earth may become, as they were in the Apollo program, the most important functions of a human explorer on the Moon or an asteroid.” Geology is a multi-step process beginning first with reconnaissance, followed by detailed field mapping. Large scale reconnaissance, especially dominating the early phases of exploration or in places where the environment is too hostile for humans, can be executed remotely with rovers and orbiters to measure the composition of rocks, soil, or the atmosphere.

Field study though requires keen observation, creation of conceptual models, and the formulation and testing of hypotheses. Often the work requires open ended or protracted research, changes in problem solving approaches, recognizing and interpretation of the unexpected, etc. Robots can collect data, but only people can conduct science (Slakey & Spudis, 2008), preferably people on site, not 20 light-minutes away. Frances Westall, an astrobiologist at the National Center for Scientific Research in France states she doesn't think robots will ever match human geologists for their knowledge and instincts in the field or their productivity. "I'm a geologist and I go into the field and I need to see things with my eyes...A human geologist can do in a week what the Mars rovers can do in a year." (Bartels, 2018) William Clancey, an expert in cognitive science and artificial intelligence currently at the Florida Institute for Human and Machine Cognition and formerly Chief Scientist of Human-Centered Computing in the Intelligent Systems Division at NASA Ames Research Center, agrees. He states that although the human brain is likened to a machine, we cannot build anything like it at this time. We don't yet have the capability to create a true robotic geologist, who can create a hypothesis, analyze choices, and apply varied instruments (Clancey, 2012). Telepresence might seem an attractive solution to extend the “reach “of the expert ground-based scientist, but at this time, the ideal technology is not yet available and the light delay for Mars makes it unlikely this could be executed effectively from Earth. In addition to the decreased effectiveness of telepresence due to communication delays back to Earth and persisting limits in imaging resolution compared to the capabilities of the human eye, the most serious obstacle is that technology cannot yet mimic the process that scientists use to conduct exploration in the field. Research will thus be most effective using a correct mix of in person and robotic exploration (Slakey and Spudis, 2008).

Lessons from Apollo underscore the importance of human intellect in lunar field study. Astronauts were able to select the most representative samples of a given locality, recognize interesting or exotic rocks, and act on discoveries, whether geologists by profession or astronauts from another profession but well-trained in geology field methods. In contrast, the unmanned Soviet Union Luna 16, 20, and 24 spacecraft collected soil samples from the Moon, but with no ability to range from the specific landing site to collect a suite of samples. As a result, less is understood about the Luna sites than the Apollo sites. People are needed in the field to analyze overabundant data and make key decisions regarding what to collect, what to ignore and what to note (Slakey & Spudis, 2008).

Although the Moon is lifeless, on Mars “you can actually go look for signs of existing life on the surface,” says Briony Horgan, a Purdue University scientist who works on NASA's Mars

2020 Perseverance rover missions. “We can do that with robots, but it’s hard.” (Koren, 2020) Ellen Stofan, NASA’s former chief scientist and currently the head of the Smithsonian’s National Air and Space Museum, says “While I’m optimistic that life did evolve on Mars, I’m not optimistic that it got very complex, so we’re talking about finding fossil microbes... That’s why I do think it will take humans on the planet, breaking open a lot of rocks to try to actually find this evidence of past life... And finding one sample is not good enough; you need multiple samples to understand the diversity” (Bartels, 2018). Exacerbating the challenge to robotic-only geology, the most interesting places to explore geologically are frequently small places, and Mars is large. These places may be hard to detect by preview from orbit, which is how we choose a location to plant a rover. Unfortunately, rovers are limited by energy and time, thus unable to venture far from a landing site in a short period of time (Clancey, 2012.)

Slakey and Spudis (2008) also point out that astronauts and cosmonauts in the past 5 decades have decisively shown that human capability is needed to install and maintain complex scientific instruments and conduct field exploration, using characteristics unlikely to be automated in the foreseeable future – flexibility, experience and judgement. Contributions were made in Earth orbit, such as for the Hubble Space Telescope, and on the surface of the Moon, such as during Apollo experiments measuring seismic activity and heat flow from 1969-1972. Future planned robotic techniques to place a complex network of seismic monitors on the Moon may not be able to overcome challenges to placement and maintenance of highly sensitive instruments. In most cases when spacecraft equipment malfunctions, astronauts “can analyze the problem, make on-the-spot judgments and come up with innovative solutions. Machines are capable of limited self-repair... designed to fix expected problems, but so far only people have shown the ability to handle unforeseen difficulties.” (Slakey & Spudis, 2008)

II. Detailed Life Science Questions to Address to Enable Human Planetary Science and Astrobiological Research on the Moon and Mars

We must consider what risks living and working in space pose to lunar and Martian explorers. This section considers the key scientific questions that must be answered about the health and performance effects of long-term human stays on planetary bodies. The information summarized below originates from the NASA Human Research Roadmap (2020) and is discussed as 3 main areas of needed key scientific research.

A. Space radiation is the most widely acknowledged hazard to human space explorers beyond Earth’s magnetosphere. What are the hazards and how can they be mitigated to ensure scientific mission success?

Space radiation consists of: galactic cosmic rays (high-energy atomic nuclei accelerated to near-relativistic velocities in galactic and extra-galactic supernovas); solar energetic particles (electrons and protons released by the sun in solar particle events, or SPEs, often in sudden intense storms); trapped radiation (charged particles trapped in Earth’s or another planet’s magnetic field); and non-ionizing ultraviolet radiation (from the Sun). The associated human risks are, in priority order: deleterious effects of prolonged cosmic ray exposure on central nervous system functions (cognition, emotional stability and well-being, etc.); acute radiation syndromes due to SPEs; cardiovascular disease and other degenerative tissue effects from radiation exposure and secondary spaceflight stressors; and radiation carcinogenesis.. Radiation carcinogenesis may increase over the post-mission lifetime of the crewmember but not during the mission *per se* and can thus probably be treated as any other cancers are treated, in medical

centers on Earth. All these risks can be mitigated by shielding, but these methods must be progressively developed, tested, and verified as protective on a planetary surface, in part using data from these studies. Lessons learned on lunar missions will be critically needed for human Mars missions.

B. Multiple gravity fields will be a consistent feature of deep space exploration missions for the foreseeable future. What will be the effects of these differing gravity fields on human systems?

While it may be strictly true that crewmembers will pass through multiple planetary gravity fields for various periods of time, physiologically, the relevant “gravity field” will be the perceptible acceleration in the crewmember’s local environment. During long periods of unpowered flight, such as in Earth orbit, lunar orbit, Mars orbit, or during coasting flight between these planetary bodies (up to ten days each way for currently envisioned lunar missions, seven months or more each way for currently envisioned Mars missions), the perceptible acceleration in the local environment will approach 0 g, commonly called “weightlessness.” We have extensive data from International Space Station studies evaluating the effects of long-term exposure to weightlessness on the human body. Similarly, we have data on the effects of gravity greater than 1, at levels and times anticipated during launch from Earth and landing on a planet.

Unfortunately, we have no data on the effects of long stays on a planetary surface with gravity less than 1 g. Significant Earth-based research using low g simulations, like multi-month head-down tilt bed rest, and potential g-replacement countermeasures, like artificial gravity, are suggestive but not definitive. On the Moon’s surface, the perceptible acceleration will be approximately 0.16 of that on Earth (for convenience, 1/6 g). On Mars’ surface, the perceptible acceleration will be approximately 0.38 of that on earth (for convenience, 1/3 g). Many of the key scientific questions for human exploration in the next 10 years will focus on collecting data about the health hazards or benefits of these g levels. Interestingly, an analysis by G.D. Nordley, described by Joseph Carroll (2019), showed that the distribution of surface gravity fields of planetary bodies with solid surfaces in our solar system cluster around these same three G levels: 1 g (Earth and Venus), 1/3 g (Mars and Mercury), and 1/6 g (Io, Earth’s moon, Ganymede, Titan, Europa, and Callisto). All asteroids have substantially lower surface gravity fields than those listed here, more like that experienced on the ISS. Thus, early scientific insights into the biological and biomedical value of local gravity fields on Earth, the Moon and Mars in maintaining crewmember health will have long-term applicability to the remaining solar system planetary surface targets. Data from the International Space Station show that countermeasures are largely effective in weightlessness and presumably will be in hypogravity, but some of these measures place significant time demands on crewmembers (for example, exercising 2.5 hours a day) or require medications with potential side effects that could de-grade the performance of a scientist exploring the surface. Early scientific research into the effects of long term stays in low g will inform which protective countermeasures or mission operations strategies we must employ for future missions to enable the accomplishment of key science tasks, such as the search for life and geological observation and sample collection on a planetary body.

The biomedical and cognitive risks currently associated with altered gravity fields include: possible increases in intracranial pressure and associated visual alterations during prolonged weightlessness; impaired control of spacecraft and associated systems and decreased mobility due to vestibular and sensorimotor alterations (and associated urinary retention on occasion), especially associated with weightlessness, hypogravity, and artificial gravity; loss of bone

integrity, increased fracture risk, increased renal stone formation risk and intervertebral disc damage upon and immediately after re-exposure to gravity; impaired performance due to reduced muscle mass, strength and endurance, and reduced physical performance due to reduced aerobic capacity; orthostatic intolerance during re-exposure to earth gravity after prolonged periods in hypogravity; adverse health effects due to host-microorganism interactions in a closed environment possibly exacerbated by weightlessness; and concern of clinically relevant unpredicted effects of medication in the face of the body fluid redistribution in weightlessness. If manifested during a mission, many of these risks are not incapacitating, but they can impact the vigorous performance of planetary surface exploration.

C. Space is an isolated, confined, and extreme environment. What are the long-term consequences of living in the conditions of space, and how do we minimize the impacts so humans can effectively perform research on the planetary surface?

a. Hostile and closed space environments present a combined physical health hazard

The environment of outer space is inherently hostile to human life processes, but the enclosed environment of the space vehicle may offer physiological challenges, too. The risk of adverse health and performance effects of planetary dust exposure is intrinsic to planetary surface activities. No amount of engineering can assure that none of the local regolith will contaminate the crewmembers' living space. The biomedical effects of even low-level exposure to local surface constituents may require rigorous environmental cleaning efforts, potentially at the expense of extravehicular activity time. The effects of lunar and Martian dust on humans are likely to be different and both have potential adverse effects that need to be further researched during planetary surface activities.

In addition, challenging EVA operations of scientific usefulness will inevitably be associated with increased injury potential and the associated compromised crewmember performance. Decompression sickness, for example, especially during EVA in space suits that will require lower internal pressure than the habitat, poses a continuing challenge. In an effort to minimize that pressure difference between the habitat and the space suit, the habitat may be maintained at a low enough pressure to cause hypobaric hypoxia in the crewmembers, which is not currently considered unhealthy, but may lead to biomedical problems if sustained for an indefinite period and potentially decrease scientific capabilities. The effects need to be documented scientifically.

In a closed environment in weightlessness, poor air mixing and ventilation may lead to acute and even chronic carbon dioxide exposure, possibly exacerbating the visual symptoms from any increased intracranial pressure. The recycling of the internal environment and filtration of toxins and waste products will inevitably lead to concentration and accumulation of toxic substances and possible health risks from such toxic exposure. These risks might lead to adverse health events compromising mission success, especially in the presence of already altered immune function associated with hypogravity exposure, and need to be explored further.

The nature of the habitat itself may cause risks that require clarification via scientific and operational analysis. The noise of constantly functioning life support machinery may cause hearing loss. In addition, even under otherwise benign circumstances, performance decrements and crew illness due to inadequate food and nutrition may occur, possibly even more likely as preferences and palatability change in response to the physiological and psychological aspects of extended mission duration. Similarly, performance decrements and adverse health outcomes will result from sleep loss, circadian desynchronization, and work overload in response to the environmental characteristics of the planetary surface site and the mission's success

requirements. These factors need to be examined carefully during planning for and execution of mission activities.

b. Isolated and confined space environments are hazardous to psychological health and functional teams

Psychological and psychosocial risks exist for prolonged, deep space exploration missions; many of the scientific questions related to these risks can be researched first on Earth, but we will need to address some of these questions in the local space environment as well. Adverse cognitive or behavioral conditions and psychiatric disorders are problems intrinsic to the individual that may become expressed with time under the intensely stressful conditions of the remote space environment, especially on Mars. Further, performance and behavioral health decrements due to inadequate cooperation, coordination, communication, and psychosocial adaptation within the team are expected in any high-performing group of individuals after prolonged isolation and confinement. These decrements can have serious consequences for human health and performance. A small team exploring Mars will be isolated and confined as no other team has ever been before in human history; it is expected that these kinds of disturbances and manifestations will occur. Accordingly, the team will need to be thoroughly trained how to work through these issues and return to smooth functioning smoothly. However, unanticipated challenges are likely to occur and will need to be accurately recorded to inform mission plans. Reduced crew performance due to inadequate human-system interaction design is also likely and still has many unknowns. Regular testing and analysis will be critical, especially as habitat and other exploration systems become more automated, including the complex robotics and artificial intelligence still evolving during the missions of the coming 10-year period.

c. Distance from Earth creates additional risks due to required remote medical care

The multitude of vehicles, habitats and work environments, and the EVA tasks required for exploration missions, equipment installation or maintenance, and space science execution raise the very real probability of injury from dynamic loads, either from vehicle acceleration or deceleration, equipment handling, or uncertain footing on the planetary surface. Adverse health outcomes and decrements in performance due to inflight medical conditions not related to overt injury, especially those not recognized before the mission and exacerbated by the conditions of spaceflight, are also likely and may increase in severity due to the lack of access to definitive medical care. These outcomes and decrements may be further complicated by the degradation in medications resulting from long term storage, not just during the mission itself, but unavoidably during long lasting prelaunch preparations and pre-placement on a planetary surface. Research into scientific and operational methods of adequate medical care delivered remotely from Earth and in the planetary field is imperative.

III. Concluding Remarks

Human explorers are needed to carry out key planetary science and astrobiological research in the next 10-year period. Technology will not replace human intellectual flexibility, analytical capabilities, or observational skills with fully robotic alternatives that can act as planetary field scientists seeking answers to questions related to geology or the presence of life. Similarly, robots cannot fully stand in for humans in the delivery and maintenance of some of the sensitive scientific tools that will be used to address these questions. Keeping the human explorer healthy, both physically and mentally, will thus be essential to ensure maximum scientific return. Doing

so, requires that additional scientific questions be addressed in preparation for and during these missions, including those related to the effects of radiation, low G, and isolated and confined conditions on the human systems. Coordinated mission plans that consider the interplay of key scientific questions for planetary science, astrobiology, and human exploration will enable humans to achieve the greatest knowledge return in 2023-2032.

IV. References

- Bartels, M. (2018, Aug. 22) Why We Can't Depend on Robots to Find Life on Mars. Retrieved from <https://www.space.com/41551-finding-mars-life-robots-versus-humans.html>
- Carroll, J. (2019) Do Humans Have a Future in Moon or Mars Gravity? *70th International Astronautical Congress*, Washington D.C.: International Astronautical Federation.
- Clancey, W. (2012) *Working on Mars: Voyages of Scientific Discovery with the Mars Exploration Rovers*. Cambridge, MA: MIT Press.
- Koren, M. (2020, Feb. 18). The Pros and Cons of a Lunar Pit Stop: NASA definitely wants to go to Mars. But does it need the moon to get there? Retrieved from <https://www.theatlantic.com/science/archive/2020/02/nasa-moon-mars-artemis/606499/>
- NASA. (2019). *America to the Moon by 2024 - NASA's FY 2020 Budget Amendment Summary* Retrieved from https://www.nasa.gov/sites/default/files/atoms/files/nasa_fy_2020_budget_amendment_summary.pdf
- NASA. (2020) *Human Research Roadmap*. Retrieved from <https://humanresearchroadmap.nasa.gov/Evidence/>
- National Research Council. (2011). *Vision and Voyages for Planetary Science in the Decade 2013-2022*. Washington, DC: The National Academies Press.
- Slakey, F. & Spudis, P.D. (2008, Feb. 1). Robots vs. Humans: Who Should Explore Space? *Scientific American*. Retrieved from <https://www.scientificamerican.com/article/robots-vs-humans-who-should-explore/>