Astrobiology on the Moon: Learning About the Early Earth While Preparing for Mars. A. Z. Longo[1], B. Damer[2], A. Gangidine[3], [1]The University of North Carolina at Chapel Hill (417 Tharps Lane, Raleigh, NC; azlmsr701@gmail.com), [2]The University of California at Santa Cruz, [3]U.S. Naval Research Laboratory.

Introduction: The search for microbial life on other worlds has been listed as the primary objective for NASA's planetary exploration program [1]. The search for life is also a topic of interest for stakeholders in the general public [2]. The Artemis Program is a bold plan which has the potential to advance several areas of research, including astrobiology [3]. Although it most likely has never hosted life, the Moon serves as a repository for the history of the inner Solar System. Several key astrobiology objectives can only be accomplished in the unique environment of the lunar surface. We propose that crewed lunar missions, beginning with Artemis III in 2024, should address three astrobiology objectives.

1. Determine which prebiotic organic molecules might have been delivered to Earth by impactors.

2. Search for Hadean impact ejecta which contains biosignatures older than any preserved on Earth.

3. Quantify the contaminants which are introduced to a planetary environment by astronauts and their machines in preparation for the human exploration of Mars.

Objective 1: Prebiotic Organics: One prerequisite for the presence of biosignatures on a planet or moon is its ability to support the emergence of life from prebiotic ingredients. Origin of life theories, developed to explain the development of life on Earth, are also highly relevant to the discipline of astrobiology [4]. Two leading alternative hypotheses postulate that the first protocells emerged at hydrothermal sites. The first states that life emerged from disequilibria conversions via electron bifurcation in submarine hydrothermal vents [5]; the second proposes that the first protocells formed in terrestrial hot springs though the process of wet-dry cycling [6].

Abiogenesis requires an ample supply of carbon-based organic compounds. These are naturally produced through catalytic processes in submarine vents, but they must be delivered to hydrothermal fields from exogenous sources. Specifically, the hot spring origins of life hypothesis postulates that meteoritic organics were a key ingredient for the first protocells [6]. Although this assertion is supported by the composition of chondritic meteorites, the identity and quantity of the organic molecules delivered to Earth during the Hadean remains unknown. The impactors which delivered the bulk of these compounds were most likely carbonaceous asteroids and comets orders of magnitude larger than the small meteorites found in Antarctica.

The polar regions of the Moon contain large deposits of water ice within permanently-shadowed craters [e.g., 7]. The Artemis Base Camp will be located at the lunar South Pole, near several of these deposits [3]. Lunar ice was most likely deposited by the same planetesimals which delivered Earth's surface water [8]. Therefore, the permanently-shadowed regions at the South Pole might also preserve a record of the organic compounds which entered the Earth-Moon system during the Hadean. Water ice would have protected these compounds from cosmic radiation.

If samples of the polar ice deposits are returned to Earth, astrobiologists will be able to create a comprehensive list of the organic molecules which were present on the Hadean Earth. This investigation will complement and improve upon results from meteorite studies, as lunar organics were deposited by larger objects experiencing a greater thermal flux. If substantial quantities of organic molecules are found on the Moon, they would support the hot spring origins of life hypothesis; conversely, their absence would weaken it and bolster the submarine vent hypothesis.

Objective 2: Hadean Earth Meteorites: The disputed discovery of an Earth meteorite in an Apollo 14 breccia sample [9] presents a novel approach to the study of the early Earth. 4.6 billion years of tectonic, hydrologic, and aeolian activity have largely erased the Hadean rock record. However, the numerous impacts of the Late Heavy Bombardment ejected numerous ancient rocks into Earth orbit. An estimated eight million tons of Earth meteorites were collected by the Moon's gravitational field [10].

In addition to enabling fundamental discoveries about Earth's initial geology and atmospheric chemistry, additional Earth meteorites collected by Artemis astronauts could advance hypotheses about the emergence of life on Earth [4]. Currently, the most ancient biosignatures known date from the Archaean period. Arguably, the most convincing of these are stromatolitic textures and putative biogenic organics from the from ancient hot spring deposits found in the 3.4-Ga Dresser Formation in Australia's Pilbara region. These discoveries represent the oldest evidence of life on land, if not on Earth in general [11, 12].

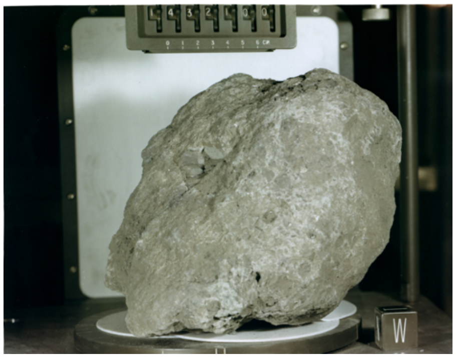

Figure 2: Apollo 14 breccia sample 14301 may contain an Earth meteorite fragment (NASA/JSC).

Some have argued that the supposed Earth meteorite collected during Apollo 14 formed on the Moon rather than on Earth. If does have a terrestrial origin, the 4.1-Ga clast is older than any surviving Hadean rocks. In fact, life first emerged around the same time that it formed [13]. Additional ancient Earth meteorites may exist on the Moon, and could be collected by Artemis astronauts to advance theories about the early Earth. It is unclear whether sedimentary rocks can survive the impact events which placed these samples on translunar trajectories. However, if they are found, Hadean rocks sourced from hydrothermal vents and fields and found during Artemis missions could refine and verify estimates of when life first appeared, and advance one or both of the leading origins of life hypotheses. Collecting a statistically significant collection of Earth meteorites will most likely require extensive mobility and in-situ sample analysis. Although it may not be a practical goal for Artemis III, we recommend that this objective be pursued as advanced exploration capabilities are introduced.

Objective 3: Biological Contaminants: One of the primary goals of the Artemis Program is to prepare for the human exploration of Mars [3]. Because astronauts are able to explore more efficiently than rovers [14], the search for ancient Martian life will be a primary objective of the first crewed landing [15]. However, human missions will inevitably introduce contaminants to the Martian environment which could impair this search [16]. Human-rated landers, airlocks, and space suits will all release organic materials and microbial life into the Martian atmosphere.

Lunar exploration provides an excellent opportunity to quantify the impacts of a continuous human presence on a lifeless world. These data can then be used to factor out biosignatures from terrestrial microbes during the search for life on Mars. To implement the Artemis program, NASA will place multiple crewed and robotic landers on the surface of the Moon. These sites could be periodically inspected by astronauts, and samples could be returned to Earth for a complete bioburden analysis.

Permanently-shadowed craters near the Artemis Base Camp will likewise be contaminated by resource extraction activities. The lunar ice deposits are a high-fidelity analog environment for an Exploration Zone on Mars, which will most likely be situated in the ice-bearing regions of the mid-latitudes [17]. Artemis drill cores could be used to document the contaminants introduced to the subsurface environment by resource extraction, which could inform how best to protect Martian subsurface aquifers situated beneath ice sheets. By identifying radiation and vacuum-resistant microbes on the Moon, Mars mission planners could create a catalog of likely false positives which could be misinterpreted as evidence of Martian life.

Conclusions: Although it is a lifeless world, the Moon nonetheless has several unique attributes which make it ideal for a set of valuable astrobiology investigations. Along with heliophysics, geology, astronomy, and life science, astrobiology could be one of the key disciplines advanced by the Artemis missions. Engaging the general public with long-term astrobiology investigations could help secure resources for sustained lunar exploration. Incorporating astrobiology objectives into the Artemis science plan will ensure that the field continues to advance during the coming decade, and that the scientific community is prepared to search for evidence of life during the first crewed mission to Mars.

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