Moon: Handle With Care

Rosemary M. Killen[1], LiHsia Yeo[1, 2], Yihua Zheng[1], Jason McLain[1], John Marshall[3], Liam Morrissey[4], Caitlin Ahrens[1,5], Phillip Phipps[1,5], Heather Graham[1], Timothy J. Stubbs[1]

[1] NASA Goddard Space Flight Center, Greenbelt, MD 20771, [2]NASA Postdoctoral Program, Goddard Space Flight Center, [3]SETI Institute, Mt. View, CA 94043 [4]Faculty of Engineering, Memorial University, St. John's, Newfoundland and Labrador, Canada, [5]Catholic University/CRESST II

Abstract

The exploration of the Moon involves multiple and complex competing interests, including those of nation states and commercial entities. The goal of this paper is to identify science questions with answers that may be obscured by human activities unless precautions are taken. We aim to encourage follow-on work to produce environmental impact assessments for various lunar activities in order to understand the degree of contamination generated by different processes. We also encourage the preservation of scientifically important regions, as proposed by others (e.g., Committee on Planetary Protection, 2020; Farrell et al., 2021; Krolikowski, 2023). In the following sections, we discuss what measurements are necessary to determine how and where science investigations and exploration (commercial or otherwise) can be carried out concurrently. We advocate a strategy of concurrent exploration and science where possible, and for a science-first approach in cases where exploration may obscure scientific evidence that is uniquely preserved on the Moon.

1. Introduction. The first question that has to be answered is "why go to the Moon". Is the purpose to establish a permanent human presence on the Moon, as a stopping-off place for Mars exploration, for National defense, or just because we can? The Moon has been discussed as a base for scientific endeavors for many years, including for geology, basic physics and astronomy (e.g. Wilson, 2005). Potter and Wilson (1990) stated that physics and astrophysics from a lunar base encompasses space physics, cosmic ray physics, neutrino physics, experiments in gravitation and general relativity, gravitational radiation physics, cosmic background radiation, particle astrophysics, surface physics, and the physics of gamma rays and X-rays. Specific issues include space-plasma physics research at a lunar base, prospects for neutral particle imaging, the atmosphere as particle detector, medium- and high-energy neutrino physics from a lunar base, muons on the Moon, a search for relic supernovae antineutrinos, and the use of clocks in satellites orbiting the moon to test general relativity. Also addressed are large X-ray-detector arrays for physics experiments on the moon, and the measurement of proton decay, arcsec-source locations, halo dark matter and elemental abundances above 10 exp 15 eV at a lunar base. It is clear that planning is necessary, as large-scale exploration can go hand-in-hand with science, or it can destroy the very evidence that scientists seek.

Corresponding Author: Rosemary M. Killen, rosemary.killen@nasa.gov, 301-286-6574

The scientific value of the Moon was outlined in The LEAG (Lunar Exploration Analysis Group) report: Advancing Science of the Moon (2017). Answers to the following science questions (Table 1) are held in the lunar environment. We have assigned a rating for the human effect on each. If the human effect is assumed to be none or unknown the rating is none; possible or uncertain human effect is possible, and definite human effect is definite. Those effects with either a possible or definite human effect are discussed in section 2. In addition to the concepts outlined in the LEAG report, we discuss the origin of life as evidenced by biotic and pre-biotic molecules found on the Moon.

Table 1. Science Questions whose answers are held in the lunar environment.

Concept	Title	Human Effect
1	Bombardment history of the inner solar system	none
2	Structure and composition of the lunar interior	none
3	Key planetary processes manifested in crustal rocks	possible
4	Lunar poles as witness to the history of the volatile flux	definite
5	Lunar volcanism as evidence of thermal and compositional history	none
6	Moon as laboratory for studying impact processes	definite
7	Moon as laboratory for studying regolith processes and weathering	definite
8	Processes involved with atmosphere and dust environment	definite

2.1 Concept 3: Processes manifested in crustal rocks

The Moon holds a repository of the history of the Earth-Moon system, whereas that history has been largely erased on Earth by the very processes that render Earth livable: active geological processes. The Moon may have a reservoir of implanted frozen volatiles that gives clues to how the Earth formed and how organics were delivered. The current level of depletion of moderately volatile elements constrains both the history of the solar rotation rate and the early lunar magnetic field (Saxena et al., 2019). Organics have mostly accumulated from meteorites and thus provide a historic record of contributions from meteoroids. Will it be possible to identify cometary organics and meteoritic organics vs. human organics once humans enter the lunar space? Are they preserved or lost? Details of the lunar subsurface reservoir – its content and depth - are important, not just for science but also for future human habitation. These details can easily be lost - for instance by dust disturbed by human activity, by rocket plumes, and by mining activity. On the other hand, mining interests and scientific interests can work hand-in-hand to determine the details of the reservoirs. We therefore should carefully plan these activities so that we don't destroy the evidence we seek.

2.2 Concept 4. Lunar polar volatiles as witness to the history of volatile flux: The case for studying polar volatiles before mining operations begin.

Can human activity on the Moon affect the measurement of water and other C and S species in the lunar cold traps?

Water is essential for life. It is also a resource for rocket fuel. By splitting the H_2O molecules into hydrogen gas molecules (H_2) and oxygen gas molecules (O_2) with an electrolyzer, and then compressing and liquefying both of those gases separately, fuel can be synthesized. O_2 is the oxidizer most commonly used in liquid-fueled rocket engines (Leucht, 2018). On the other hand, lunar polar volatiles serve as a unique inventory of volatiles that made up the Earth-Moon system. Collection of data on pristine polar water and the polar regolith is a key science priority, and also the number one priority for exploration. Not only are polar volatiles important for human consumption and other uses like rocket fuel, but they retain a historical account of how ice deposits were emplaced over time (Hurley et al., 2012). This will tell us whether the ice is replaceable, and if not, how long will it last for human consumption under what scenarios? The pristine lunar atmosphere tells us about the interaction of the interplanetary environment with the lunar surface, including the formation of water from the impinging solar wind protons, and its subsequent sequestration at the lunar polar cold traps. The rate of formation, sequestration and loss of water tells us an important piece of information: are the water ice reservoirs growing, in steady state, or being slowly depleted? Were the ice deposits delivered suddenly and massively by a large comet impact, slowly by meteoroid bombardment, or steadily by solar wind radiolysis? If this water is not a renewable resource, the users must develop and employ efficient recycling of water for human consumption, lunar agriculture and, most importantly, industrial processes. We need to know whether there is a lunar subsurface reservoir and if so, what is in it along with ice, and how deep is it. How much has been lost over time and how fast will it be lost during extraction? Will drilling for ice destroy the history of Its emplacement? We need to know how much there is, and how stable the deposits are, before we start mining. These details can easily be lost. Thus, it is essential to study the details of the polar ice deposits before large scale mining occurs (Farrell et al. 2021). However, science and exploration can exist side-by-side as scientists gain access to drill cores, especially exploratory drill cores at different sites.

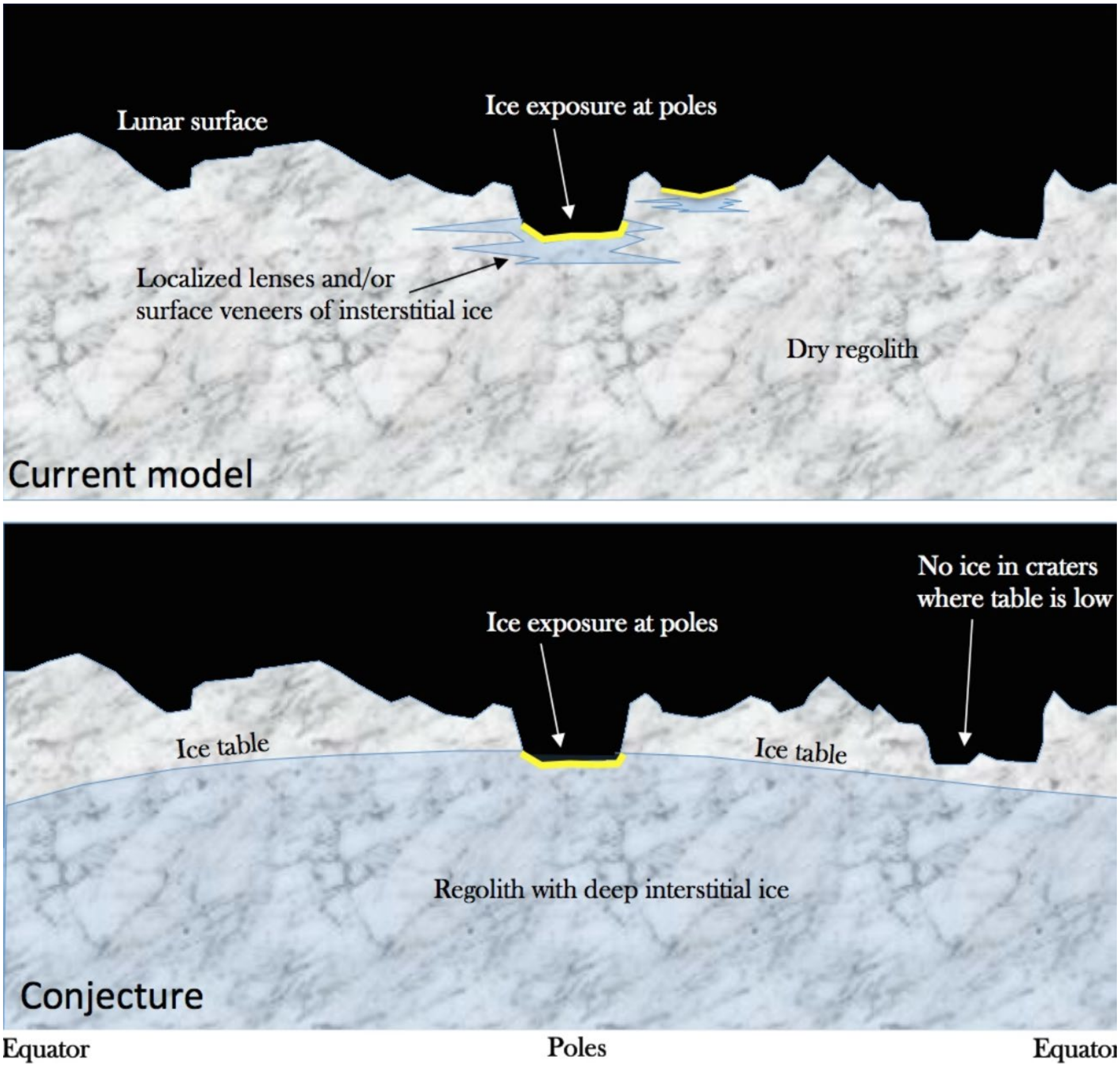

Figure 1. (a) The current model envisions the lunar polar ice as surface veneers of pure ice or of interstitial ice. (b) Figure 1 b. illustrates a model of regolith with deep interstitial ice below an ice table.

Figure 1a illustrates the current model of lunar polar ice: a surface veneer of pure ice or interstitial ice. Figure 1b illustrates a very deep and stable ice layer that has been in place since near the Moon's formation, similar to the thick ice/brine layer found by the Phoenix lander on Mars (Martinez and Renno, 2013). A definitive test of the origin of water on the Moon, and by inference the Earth, is the D/H ratio of lunar ice. If the D/H ratio is cometary then that implies a one-time origin of the ice. If the D/H ratio is solar, that implies a solar wind origin of the ice and continued renewal. Intermediate ratios might point to a meteoritic origin. Calculations must be made on the basis of the D/H ratio and the ice thickness and distribution to determine whether the ice is in equilibrium, shows a net accumulation rate or a net loss rate. How deep is the ice layer? Where are the ices? Are there paleo deposits associated with the former lunar poles? Are the ices contaminated?

In addition, lunar prospectors will likely want to know what the ice is made of and whether it is of a high grade—that is, not too dusty or otherwise contaminated. What contaminants are there and in what amounts? Some comets may have on the order of 5 percent cyanide in their cores (Ulich and Conklin, 1974; Matthews, C.N. and Minard, R.D., 2006). In addition, Mercury (Hg) is the second most volatile species on the Moon (Jovanovic and Reed, 1972; 1982) and will undoubtedly be sequestered in the same places as the water (Hodges, 1982; Reed, 1999). These factors are critical to know in advance of large-scale mining operations.

Although human activities on the Moon have little or no effect on the lunar interior, the pristine lunar atmosphere holds information on the deep interior through radioactive decay products, such as ^{40}Ar and ^{40}Ca from ^{40}K. The isotopic ratios can give us information on the source(s) of lunar volatiles, for instance comets, meteoroids, the solar wind, and the interior of the Moon. The D/H ratio found on the Moon is key to the origin of the lunar hydrogen: is it cometary, solar or endogenous? Answers to these and other questions held by the pristine lunar atmosphere will be quickly lost as massive rocket exhaust as well as slow but steady leakage overwhelms the original exosphere and surface. It is therefore essential to measure the isotopic ratios as soon as possible and at every region visited.

From the lunar volatiles, we can learn not only about the Moon but also about the Sun and its variation both on the short term and over millennia. Information on the past solar activity is preserved on the Moon and this information is fragile. Short term variation of the solar and galactic radiation is vitally important to assess risk to astronauts as well as instruments on and around the Moon. This must be assessed, and predictive methods need to be improved before large scale habitation can be undertaken. A 5-meter core sample taken before large scale mining operations would be a vital resource to scientists interested in the origin and evolution of the solar system (Crider and Vondrak, 2003).

Prem and Hurley (2019) show that a Chang'e 3-class lander can increase the local exosphere density by several orders of magnitude. The molecular concentrations in the exosphere and regolith will change progressively as the frequency and type of landers increase. Spacecraft outgassing observed by the Bepi Colombo in spectrometers was dominated by water molecules, and was observed not only during the Mercury flybys but also during cruise phase (Franz et al., submitted). Outgassing by the Rosetta spacecraft (Schlappi et al., 2010) maintained a permanent thin gas cloud around the spacecraft for many years, dominated by water, but also containing hydrocarbon compounds, nitrogen-bearing compounds, halogen and sulfur-bearing molecules. As instruments warm the outgassing increases. The rovers, landers, astronaut backpacks and clothing will all contribute background gas that will eventually be trapped in the regolith and ice.

2.3 Concept 6. The Moon as a laboratory for studying impact processes

Lunar landings result in dust and rocks being blown away to great distances, as well as the production of small craters under the rocket plume (Metzger, 2020; Watkins et al., 2021). In addition to small impact craters, there are other chronological signatures of lunar evolution that may not be as obvious or accessible from Earth or orbiting platforms, and these may be at risk, not only from collateral damage from exploration in the interest of science but by exploitation of resources (Scotkin et al., 2022). Signatures of lunar history that may be destroyed include bombardment, especially by small impactors (Holcomb et al., 2024), volcanism, CME (Coronal Mass Ejection), and SEP (Solar Energetic Particle) frequency with time (Phipps et al., 2022), and evidence of the history of the lunar paleo-magnetic field (Sauvet et al, 2013; Saxena et al., 2019).

2.4 Concept 7. The Moon as a laboratory for studying regolith processes

The study of regolith processes can be accomplished through means of modeling, remote sensing observations, laboratory experiments, and returned sample analyses (from the Apollo era and other spacecraft) (Papike et al. 1982; Schreiner et al. 2016; Metzger et al. 2018). The anthropogenic processes that may influence these volatiles would certainly be another challenge when collecting regolith and volatile samples. Rovers, landers, ascent – descent vehicles, and human activity (e.g., mobility, tool usage, etc.) would have several influences on the lunar regolith environment: (i) dust transport; (ii) outgassing; (iii) electricity; (iv) regolith porosity.

Dust transport through rover and astronaut mobility and use of tools also pose an interesting challenge of electrical discharge. Such discharge may depend on the tool used, but influence of electrical and magnetic output from these tools (and scientific payloads in general) would need to be monitored at the lunar surface. The interactions between the ambient space plasma environment and crustal magnetic fields (Halekas et al. 2011, 2015], as well as electrostatic fields at the lunar surface (Zimmerman et al. 2011; Stubbs et al. 2014; Fatemi et al. 2015] are still poorly understood, especially at the lunar poles or lunar swirls (which is also a region of interest for future exploration [Robinson et al. 2018]). Such anthropogenic interactions of rovers and scientific equipment may disrupt the ambient, natural lunar environment. This may inadvertently disrupt solar wind interactions through varying degrees of charged dust enhanced by human and robotic activity, which in turn may transport energetic particles (from stated exploration activity) to the regolith, volatiles (causing more insulation from dust coverings), and potentially lunar swirls (Jackson et al. 2011; Futaana et al. 2013; Haviland 2021; Cucinotta & Saganti 2023; Lorenz et al. 2023].

Dust transport through anthropogenic activity is a challenge on several factors to exploration. Dust can be mobile through walking movements, roving, tools (such as drills), and ascent/descent vehicle activity (Cain 2010; Chunjian 2023). This includes hazards on many levels, such as to astronaut health, decrease in power (e.g., solar cell) efficiency (Katzan & Edwards 1991), coverings (which can also be a tripping hazard) and decreasing efficiency in tool usage, and decrease in suit capabilities.

Outgassing of materials, whether through the ascent/descent stages of lunar vehicles, rover or astronaut suit depressurizing, may cause an effect of unwanted accumulation of volatiles at the surface. This is especially important at (or proximal) to PSRs at the lunar poles. Astronaut suits produce some level of oxygen outgassing (Helou et al. 2022), which may transport and condense in these PSRs, even in micro-cold traps (Glavin et al. 2010).

Regolith porosity is an important parameter in light scattering, and sputter yield with incidence angle. The highly porous extreme surface is easily destroyed by rovers, dust and rocks thrown out by landers, and astronaut maneuvers. Care should be taken especially at high latitude regions and near the lunar swirls where "fairy castle" surfaces are possible.

2.5 Concept 8. Processes involving the atmosphere and dust environment

Temporary atmospheres result from various anthropogenic sources. Table 2 below lists the anthropogenic sources and their compositions. Depending on the frequency of each type of source, the anthropogenic atmosphere will be temporary or permanent.

Table 2. Source Compositions

Source	**Composition (by mass)**	
xEMU (Backpack)	100% H_2O	
Airlock (P_{atm} = 14.7 psia)	23.301% O_2, 76.699% N_2	
Airlock (P_{atm} = 10.2 psia)	29.711% O_2, 70.289% N_2	
Airlock (P_{atm} = 8.2 psia)	37.057% O_2, 62.943% N_2	
Mining	100% H_2O	
Trash	56.7% CO_2, 6.8% CO, 36.6% CH_4	
Large-CH4-O2 Rocket Exhaust	45% H_2O	46% CO_2, 8.5% CO
Large H2-O2 Rocket Exhaust	97% H_2O	3% H_2
Small-Rocket Exhaust	21% H_2O	42% N_2, 30% CO_2, 3.9% CO

Killen et al. (2024) estimated the composition and column abundance of exospheres created by outgassing from human sources on the Moon. These include astronaut backpacks, airlocks, mining of water ice to produce oxygen, trash incineration, rovers and landers. Water is the most abundant source, but other sources include O_2 and N_2 from airlocks, CO_2, CO, and CH_4 from trash. Large rocket plumes are either purely H_2O, H_2O and CO_2. Small rocket plumes include H_2O, N_2, CO_2 and CO. All of these sources produce temporary exospheres that may contaminate the search for the pristine exosphere, most notably the indigenous water. H_2O, O_2 and N_2 anthropogenic sources are much greater than the pristine exosphere, although they are local and transient.

Table 3. Resulting Exospheric Column Abundances from various sources

Source	**Gas**	**Column Abundance (cm^{-2})**	**Notes**
Rover	H_2O	$5x10^4$ - $2x10^8$	VIPER Size
Mining of ice for O2	H_2O	2 - 6 $x10^8$	Assumes 10% loss
Trash incineration	CO_2 CH_4 CO	$7x10^7$ - $1x10^8$ 3 2.6 - 6.6 $x10^8$ 9 $x10^7$	Assumes no gas sequestration
Lander	H_2O	$1x10^{10}$	Chang'E 3 size
Starship Lander	H_2O	$1x10^7$ - $3.4x10^{10}$	Thermal, polar lander
Airlock	O_2 N_2	$7x10^9$ - $3x10^{10}$ 1 - 2 $x10^{10}$	Various designs

At least five electrical phenomena are in need of further study before large scale human activity commences on the Moon. These include (1) natural solar wind-induced charging on the sunlit side caused by the photoelectric effect that produces a positive charge on the dayside; (2) natural charging of the dark side or in shadows; (3) anthropogenic triboelectric charging of equipment, structures and spacesuits (e.g. Stubbs et al., 2007) a known phenomenon but poorly understood for the lunar environment; and (4) the terminator expression of these charging effects, also a poorly understood phenomenon, especially with respect to the various changing solar conditions. There is no equivalent of Earth for grounding on the Moon.

Study of the electrostatic environment on the Moon is of vital importance, not only for the science content but because of the threat of charging – and discharging – to astronauts and their equipment (Zimmerman et al., 2001; Jackson et al., 2011). A comprehensive study of several locations near the polar regions is required to learn how to protect machinery and astronauts.

2.6 Science Questions: Organics

2.6.1 Lunar Organics Are Clues to the Origin of Life

The origin and proliferation of life in our solar system is a profound question that continues to be one of the most important avenues of scientific inquiry. On Earth, historical records of this process have been all but wiped out due to active geological processes and the wide reaches of biological activity (Fedo and Whitehouse, 2002, Lepland et al., 2005). The Moon, however, holds a repository of the history of the Earth-Moon system, (Armstrong et al., 2002, Crawford et al., 2008), preserved in dry vacuum conditions. At the poles, the Moon may have a reservoir of implanted frozen volatiles (Basilevsky et al., 2012) that gives clues to how the Earth formed and how organics could have proliferated throughout our solar system (Matthewman et al., 2015). Such knowledge is important in the search for the origin of life. A recent study reported the possible existence of niches in the South Pole that microbes can survive in (Saxena et al., 2023a,b).

It is therefore of incredible importance that the evidence described above is available for careful study. Human activity on the Moon, if not performed with care, threatens to compromise the integrity of precious evidence that could point to the origin of life. Many profound scientific questions depend on the availability of pristine lunar samples: Did organics survive on the Moon and to what extent can they survive today? Is there a pre-biotic inventory sequestered in the ice? If biotic and/or prebiotic molecules survive on the Moon, will these bacteria prove to be harmful to astronauts, human, plant, and animal species or does this imply that life can survive on the Moon? Lunar polar regions may provide an inventory of volatiles and possibly pre-biotic organic materials carrying evidence for the formation/evolution of life. Even the absence of significant amounts of organics would be a profound finding that will spur better understanding of the origins of life. We argue that keeping that evidence relatively uncontaminated by future lunar landings until the inventory can be measured is therefore crucial.

2.6.2 Important Historical Records in Lunar Organics

Besides holding key information about the proliferation of organic matter and even life in the Solar System, the detection of organic molecules on the Moon has important implication for other aspects of our Solar System's history. The current level of depletion of moderately volatile elements constrains both the history of the solar rotation rate and the early lunar magnetic field (Saxena et al., 2019). Organics have been thought to have mostly arrived from meteorites and interplanetary dust (Alexander et al., 2010, Quirico et al., 2013, Thomas-Keprta et al., 2014) and thus provide a historic record of contributions from meteoroids. Will it be possible to identify cometary organics and meteoritic organics vs. human organics once humans enter the lunar space? Are they preserved or lost? Details of the lunar subsurface reservoir – its content and depth - are important, not just for science but also for future human habitation. These details can easily be lost - for instance by dust thrown up by human activity, by rocket plumes, and by mining activity. On the other hand, mining interests and scientific interests can work hand-in-hand to determine the details of the reservoirs. We therefore should carefully plan these activities so that we do not destroy the evidence we seek.

2.6.3 Implications for Human Habitation of the Moon

Will humans introduce bacteria or other organisms that will survive on the Moon and other planetary bodies? Studies designed to search for biologically-derived organic compounds could provide ground truth data and help define planetary protection requirements for future missions to the Moon and Mars (Glavin et al., 2010). A variety of microorganisms have been found to survive the harsh conditions outside the International Space Station (Deshevaya et al., 2024), further raising the stakes for possible cross-contamination. There is therefore a significant need to understand not only the possible impact that human presence can have on organics on the Moon, but also the impact that the survival of organics and even organisms on the Moon could have on human inhabitants. These are not only scientifically important, but also existential questions that we need to address prior to human habitation.

3. Conclusions: Last Chance for the Moon

We define the beginning of the Anthropocene for planet Earth as having a geological signature containing a radiation level in sediments worldwide created by nuclear bomb testing in the middle of the last century. The Moon is about to enter its own Anthropocene (Holcomb et al., 2024) which might be marked by one of our study areas. This could be a dust layer containing hydrazine chemistry that becomes ubiquitous on the Moon. Potential sources of contamination during the Apollo missions were noted by Simoneit and Flory (1970) including dimethyl hydrazine and nitrogen tetroxide, lunar module outgassing, astronaut spacesuit venting of life support backpacks, particulates from spacesuits, and venting from the lunar module fuel and oxidizer tanks. Water extracted from lunar soils collected by the Apollo astronauts was determined to be of terrestrial origin (Epstein and Taylor, 1972). Before large scale contamination happens, we need to address the scientific questions, the answers to which are held at the surface and near surface of the Moon. Crawford et al. (2022) have suggested that the best compromise between scientific investigation and commercial exploration and utilization of resources would be to place a moratorium on activities at the North Pole until the full consequences of human activities at the South Pole are understood. In addition, we suggest that a moratorium be placed on use of frequencies on the far side of the Moon that would interfere with radio and astronomical observations. Important scientific questions whose answers are held in the pristine Moon include the early Earth history, organic reactions in ices, and the origin or organics brought in by meteoroids.

What should we seal off from human presence on the Moon, and how will that be different at Mars? Moon restrictions (Special Regions) need to be kept pristine (Kelso and O'Leary, 2011).

However, it is recognized that it is a matter of degree what it means to be pristine, and to what degree this is possible, since gases travel quickly around the globe and dust does something similar. Given that rapid deterioration is almost certain once spacecraft landings on the Moon become routine, lunar science missions such as VIPER should be prioritized.

We advocate planetary conservation for the Moon, meaning the proper use of natural resources. Actions that need to be limited or contained long enough to understand and mitigate threats to the science topics noted above include but are not limited to:

Short to medium term **particulate contamination** of the exosphere (i.e. dust, pebbles and rocks) is caused by erosion of regolith by spacecraft engines, construction, mining and or quarrying. It physically alters the surface physics and chemistry of the region. The dust hazard is global, and the projectile hazard is local.

Rocket fuel contamination of the environment. Non-reversible chemical reactions with water and other surface compounds pollute the environment.

Physical disturbance of geological features and regolith by astronaut tramping, rovers, landers and other vehicles and machinery transform the geological environment and erase scientifically important data.

Chemical contamination of regolith and PSRs by rocket exhaust, machinery, vehicles, and human and industrial waste is an irreversible process.

Acknowledgments

This work was supported by the NASA Solar System Exploration Research Virtual Institute, United States (SSERVI LEADER: Lunar Environment and Dynamics for Exploration Research).Yeo's research was supported by an appointment to the NASA Postdoctoral Program at the NASA Goddard Space Flight Center, administered by Oak Ridge Associated Universities under contract with NASA. C. Ahrens was supported by NASA's Lunar Reconnaissance Orbiter (LRO) award number 80GSFC21M0002. P.H. Phipps is supported by NASA's LRO mission under award number 80GSFC21M0002.

References

Alexander, C. M. O. D., Russell, S.S., Arden, J.W., Ash, R.D., Grady, M.M., and Pillinger, C.T. 1998. The origin of chondritic macromolecular organic matter: a carbon and nitrogen isotope study. *Meteorit Planet Sci* 33:603–622.

Armstrong , John C., Wells , Llyd E., Gonzalez, Guillermo, 2002. Rummaging through Earth's Attic for Remains of Ancient Life, Icarus, Volume 160 # 1, 183-196, ISSN 0019-1035, https://doi.org/10.1006/icar.2002.6957.

Basilevsky, A.T., Abdrakhimov, A.M. & Dorofeeva, V.A. 2012. Water and other volatiles on the moon: A review. *Sol Syst Res* **46**, 89–107. https://doi.org/10.1134/S0038094612010017

Burns, J. O. et al., Dark Cosmology: Investigating Dark Matter & Exotic Physics in the Dark Ages using the Redshifted 21-cm Global Spectrum. 2019. *arXiv* preprint arXiv:1902.06147.

https://doi.org/10.48550/arXiv.1902.06147

Burns, J. O. 2020. Transformative science from the lunar farside: observations of the dark ages and exoplanetary systems at low radio frequencies. *Philos. Trans. Royal Soc. A Math. Phys. Eng. Sci.* **379**, doi: 10.1098/rsta.2019.0569

Cain, J. R. 2010. Lunar dust: the hazard and astronaut exposure risks. *Earth, Moon, and Planets*, *107*(1), 107-125. doi: 10.1007/s11038-010-9365-0

Chunjian, P. A. N. 2023. A module based modeling framework for estimating lunar dust deposition due to human activities. *Chinese Journal of Aeronautics*. doi.org/10.1016/j.cja.2023.11.003

Committee on Planetary Protection, National Academies of Sciences, Engineering, and Medicine 2020. Report Series: Committee on Planetary Protection: Planetary Protection for the Study of Lunar Volatiles. Washington, DC: The National Academies Press. https://doi.org/10.17226/26029.

Crawford I.A., Baldwin E.C., Taylor E.A., Bailey J.A., and Tsembelis K. 2008. On the survivability and detectability of terrestrial meteorites on the Moon. *Astrobiology* 8:242–252. doi: 10.1089/ast.2007.0215

Crawford, I. A., P. Prem, Carle Pieters, and Mahesh Arnand 2022. Managing Activities at the lunar poles for science. *Space Research Today*, 215, 45 – 51.

Crider, D. H. and R. R. Vondrak. 2003. Space weathering effects on lunar cold trap deposits. Journ Geophys. Res. 108 #E7, doi.org/10.1029/2002JE002030

Cucinotta, F. A., & Saganti, P. B. 2023. Radiation Environment of the Moon: Human Radiation Protection Issues for Extended Missions to the Lunar Surface. In *Encyclopedia of Lunar Science* (pp. 997-1006). Cham: Springer International Publishing.

Deshevaya, E.A., Fialkina, S.V., Shubralova, E.V. *et al.* 2024. Survival of microorganisms during two-year exposure in outer space near the ISS. *Sci Rep* **14**, 334. https://doi.org/10.1038/s41598-023-49525-z

Epstein, S. and H. P. Taylor, Jr. 1972. O18/O16, Si30/Si28, C13/C12, and D/H studies of Apollo 14 and 15 samples, in *Proceeding 3rd Lunar Science Conference* (1972), pp. 1429–1454.

Farrell, W. M. & 18 C0-Authors. 2021. Lunar polar volatile resources: Obtaining their origin prior to extraction. *BAAS* 53 #4. Doi: 10.3847/25c2cfeb.8300680a

Fatemi, S., Lue, C., Holmström, M., Poppe, A. R., Wieser, M., Barabash, S., Delory, G. T. 2015. Solar wind plasma interaction with Gerasimovich lunar magnetic anomaly. *Journ. Geophys. Res.: Space Physics*, *120*(6), 4719-4735. doi: 10.1002/2015JA021027

Fedo, Christopher M., Whitehouse, Martin J., Metasomatic Origin of Quartz-Pyroxene Rock, Akilia, Greenland, and Implications for Earth's Earliest Life.*Science* **296**,1448-1452(2002). doi:10.1126/science.1070336

Franz, M. et al. 2023. Spacecraft outgassing observed by the BepiColombo ion spectrometers. Journ *Geophys Res. Space Physics*. In review.

Futaana, Y., Barabash, S., Wieser, M., Lue, C., Wurz, P., Vorburger, A., et al. 2013. Remote energetic neutral atom imaging of electric potential over a lunar magnetic anomaly. *Geophysical Research Letters*, *40*(2), 262-266. doi:10.1002/grl.50135

Glavin, D. P. et al., 2010. In situ biological contamination studies of the Moon: Implications for planetary protection and life detection missions. *Earth Moon and Planets* 107, 87-93. Doi: 10.1007/s11038-010-9361-4.

Halekas, J. S., Saito, Y., Delory, G. T., & Farrell, W. M. 2011. New views of the lunar plasma environment. *Planetary and Space Science*, *59*(14), 1681-1694. doi:10.1016/j.pss.2010.08.011

Halekas, J. S., Brain, D. A., & Holmström, M. 2015. Moon's Plasma Wake. In *Magnetotails in the solar system*, Geophysical Monograph Series, pp. 149-167. doi: 10.1002/9781118842324.ch9

Haviland, H. F. 2021. The Changing Lunar Surface Environment: Hazards and Resources. *The Human Factor in the Settlement of the Moon: An Interdisciplinary Approach*, ch 3. 43-53. doi: 10.1007/978-3-030-81388-8

Helou, E. M., Wang, J., & Brieda, L. 2022. Spacesuit Outgassing and Its Effects on Electrostatic Discharge/Arcing: Laboratory Investigations. In *AIAA SCITECH 2022 Forum* (p. 2185). View Video Presentation: https://doi.org/10.2514/6.2022-2185.vid

Hodges, R. R. 1982. Migration of volatiles on the lunar surface, *LPSC XII*, pp. 451-453.

Holcomb, J. A., R. D. Mandel and K. W. Wegmann, 2024. The case for a lunar anthropocene. *Nat. Geoscience* 17, 2-4, doi: 10.1038/s41561-023-01347-4.

Hurley, D. M., D. J. Lawrence, D. B. Bussey, R. R. Vondrak, R. C. Elphic, and G. R. Gladstone, 2012. Two-dimensional distribution of volatiles in the lunar regolith from space weathering simulations. Geophys. Res. Lett. 39, L09203, doi:10.1029/2012GL051105.

Jackson, T. L., W. M. Farrell, R. M. Killen, G. T. Delory, J. S. Halekas and T. J. Stubbs. 2011. Discharging of roving objects in the lunar polar regions. *Journal of Spacecraft and Rockets*, 48 #4. doi: 10.2514/1.51897

Jovanovic, S. and G. W. Reed, Jr. 1972. Trace element profiles, Notably Hg, From a preliminary study of the Apollo 15 deep-drill core. *Earth and Planet. Sci. Lett.* 16, 257-262, 1972.

Jovanovic, S. and G. W. Reed, Jr. 1982. Trapping of gases and low temperature volatiles in lunar samples. *Conference on Planetary Volatiles,* Alexandria, VA. 1982 LPI Co. 488, pp. 54-55.

Katzan, C. M., & Edwards, J. L. 1991. *Lunar dust transport and potential interactions with power system components* (No. NAS 1.26: 4404). NASA.

Kelso R, & B. O'Leary. 2011. NASA's Recommendations to space-faring entities: how to protect and preserve historic and scientific value of US government artifacts. NASA's Human Exploration & Operations Directorate, Strategic Analysis & Human Integration Division, NASA Headquarters: Washington, D C.

Krolikowski, Alanna. 2023. Time to protect scientific opportunity on the Moon, *Nature Astronomy*, 7, 637-639. doi: 10.1038/s41550-023-02002-z

Kuhns, M. & 11 co-authors. 2021. Deep regolith cratering and plume effects modeling for lunar landing sites. *ASCE Earth and Space Conference*, April 19-23, 2021.

Lepland, Aivo, van Zuilen, Mark A., Arrhenius, Gustaf, Whitehouse, Martin J., Fedo, Christopher M. 2005. Questioning the evidence for Earth's earliest life—Akilia revisited. *Geology*, 33 (1): 77–79. doi: https://doi.org/10.1130/G20890.1

Matthewman, Richard, Court, Richard W., Crawford, Ian A., Jones, Adrian P., Joy, Katherine H. and Sephton, Mark 2015. The Moon as a Recorder of Organic Evolution in the Early Solar System: A Lunar Regolith Analog Study. Astrobiology 15 #2, 154-168. http://doi.org/10.1089/ast.2014.1217

Lunar Exploration Analysis Group. 2017. Advancing Science of the Moon: Report of the Specific Action Team. LEAG 2017, held 7-8 August 2017, Houston, Texas, 2017.

Leucht, K. W. 2018. "How NASA will use robots to create rocket fuel on Mars: The year is 2038," in *IEEE Spectrum*, 55, # 11, pp. 34-39, Nov. 2018, doi: 10.1109/MSPEC.2018.8513782.

Lorenz, C. A., Basilevsky, A. T., Dolgopolov, V. P., & Kozlova, T. O. 2023. Estimation of the Influence of Contamination by Rocket Fuel Combustion Products on the Chemical and Isotopic Composition of the Lunar Regolith in the Polar Regions. In *Advances in Geochemistry, Analytical Chemistry, and Planetary Sciences: 75th Anniversary of the Vernadsky Institute of the Russian Academy of Sciences* (pp. 411-423). Cham: Springer International Publishing.

Martínez, G. M., Renno, N. O. 2013. Water and Brines on Mars: Current Evidence and Implications for MSL. *Space Sci. Rev*. 175, 29–51. https://doi.org/10.1007/s11214-012-9956-3

Matthews, C.N. and Minard, R.D., 2006. Hydrogen cyanide polymers, comets and the origin of life. *Faraday discussions*, 133, pp.393-401. doi: 10.1039/b516791d

Metzger, P. T., Anderson, S., & Colaprete, A. 2018. Experiments indicate regolith is looser in the Lunar polar regions than at the lunar landing sites. In *16th Biennial International Conference on Engineering, Science, Construction, and Operations in Challenging Environments* (pp. 79-85). Reston, VA: American Society of Civil Engineers.

Metzger, P. T. 2020. *Lunar Dust on Human Exploration Workshop*, Houston, TX, Abstract #5040.

Outer Space Treaty (UN Resolution 2222 (XXI) *Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies,* United Nations Office for Outer Space Affairs, 1966.

Papike, J. J., Simon, S. B., & Laul, J. C. 1982. The lunar regolith: Chemistry, mineralogy, and petrology. *Reviews of Geophysics*, *20*(4), 761-826. Paper 2R0812.0034-6853/82/002R-0812

Phipps, P. H., T. J. Stubbs, M. D. Loper, H. E. Spence and L. W. Townsend, 2022. Mapping biologically relevant radiation dose around the lunar south pole. *LEAG 2022*, *LPI Contrib*. 2696.

Potter, A. E. and T. L. Wilson, 1990. Physics and Astrophysics from a Lunar Base. *AIP Conf. Proc.* 202, [Ed. A. E. Potter and T.L. Wilson], Am. Inst. Phys., N.Y.

Prem, P. and D. M. Hurley. 2019. Modeling the Response of the Lunar Exosphere to the Release of Spacecraft Exhaust Volatiles. *SSERVI Exploration Sci. Forum*, Abstract #NESF2019-025.

Quirico E., Raynal P.I., and Bourot-Denise M. 2003. Metamorphic grade of organic matter in six unequilibrated ordinary chondrites. *Meteorit. Planet. Sci.,* 38:795–811.

Reed, G. W., Jr. 1999. Don't Drink the Water. *Met. Planet. Sci.,* 34, 809-811.

Robinson, M. S., Thangavelautham, J., Anderson, B. J., Deran, A., Lawrence, S. J., Wagner, R., ... & Genova, A. L. 2018. Swirl mission concept: Unraveling the enigma. *Planetary and Space Science*, *162*, 73-88. https://doi.org/10.1016/j.pss.2018.05.017

Sauvet, C. + 9 Co-authors. 2013. Persistence and origin of the lunar core dynamo. *Proceedings of the National Academies of Science,* 110, 8453-8458. /doi/10.1073/pnas.1300341110

Saxena, P., H.V. Graham, S. Bertone, A. Regberg, N. M. Curran, D. B. Pugel, A. Needham, and N. E. Petro. 2023a. Identifying potentially survivable niches and areas of high biological interest on the lunar south pole. *LEAG 2023*.

Saxena, P. et al.. 2023b. Habitable Niches for Microbial Life on the Lunar Poles. *NASA Exploration Science Forum,* 2023.

Saxena, P., R. M. Killen, V. Airapetian, N. E. Petro, N. Curran, and A. M. Mandell. 2019. Was the sun a slow rotator: Sodium and Potassium Constraints from the Lunar Regolith. *Astrophys. Journ. Lett.,* doi:10.3847/2041-8213/ab18fb.

Schlappi, B. et al., 2010. Influence of spacecraft outgassing on the exploration of tenuous atmospheres with in situ mass spectrometry. *Journ. Geophys. Res*. 115, A12313. doi.org/10.1029/2010JA015734

Schreiner, S. S., Dominguez, J. A., Sibille, L., & Hoffman, J. A. 2016. Thermophysical property models for lunar regolith. *Advances in Space Research*, *57*(5), 1209-1222. doi:10.1016/j.asr.2015.12.035

Scotkin, M., S. Beard, and M Kuhn. 2022. Cratering effects of hot and cold gas rocket plumes on frozen and unfrozen simulated lunar regolith. *53rd Lunar and Planetary Sci. Conf*., Abstract 1300.

Simoneit, B. and D. Flory, 1970. Apollo 11, 12, and 13 Organic Contamination Monitoring History, *UC BerkeleyReport to NASA*.

Stubbs, T. J., Farrell, W. M., Halekas, J. S., et al. 2014. Dependence of lunar surface charging on solar wind plasma conditions and solar irradiation. *Planetary and Space Science*, *90*, 10-27. http://dx.doi.org/10.1016/j.pss.2013.07.008

Stubbs, T. J., R. R. Vondrak and W. M. Farrell. 2007. Impact of dust on lunar exploration. *Proc. Workshop on Dust in Planetary Systems*, Sept. 26-30, 2005, Kauai, Hawaii [ESA SP-643, Krueger, H. and Graps, A., Eds.], p 239-243.

Thomas-Keprta, Kathie L., Simon J. Clemett, Scott Messenger, Daniel K. Ross, Loan Le, Zia Rahman, David S. McKay, Everett K. Gibson, Carla Gonzalez, William Peabody, 2014. Organic matter on the Earth's Moon, Geochimica et Cosmochimica Acta, 34, 1-15, https://doi.org/10.1016/j.gca.2014.02.047.

Tronchetti, Fabio. 2015. The Space Resource Exploration and Utilization Act: A move forward or a step back? *Space Policy* 34, 6-10. doi:10.1016/j.spacepol.2015.08.001

Ulich, B. & E. Conklin. 1974. Detection of methyl cyanide in Comet Kohoutek. *Nature* **248**, 121–122. https://doi.org/10.1038/248121a0

Watkins, R. N. & 10 Co-authors. 2023. Understanding and mitigating plume effects during powered descents on the Moon and Mars. A White Paper submitted to the Planetary Science Decadal Survey 2023-2032.

Wilson, T. L. 2005. Physics and Astrophysics from the Moon, *LPI Contribution* 1318.

Zimmerman, M. I., W. M. Farrell, T. J. Stubbs, J. S. Halekas, and T. L. Jackson. 2011. Solar wind access to lunar polar craters: Feedback between surface charging and plasma expansion. *Geophys Res. Lett*. 38 #19 https://doi.org/10.1029/2011GL048880