SCIENCE FROM THE LUNAR PERMANENTLY SHADOWED REGIONS. D. Hurley[1], P. Prem[1], A. Stickle[1], C. Hibbitts[1], A. Deutsch[2], A. Colaprete[3], R. Elphic[3], S. Li[4], P. Lucey[4], Y. Liu[5], S. Hosseini[5], K. D. Retherford[6], K. Zacny[7], J. Atkinson[7], M. Benna[8], W. Farrell[8], D. Needham[9], L. Gertsch[10], M. Delitsky[11], and P. Hayne[12], [1]Johns Hopkins Applied Physics Laboratory (Dana.Hurley@jhuapl.edu), [2]Brown University, [3]NASA Ames Research Center, [4]University of Hawaii-Manoa, [5]Jet Propulsion Laboratory, [6]Southwest Research Institute, [7]Honeybee Robotics, [8]NASA Goddard Space Flight Center, [9]NASA Marshall Space Flight Center, [10]Missouri Science and Technology University, [11]California Specialty Engineering, [12]University of Colorado, Boulder.

Introduction: The cold traps in persistently shadowed regions (PSRs) on the Moon have been caching an unparalleled scientific record of volatiles from many sources for billions of years. They likely contain volatiles from early lunar outgassing events, from asteroids and comets encountering the Earth-Moon system over time, and volatiles delivered to or liberated from the Moon continually via solar wind interactions and meteoroid bombardment. There is no other reservoir of solar system volatile history as accessible as the Moon's PSRs.

Science Objectives: The Polar Ice Prospecting Explorer for Lunar No-light Environments (PIPE-LiNE) mission concept would sample volatile composition, abundance, physical form, and distribution in situ within a lunar PSR. These measurements would unravel the processes that govern the origin, retention and loss of volatiles, the contributions of various sources, and the utility of these volatiles as a resource for further human and robotic exploration.

Ground-truthing of remotely sensed measurements. To date, most understanding of lunar volatile abundance, distribution, composition, and physical form is derived from remotely sensed observations of the Moon [e.g., 1-8]. However, the spatial resolutions of these observations are substantially coarser than the likely scale that lunar volatiles vary laterally and with depth. While the ejecta probed by the Lunar Crater Observation and Sensing Satellite (LCROSS) measurements may be within this scale, they only provide data for a single location on the surface. It is undetermined how representative these data are of the lunar poles. Additional in situ data would provide the critical ground-truthing required to better understand the existing database of polar data.

Processes modulating volatile abundance, distribution, composition, and physical form. It is not well understood how the abundance, distribution, composition, and physical form of volatiles are altered after emplacement. A variety of factors may physically and chemically alter lunar volatiles through time. For example, volatiles delivered by some continuous delivery mechanism at a lower rate should have a more homogeneous and diffuse distribution than volatiles delivered in episodic pulses. Impact gardening can produce spatial heterogeneities in volatile distribution because impacts remove volatiles via vaporization but also preserve volatiles through the emplacement of ejecta [9-10]. Additionally, the surface and near-surface thermal environments have a major effect on volatile distribution, stability, and transport because the rates of diffusion and sublimation are modulated by temperature [11-17]. In situ compositional measurements would inform our understanding of modification processes that have altered volatiles in situ, including impacts [10-11; 18], cosmic rays [19], solar wind sputtering [20], and dielectric breakdown [21]. Subsequently, this understanding can be applied to volatiles on Mercury, asteroids, and other airless bodies in the solar system.

Activity and transport of volatiles. Complementary to understanding the processes that modify volatiles over long periods of time is witnessing the processes that are acting today. Recent results from Lunar Atmosphere and Dust Environment Explorer (LADEE) imply the Moon is in a state of losing water [22]. Measuring the present-day rates of mass change will reveal the efficiency of volatile transport on the Moon. Monitoring the surface volatile contents daily, seasonally, and yearly can help to assess how dynamic the PSR volatiles are, which can be linked to exosphere, surface, and subsurface processes [11; 23-29]. In addition, soil chemistry is important to test transport models of lesser volatile elements such as Zn, S, and Cl [30].

Source and time history of volatiles. Direct compositional measurements of volatiles cold-trapped in lunar PSRs have been difficult to acquire due to viewing conditions in permanent darkness [8]. D/H ratios inform our understanding of the origin of water ice [31-33]. Sulfur content is a direct link to provide the contribution of volcanic outgassing to polar volatiles [34]. The presence of organics constrains valid delivery sources [35-36]. Therefore, analyzing the present-day composition of volatiles would provide insight into the original sources of volatiles.

Because modification processes acting in PSRs take time, spatial heterogeneity is related to the exposure age of the volatiles [37]. The distribution of volatiles with depth provides a window into the age and emplacement timing of volatiles. The physical form of the volatiles, whether they exist as ice blocks, pore-filling ice, adsorbed volatiles, or incorporated in the minerals, is indicative of the source and history. Quantification of the coherence of deposits and the relationship to thermal conditions would provide insights into the age of PSR volatiles.

Thermophysical and geotechnical properties. Many questions remain regarding the thermophysical and geotechnical properties of polar regolith. For example, regolith porosity appears to be higher inside PSRs than in illuminated regions [5; 38-40]; however, it is not clear what processes have generated the high porosity [21; 41-42]. Measurements of regolith porosity would improve our understanding of electrostatic and thermophysical environments at the poles and would quantify the pore-space available to cold-trapping. Given the importance of geotechnical properties for in situ resource utilization, better constraints on bearing capacity [43] and mechanical strength [44] would inform not only scientific objectives but also exploration priorities [45].

Mission Concept: The PIPELiNE mission concept is a nuclear-powered rover that would assay the volatile contents deep within the heart of a lunar PSR. A comprehensive Flagship concept would be a rover equipped with a gas chromatograph mass spectrometer (GCMS), neutron spectrometer (NS), Raman spectrograph (Raman), ground penetrating radar (GPR), infrared spectrometer (IRS), spatial heterodyne spectrometer (SHS), atmospheric neutral mass spectrometer (NMS), ion spectrometer (IS), traverse and context cameras (Cam), and a drill with temperature probes. At the New Frontiers cost cap, the payload would be smaller, perhaps similar to the instrumentation planned for the Volatiles Investigating Polar Exploration Rover (VIPER) mission.

While traversing, PIPELiNE would survey by remote sensing volatiles on the surface via IRS and SHS and in the subsurface via NS. The observations would indicate locations where the rover stops to perform more detailed analysis of the volatiles. The detailed assessments would include drilling into the regolith, measuring the temperature as a function of depth, and analyzing the drillings via GCMS, Raman, and IRS.

The PSR environment drives significant parts of the PIPELiNE design. An MMRTG would be enabling for this mission in two ways. First, solar power would only allow short sorties on the order of 50 m into shadow, requiring frequent returns to sunlight for recharging. Target study areas are inaccessible via 50-m sorties. A battery-only mission would require massive batteries, limiting payload capacity and mission duration [46]. In contrast, by using an MMRTG and battery, PIPELiNE is able to explore deep into PSRs with a mission duration of several months. A second advantage of the MMRTG system is that it emits heat needed to maintain functionality of the spacecraft systems in the cold (<100 K) PSR environment.

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