THE IMPORTANCE AND STRATEGY OF STUDYING LUNAR POLAR VOLATILES THROUGH THE ARTEMIS III MISSION.

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Introduction: The study of lunar polar volatiles is a motivating rationale for targeting NASA's Artemis crewed Moon landings in the lunar south polar region. The low angle between the Moon's rotational axis and the normal to the ecliptic plane plus the low inclination of Earth's orbit around the Sun, coupled with lunar topography, enable environmental conditions (including thermal and lighting) that can create thermodynamically favorable regions for volatiles to collect and persist to exist at both poles of the Moon. These regions are among the coldest locations in the Solar System [1-7]. Depending on the supply rates and mechanisms, volatiles (ices) delivered to such thermodynamic stability regions may be sequestered, in some cases potentially for billions of years [7].

The high scientific priority of understanding the age, origin, and evolution of lunar polar volatiles has been highlighted in multiple guiding community documents including the Artemis III Science Definition Team report [8] and the U.S. National Academies Planetary Science and Astrobiology Decadal Survey 2022-2032 [9]. Detecting and characterizing lunar polar volatiles is also important to enabling long-term human exploration of the Moon through in situ resource utilization (ISRU) [9,10]. Therefore, a concerted strategy for studying lunar polar volatiles is being developed for the Artemis III mission, focusing on crew observations, sampling, and deployed instrumentation on the lunar surface.

Science Objectives: The Artemis III mission will address the following three science objectives relevant to lunar polar volatiles science [11].

Evaluate the nature, origin, and abundance of volatiles that may exist in polar regolith. Little is known about the age and composition of polar volatiles, or the general ability of the Moon to retain volatiles over time. The specific volatile species that might be retained in polar regolith depends on the maximum temperature that the surface/near-surface has experienced over time (18.6-year nodal precession cycle; millions/billions of years of surface and orbital dynamics evolution). Assessing volatiles in varying thermal environments (e.g., depths, locations) and ages will provide new key observations to understand their depositional history.

Assess the nature, origin, abundance, and transport processes for transient volatiles. Surficial volatiles have been observed at the lunar poles with concentrations that vary throughout the lunar day and season [12]. Migration of these surficial volatiles is likely driven primarily by diurnal temperature changes, but such transport has yet to be measured in situ on the Moon. If present-day migration of surficial volatiles is efficient, then solar wind, micrometeoroid delivery, and/or interior degassing across the Moon could be a significant contributor(s) of volatiles to thermodynamic stability regions at the south pole.

Determine how exploration activities modify the record of volatiles at the lunar surface. Another variable must be considered to ensure robust interpretation of measurements for understanding native lunar polar volatiles. The Artemis III mission will inevitably deliver volatile species to the surface, through the rocket exhaust plume and venting from spacesuits and the lander. Whether these volatiles stick to the surface for long durations is an unanswered question, with implications for understanding volatile transport and for how volatile investigations are conducted by any future landed missions.

Crew Field Science: To address these science objectives, the Artemis III crew will be uniquely positioned to make observations and collect samples on the lunar surface.

Crew Observations. The Artemis III crew will document any albedo differences that could potentially be related to frost. While ShadowCam observations have yet to conclusively identify any albedo features related to the presence of volatiles [13], in situ observations may reveal albedo differences not visible from orbit, and crew handheld camera images can be collected at varying phase angles that may help identify differences between regolith inside and outside of cold traps. Sampling or trenching activities will also reveal regolith from beneath the surface, which can be examined for differences in albedo or changes over time that could indicate sublimation of freshly exposed volatiles. While exploring areas with distinct thermal regimes, the crew will describe regolith properties and any differences such as texture, albedo, or porosity potentially related to the presence of volatiles. Such differences may be related to geotechnical properties and be experienced as changes in traversability or compaction of the regolith underfoot and during sampling activities. The crew can also look behind boulders, e.g., on the poleward facing side of the boulder that may be in shadow.

Sample Return. Crew will also have the ability to collect samples for return to Earth during the Artemis III mission. Samples collected from environments or regions where volatiles may be stable in the near-surface and sealed in the lunar environment will provide the first opportunity for laboratory analysis of lunar volatiles derived from sources other than the solar wind. Samples from Artemis III will be returned at ambient temperature during transport but can still provide volatile compound elemental and isotopic composition despite the potential for chemical reactions among headspace gases. In the context of volatile age inferred from the age of the host regolith, the isotopic and elemental composition of gas extracted from sealed samples will help distinguish between origins such as continual delivery from steady sources such as the solar wind (D/H ratios and noble gas isotopes similar to present-day solar wind) and micrometeoroids (enrichment of ^{17}O, ^{18}O; unique D/H ratios, non-lunar nitrogen isotopes) or episodic delivery from comets (complex organics and distinctive noble gas ratios), asteroids (same as micrometeoroids), or volcanic outgassing (elevated sulfur-bearing molecules and S:C ratios). Collecting separate sealed regolith samples at multiple depths, including the surface (skim sample), shallow subsurface (e.g., top half of double drive tube, upper ~35 cm) and deeper subsurface (bottom half of double drive tube, ~35-70 cm depth) will provide a first look at volatile stratigraphy. Even if likely locations of persistent volatiles cannot be sampled (e.g., due to high local max temperatures in the upper ~m of regolith or inaccessible terrain), samples in less favorable thermal regimes would test volatile stability predictions and "dry" (e.g., anhydrous or volatile-poor) samples will result in science progress that will inform future Artemis science strategies. Such sealed surficial regolith samples will also provide opportunities to assess temporal change in volatile types and abundances in response to thermal drivers. This assessment can be accomplished by collecting sealed surficial regolith samples in a location that has been in shadow for an extended duration (i.e., the lunar night), and again in the same location after it has been illuminated (here, the extreme and changing illumination conditions in the south polar region are beneficial). Sealed surficial samples collected at varying distances from the lander in regions that remained in shadow since landing – but with temperatures incompatible with long-term sequestering of volatiles – would demonstrate how lander contamination (the primary byproducts of the liquid oxygen (LOX)–methane reaction include H_2O and CO_2) is distributed across the landing site [14]. To address these questions about the native volatile cycle on the Moon, age and origin of the volatiles, and how lunar exploration with humans affects the lunar volatile cycle, it is crucial that sealed sampling containers are delivered to the lunar surface clean and dry. It is also imperative to maintain sample integrity during all stages of the mission until arrival at the curation facility upon Earth return.

Deployed Instruments: The Lunar Dielectric Analyzer (LDA) is a payload that will be deployed on the lunar surface by the crew during the Artemis III mission. LDA is an internationally contributed payload led by Dr. Hideaki Miyamoto of the University of Tokyo and supported by JAXA (Japan Aerospace Exploration Agency). LDA will measure the regolith's ability to propagate an electric field, which is a key parameter in the search for lunar volatiles, especially water ice. LDA capitalizes on the fact that detecting a small amount of water ice depends on permittivity changes in the regolith while understanding its dependent parameters such as the frequency, temperature, porosity, and chemical composition [15]. LDA will gather essential information about the structure of the Moon's subsurface, monitor dielectric changes caused by the temperature changes related to varied shadowing, and look for possible frost formation or ice deposits. The returned samples from Artemis III can also be used to interpret and understand LDA data.

Conclusions: The Artemis III mission will be the first crewed mission to land in the south polar region of the Moon. As such, Artemis III provides an excellent opportunity to address the high priority science and exploration goals of understanding the age, origin, and evolution of lunar polar volatiles. Artemis III will utilize crew observations, sample return, and scientific instrumentation on the lunar surface to detect and characterize volatile species, thereby providing valuable and critical information for both science and future human exploration.

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