THE CASE FOR IN SITU EXPLORATION OF VOLATILE DEPOSITS AT THE LUNAR POLES. B. A. Cohen[1], B. L. Jolliff[2], E. B. Bierhaus[3], B. C. Clark[3]; S. M. Clegg[4], R. C. Elphic[5], D. P. Glavin[6], J. J. Hagerty[7], D. J. Lawrence[8], P. R. Mahaffy[6], A. Wang[2], and R. C. Wiens[4]; [1]NASA Marshall Space Flight Center, Huntsville AL 35805 (Barbara.A.Cohen@nasa.gov), [2]Washington University, St. Louis MO; [3]Lockheed Martin Space Systems, Littleton CO; [4]Los Alamos National Laboratory, Los Alamos NM; [5]NASA Ames Research Center, Moffett Field CA; [6]NASA Goddard Space Flight Center, Greenbelt MD; [7]USGS, Flagstaff, AZ; [8]Johns Hopkins University Applied Physics Laboratory, Laurel MD.

Introduction: One of the scientific frontiers of our Solar System lies at the north and south poles of the Moon, where temperatures in permanently shaded regions (PSRs) reach a few tens of K. Under these ultra-frigid conditions, volatile elements and molecules that arrive at the poles become trapped in the regolith. Results from orbital remote sensing and impactor missions provide evidence that significant concentrations of hydrogen exist in the lunar PSRs, capturing worldwide public and scientific interest. In-situ exploration of the lunar polar volatile deposits is a logical scientific step following these successes, to determine what these ices are, where in the regolith they are located, and how they got there, to decipher the history of volatiles in the inner Solar System.

Water on the Moon: In the last ten years, advances in laboratory analyses and remote sensing have fundamentally altered our understanding of water on the Moon. Volcanic glass and apatite grains from Apollo samples and lunar meteorites contain trace amounts of water (5-50 ppm), suggesting that the lunar mantle contained water very early in lunar history [1, 2]. At the other extreme, trace amounts of both water (H_2O) and hydroxyl (OH) molecules are present on the lunar surface even today [3-5].

In contrast to these very small amounts of indigenous lunar water, the Moon has vast, complex stores of water and other volatile compounds at its north and south poles. Surface temperatures in PSRs can reach as low as 25-35 K (-240 to -250°C) [6]. Molecules of water and other volatile compounds that find their way into these areas would become so cold they would never gain enough energy to leave [7, 8].

Observational evidence of H_2O ice at the lunar poles has come from the Clementine bistatic radar experiment and the LP Neutron Spectrometer (NS) experiment [9, 10], but the form of the deposits (e.g., layers of ice vs. disseminated ice) and their composition remains unknown. Additionally, the resolution of these data are too coarse to determine directly if the H enhancements are associated specifically with permanently shadowed craters and not the polar regions in general. Radar images from the Mini-SAR instrument on Chandrayaan-1 identified a group of craters at the north pole whose interiors may contain nearly pure water ice [11]. All these craters are either completely or partially in permanent shadow and are spatially correlated with H-rich locations in the LP-NS data.

The Lunar Crater Observation and Sensing Satellite (LCROSS) mission ejected debris, dust, and vapor from regolith in a south pole PSR, estimating the concentration of water ice as 5.6 ± 2.9% by mass [12]. In addition to water, spectral bands of other volatile compounds were observed, including light hydrocarbons, sulfur-bearing species, and carbon dioxide. The LCROSS impact site exhibits no radar signature indicative of ice, suggesting that such an amount of water ice may not be detectable by radar [13].

Outstanding questions for in-situ science: The science of lunar volatiles is richer than the single question, "Is there water on the Moon?" Our current understanding of hydrogen in lunar polar regions is that it exceeds levels expected from simple solar-wind implantation and that some of it exists as water ice. It is not yet known what proportion of the H is present as water ice, or whether H occurs in other forms, such as OH-bearing minerals, H_2O adsorbed on grain surfaces, or C-H or N-H compounds. Nor is the form of water ice known from orbit, whether it exists as discrete layers or chunks of ice, or as finely disseminated grains of ice. Identification of the different forms and proportions of H and other volatile compounds are fundamental to understanding PSRs as geologic deposits and potential resources, and to addressing additional questions about volatile-compound origins, transport, and deposition mechanisms.

Possible sources of volatiles includes those indigenous to the Moon (e.g., volcanic outgassing), solar-wind, meteoritic and cometary addition, and giant molecular clouds. What currently resides at the poles will be the result of the history of deposition from all of these mechanisms and sources. Distinguishing between these sources requires knowledge of the elemental and molecular makeup of the species, as well as characteristics that vary as a function of source, such as organic compounds and isotopic ratios.

The *Scientific Context for the Exploration of the Moon* notes that the lunar polar regions offer "a unique opportunity to characterize the volatile compounds of polar regions on an airless body and determine their importance for the history of volatiles in the Solar System." This report also makes the point that "orbital remote sensing missions are unlikely to answer the most compelling scientific questions; these can only begin to be addressed by in-situ measurements." An appropriately-designed in situ investigation must in-

clude a mobile element equipped with appropriate instruments and subsurface access.

Orbital NS data has a relatively large footprint compared with the area available to a landed experiment, masking small-scale variations in H abundance. For example, within the Cabeus PSR, LCROSS detected ~6% water ice but orbital neutron spectroscopy indicates significantly lower average concentrations across the area [14, 15]. The distribution of volatile deposits appears to vary, possibly in response to the mechanisms of initial deposition and any post-deposition processing. A mission would require mobility to prospect for enhanced H concentrations and to characterize the lateral variability of the volatile deposits on a length scale that is consistent with what is anticipated from geologic processes [16].

Orbital neutron spectroscopy has an effective sensing depth of about 1 m in typical lunar regolith. Thus, we know that H occurs in the upper meter, but not how it is distributed within the upper meter. Deposits are likely buried beneath a layer of dry soil 5-20 cm thick [17]. Therefore, the ability to sample below a desiccated layer is crucial.

Finally, appropriate instruments must be carried to determine the speciation and concentration of H-bearing and other volatile compounds. Concentrations must be determined with sufficient accuracy to constrain deposition and loss processes and rates. Capabilities are needed to discriminate different forms of OH and H_2O, C-H compounds and more complex organics, N-H-bearing compounds, and mixtures of these with other regolith components (silicates, oxides, glasses, metallic Fe). Adequate sensitivity is needed to discern trends, for example in diffusivity or volatility, as a function of thermal gradients and depth profiles. This knowledge is also required to understand the origins and source of the material.

Mission Studies: In 2008, two of nine proposals selected for development under the "Discovery and Scout Mission Capabilities Expansion" opportunity were in-situ investigations of lunar polar volatile deposits: "Locating and Characterizing Lunar Polar Volatiles: Feasibility of a Discovery-Class Mission," or ExoMoon [18, 19], and "JEDI: A Lunar Polar Volatile Explorer" [20]. Both studies accomplished the goals of in situ lunar polar science, including mobility and subsurface access. Both concluded that the availability of Advanced Stirling Radioisotope Generators (ASRGs) uniquely enabled the mission. Non-nuclear power systems would require batteries (severely limiting mission lifetime), or periodic return to sunlight for recharging (increasing risk of mission loss if the mobile element cannot reach sunlight). Furthermore, both studies produced mission concepts for viable spacecraft within a Discovery budget.

Most recently, the Planetary Science Decadal Survey commissioned a rapid mission architecture study for a Lunar Polar Volatiles Explorer, also to conduct an in situ investigation of lunar polar volatiles, including mobility and subsurface access. This study identified several mission components at TRLs less than 6, but these technology advancements were believed to be achievable and consistent with the outlined mission schedule. Though the Decadal Survey study priced their specific point design as a New Frontiers mission, both DCSMCE studies showed less-expensive alternate designs. These studies show that the final cost of such a mission may vary dramatically in response to lifetime requirements, specific instrument complement and capabilities, and operations scenarios.

Conclusions: The science of lunar polar volatiles addresses a broad range of solar-system and lunar science issues. In-situ characterization of hydrogen-bearing and other volatile compounds in lunar PSRs will accomplish science that provides fundamental knowledge about the Earth-Moon system and inner Solar System evolution. Such an in situ mission is a natural follow-on to the excitement generated by lunar orbital remote sensing and would greatly leverage the substantial NASA investment in the lunar science community in the last decade. Mission concepts have been studied in enough detail to show that a lunar polar rover is technically feasible at multiple price points.

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