Lunar Polar Volatiles and Associated Processes

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1. Executive Summary

Many pieces of observational evidence support the presence of volatiles in the extremely cold, permanently shaded regions near the poles of the Moon. Bistatic radar observations (Nozette et al., 1996) and neutron measurements (e.g., Feldman et al., 1998) have returned signatures consistent with the presence of water ice, but none to date confirms the existence of water ice on the Moon. Given the non-unique interpretation of the observations, the existence of water and other volatiles in enhanced concentrations in permanently shadowed regions (PSRs) on the Moon remains a controversial topic (e.g., Simpson and Tyler, 1999; Nozette et al., 2001; Starukhina, 2001; Hodges, 2002; Vondrak and Crider, 2003; Campbell et al., 2006; Lucey, 2009). There are recent and ongoing missions that are increasing our understanding of the polar environment of the Moon and the characteristics of its putative volatiles. At the successful conclusion of these missions, surface-based, in situ measurements will still be needed to positively, uniquely, irrefutably identify the volatiles and their physical states in the lunar PSRs.

In the 2013-2022 decade, NASA should definitively identify the composition, abundance, and distribution of volatiles in lunar PSRs. A landed/mobile mission to a lunar PSR to provide ground truth for remote sensing measurements is a high priority in this decade. Once the composition, physical state, and abundance of the volatiles is established, we can begin to evaluate them as a resource for further scientific inquiry as well as human exploration. The next step in scientific investigation is obtaining a detailed understanding of the volatile processes. Without understanding the entire delivery/transport/retention system, we will not be able to unravel the history of polar volatiles. In particular, the relevant processes involved in deposition and maintenance of the volatile reservoirs need to be studied. To accomplish these studies, modeling, data acquisition and analysis, and laboratory experiments should be supported. Long term monitoring of associated processes should be accommodated on lunar landed network assets (e.g., ILN, International Lunar Network), as some plasma-surface, atmosphere-surface, and gardening interactions can be studied from non-polar lunar sites as well as within PSRs. Conversely, a landed mission to a PSR can also conduct studies of lunar geology that are not specific to PSRs.

The science of volatiles in PSRs is an intellectually rich endeavor, encompassing unanswered questions, unexplored worlds, unsampled environments, and unresolved controversies. A brief description of the outstanding science questions follows in Section 2. Section 3 places the science questions into context with planned and unplanned activities that comprise high priority objectives for the planetary science community and its sponsors.

Objectives for Lunar PSR Research
- Identify the composition, abundance, and distribution of volatiles in lunar PSRs.
- Characterize volatiles as resource for scientific inquiry and human exploration.
- Obtain a detailed understanding of volatile processes in delivery, transport, retention.
- Unravel the history of polar volatiles.

2. Volatile Science

The idea that there are long-lived cold traps on the Moon originated with Urey (1952) and was examined by Watson et al. (1961) and Arnold (1979). The possibility of water ice on the Moon is scientifically tantalizing for several reasons (**Figure 1**). The permanently shadowed regions offer a cold, dark, reduced-gravity, vacuum environment that is difficult to reproduce in a terrestrial laboratory. Exploring the physics, chemistry (both abiotic and prebiotic), and geology of lunar PSRs expands our knowledge of processes in extreme limits, eliminating our need to extrapolate from terrestrial experiments and observations. Yet, the environment in lunar PSRs is similar to environments that exist at asteroids, satellites of the outer planets, and the poles of Mercury. The processes that occur in PSRs on the Moon are therefore applicable across the Solar System. Thus lunar PSRs are the most accessible laboratory for this class of environments. The lunar PSRs are a stable environment in which volatiles may have been trapped over about 2 billion years, owing to the long-term stability of the Moon's obliquity. Thus, the PSRs contain a history of volatiles in the inner solar system dating to almost half the age of the solar system, a far greater record than the Earth retains. This volatile reservoir contains an unprecedented geological record, but also has the potential to become a resource useful to future exploration activities on the Moon.

Erlanger Crater, NASA LRO NAC image

Figure 1. Lunar volatiles and permanently shadowed regions offer a unique laboratory, serve as a planetary analog, contain a historical record of the solar system, and store resources.

Our current understanding (**Figure 2**) suggests that volatiles are delivered to the Moon constantly by comets, asteroids, micro-meteorites, giant molecular clouds, interplanetary dust particles, and the solar wind. If the volatiles are not delivered or formed directly in the PSRs, they are transported to the PSR, where they are cold-trapped. They experience space weathering in addition with regolith interactions to reach their current concentration, physical state, and distribution. The details of this scenario are poorly known and include many interesting science questions as briefly discussed below.

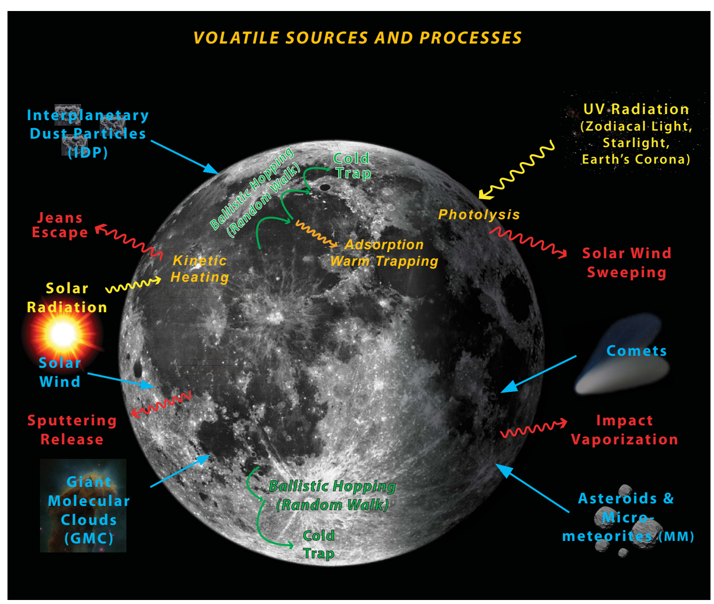

Figure 2. Sources and processes controlling volatiles in lunar PSRs are shown.

2.1 Sources

The Apollo missions to the Moon's surface found an extremely dry environment at the low-latitude regions on the Moon (Desmarias et al., 1974). Although the Moon is outgassing even currently (Crotts, 2009) and there is evidence for the presence of OH of magmatic origins in volcanic glasses (Saal et al., 2008), most of the volatiles sequestered in PSRs on the Moon today are thought to be exogenous. Plasma from the solar wind and Earth's magnetosphere continuously bathes the Moon's surface. Micrometeoroids constantly rain down on the Moon, adding some fraction of their volatiles to the local inventory upon vaporization. Occasional larger impacts of asteroids or comets contribute greater amounts of volatiles at once, albeit with a low frequency. Exactly how these distinct sources contribute to the sequestered volatile inventory is poorly quantified. However, the various sources have different compositions. Thus, distinguishing the composition of volatiles in PSRs, including isotopic ratios, will reveal the relative contribution of the possible sources of volatiles to the lunar PSRs.

2.2 Transport and Deposition

Once volatiles are delivered to the Moon, they are subject to transport through exospheric migration. This is a very inefficient process, with many loss mechanisms. Our understanding of this process is far from complete because the many interactions involved have not been studied or cannot be reproduced in the laboratory to match the conditions present on the Moon. Transport, being a leaky conduit from delivery to the final repository, is a crucial piece relating the current volatile inventory in the cold traps to the volatile sources that were delivered to the Moon. Multiple jumps of a given volatile molecular species are further subject to temperature-dependent grain-volatile interactions that retard the rate of migration. This process is also poorly understood at this time, with considerable compositional dependencies remaining to be unraveled.

Large gas releases, e.g. from a comet impact on the Moon or a major outgassing event, have not been observed. Data from formations like Ina (Schultz et al., 2006), impact craters, and understanding of the population of impacting bodies provide a basis for modeling of such events. However, there is uncertainty in these models in the amounts, composition, and energies of the released volatiles, which translates into uncertainty in the efficiency of delivery from large impacts.

The process by which atoms and molecules of the neutral exosphere interact with surface grains is crucial in determining transport, yet is poorly constrained. Neutral atmospheric atoms or molecules with long lifetimes against photoionization and masses heavier than a few atomic mass units can undergo tens to thousands of bounces in the lunar surface bounded exosphere before being lost from the Moon. How the atmospheric particles interact with the surface determines the release velocity and subsequent trajectory, affecting the delivery rate to the PSRs.

The solar wind and other plasmas also interact with surface grains. The sputtering of the lunar regolith by solar wind ions has not been measured, and only some analogous work has been conducted in the laboratory (Elphic et al., 1991). Recent Kaguya data may constrain sputtering yields (Yokota et al., 2009). Sputtering yields of keV ions are strongly dependent on energy. Thus the effectiveness of sporadic, high energy events (e.g., solar energetic particle events, coronal mass ejections) may exceed the cumulative yield from the ambient solar wind.

Finally, we need to understand the various scenarios of volatile deposition, including the roles and relative importance of equilibrium vs. stochastic deposition. The apparently heterogeneous distribution of polar volatiles suggests that rare high-rate deposition events may be more important than continuous, slow deposition. Understanding the relative importance of both processes requires both modeling and observational information.

2.3 Retention

Once deposited in a cold trap in a lunar PSR, volatiles are subjected to an array of processes that can modify the volatile content and/or distribution. Space weathering, which encompasses a variety of processes that alter the surface of the Moon due to its exposure to space, affects the amount, form, and distribution of volatiles in PSRs. For volatiles, relevant space weathering processes include impact gardening, sputtering, agglutination, comminution, and Lyman-alpha photolysis.

Micrometeorite bombardment grinds surface rocks into powder over time. Surface particles interact with the extralunar environment, including implantation of gas molecules and radiation damage to dust grains, and significantly affect volatile history and distribution. We must understand how the volatiles interact with and are affected by regolith growth and formation.

Furthermore, small and large impacts in a PSR can release, or expose to space, volatiles trapped in the regolith. The inhomogeneous nature of bombardment implies that lateral variations can be expected in PSRs even if the initial deposit was homogeneous. Quantifying the scale of heterogeneity and the overall lateral distribution is an important task. Understanding gardening anywhere on the Moon improves understanding of gardening in cold traps. However, special focus on the effects of impacts in PSRs is also required.

Temperatures in PSR are as low as 20 K (Paige et al., 2009), and sublimation and molecular diffusion of water are stilted in the frigid PSR. However, the effects of temperature waves (e.g., from an occasionally illuminated crater rim or a nearby impact) at both macroscopic and microscopic levels in these cold areas are poorly understood and require additional laboratory research and more importantly, data from surface exploration.

Although a PSR is permanently shaded from sunlight, photons from scattered sunlight and direct and indirect starlight have access to the PSR (e.g., Haruyama et al., 2008). Similarly, if the Moon ever had a temporary atmosphere (Stern, 1999), scattered light would shine into PSRs. Ions from the solar wind and the Earth's plasma sheet also have access to PSRs because the ions do not travel on straight lines like photons (Farrell et al., 2009). However, sputtering yields for ions strongly depend on the target material. In the case of icy substances, sputtering yields are high. When the ice concentration is reduced, the sputtering yield drops at a rate greater than the proportion of ice. Thus the significance of sputtering as a loss process depends on the ice concentration and its possible depth of burial. Quantifying these loss processes will constrain the durability of volatiles in PSRs, which is a critical factor in relating what is currently in a PSR to what was originally delivered to the Moon.

It is also important to understand the role that electrostatically-levitated dust may have in covering and protecting recently trapped volatiles. In sunlight and average solar wind or magnetospheric conditions, silicate grains charge positive due to photoemission. In shadow, electron flux dominates and surface materials charge negatively. Positively-charged dust grains may be preferentially attracted to negatively-charged permanent shadow, affording a mechanism to protect cold-trapped volatiles from scattered Lyman-alpha or other energetic photons (see also the white paper submitted by Farrell and Horanyi).

2.4 Comparative Planetology

The potential long lifetime of cold-trapped volatiles in PSRs implies that they contain a significant, unparalleled geologic record of the delivery of exogenous volatiles to the inner solar system. The PSR deposits provide information about the volatile flux to the Earth-Moon system over the last couple of billion years, linking this record to its bombardment history. The material in the PSRs has been redistributed and modified over time, providing information about the geological processes that have been important on the Moon and by implication elsewhere in the solar system.

Mercury similarly has a low spin-axis obliquity and presumed extremely cold temperatures in PSRs (e.g., Ingersoll et al., 1992). Existing radar data from Mercury indicate a strong backscatter signature consistent with ice (Harmon et al., 1992). The signature is stronger in the Mercury observations than similar radar observations of the Moon. Gathering equivalent data from the Moon and Mercury and investigating how processes may or may not vary on the two bodies will enable us to understand how the different deposits arose on the planets. When there are not equivalent observations, predictions can be made for Mercury based on knowledge acquired from the Moon and vice versa.

Many of the processes occurring on the Moon are applicable elsewhere in the Solar System. A surface-bounded exosphere plays a key role in transport processes, and other such surface bounded exospheres exist throughout the solar system (see Killen and Ip, 1999). Based on our limited knowledge, Mercury's exosphere has similarities to the lunar exosphere. Surface bounded exospheres of outer planet satellites have similarities and differences. The icy nature of the surfaces of outer planet moons induces different surface interactions than occur on the silicate grains of the Moon or Mercury. Asteroids' low gravity and, sometimes, rapid rotation rate are parameters that affect their exospheres compared to the Moon's.

Likewise, these related bodies are subject to plasma environments. Mercury has a global magnetic field and magnetosphere, which are quite different than those of the Jovian satellites situated in the Jovian magnetosphere. These are, in turn, different from the Moon, which is mostly exposed to the solar wind. How different types of plasma interact with the surface will affect the possible sources of volatiles and the retention of volatiles.

Clearly, data from other planetary bodies can inform the study of lunar PSRs. In turn, comparative studies can distinguish which processes have the greatest impact on PSRs. Finally, lunar PSR studies can inform future missions and science of other planetary bodies.

Because of the extreme conditions, the data acquired in PSRs, where available, are more applicable to studies of other planets with similar environments than laboratory analog data. Furthermore, data acquired in these extreme environments can provide key constraints to ongoing lab work to extend the geochemical understanding of regolith grains and how they interact with each other, gases, and plasmas at very low temperature and pressure.

3. Lunar Polar Science Objectives: 2013-2022

Quantifying, characterizing, and mapping the composition of deposits within the PSRs and characterizing their environments are high value scientific objectives as well as an operational tool. But the volatiles themselves are not the ultimate goal. Understanding the processes associated with the PSRs is the overarching theme that motivates this investigation.

3.1 Characterize PSR Volatiles

Finding and characterizing the volatiles comprises three steps (**Figure 3**): 1) identify the constituents (isotopes, elements, molecules, mineralogy); 2) quantify abundances globally and locally; and 3) map distribution (laterally and vertically on scales of meters to kilometers).

Composition of the volatiles is a crucial clue to their sources. We must understand the type of source(s) for volatiles (i.e., comets, solar wind, etc.) and the relative abundances from each source by linking the constituents of PSRs to the constituents of the sources. Isotopic abundances should be measured in situ, which will require mobility and a long-lived power source. They also require development of sample acquisition and handling technologies, which are currently at relatively low TRL (Technology Readiness Level). Sample handling systems are critical to accurately determine composition and characteristics of volatiles. Characterization of the chemical form of the volatiles (i.e., going beyond the neutron spectroscopy method of detecting an element irrespective of its chemical form) provides links to surface interactions and chemistry.

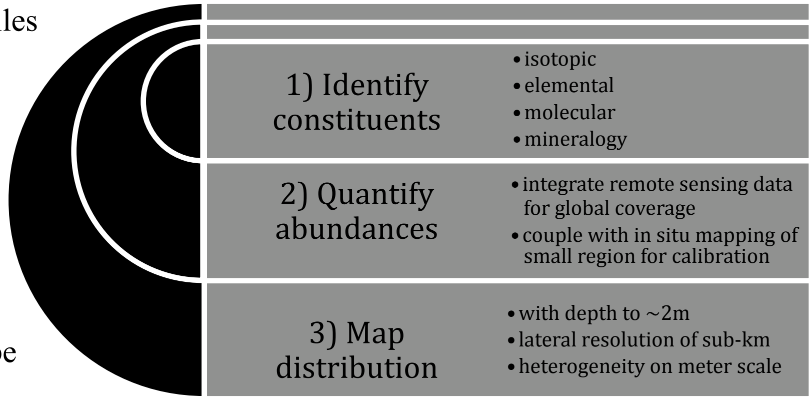

Figure 3. Tasks required to definitively find volatiles in lunar PSRs are listed.

The total abundance of lunar volatiles is an important measurement related to the volatile inventory of the source and to the flux of the source at the Moon. Total volatile contents of PSRs should be assessed from remote sensing measurements coupled with in-situ, ground truth measurements from multiple spots in the polar regions.

We must also learn the timing of the emplacement of volatiles in the lunar PSRs. The spatial distribution, especially with depth, is a function of the timing of volatile delivery and processes that affect them after deposition. In situ sampling from depths of a few 10s of cm to about 2 m coupled with depth-sensitive remote sensing (e.g., radar, neutrons) would provide a full account of the distribution of volatiles with depth.

3.2 Monitor Processes

Transport to the PSRs and retention within a PSR comprise a chain linking the volatiles that are currently in PSRs to those that were originally released on the Moon. Many poorly constrained pieces of the system (see box) can be resolved with monitoring by a combination of techniques. Experiments set up on the Moon or conducted from lunar orbit can quantify sputtering yields, atmospheric constituents, impact gardening rates, loss fluxes from PSRs, and low temperature geochemistry.

Poorly Constrained Factors Influencing Volatile Delivery and Retention

- ion sputtering
- atmosphere-surface interactions
- bulk gas release
- impact gardening
- low T gas phase diffusion
- low T geochemistry
- loss flux from PSRs

A landed atmospheric monitor would analyze the properties of lunar atmospheric particles near the lunar surface through a variety of conditions to help constrain the atmosphere-surface interaction. Any such asset on the surface of the Moon fortuitously would be in place to observe the passing cloud if an impact or gas release (manmade or natural) were to occur. Another desired experiment is the deliberate release of a known quantity of volatiles and monitoring their dissipation with time.

Atmosphere-surface interactions, bulk gas releases, and plasma surface interactions can be assessed by combining modeling with observations. Laboratory measurements that simulate lunar conditions with appropriate lunar soil simulants will also increase the understanding of bulk gas releases, low temperature geochemistry, low temperature gas phase diffusion, ion sputtering, atmosphere-surface interactions, and impact gardening. Thus there are several ways to increase the understanding of processes associated with polar volatiles in addition to sending a landed mission to a PSR to monitor them.

3.3 Derive Science Results

The groundbreaking science results from studies of lunar polar volatiles come from the synthesis of diverse observations and understanding the system from delivery to maintenance (see box). Linking the knowledge of retention processes and the assessment of the spatial distribution enables the inference of the timing of volatile delivery to the Moon. Knowledge of the timing then constrains the historical fluxes of volatiles near Earth. Assessing the abundance of volatiles and the source and loss rates is necessary to characterize their resupply rate if they are to be used as a resource. The science is applicable in regions throughout the Solar System, expanding the realm of the explored universe to include a permanently shadowed region. The study of lunar polar volatiles is a diverse investigation with scientific goals that are achievable in the next decade (2013-2022.)

Science results
- Determine types of sources of volatiles
- Infer timing of delivery
- Determine historical fluxes of volatiles in Cislunar space
- Study physics/chemistry/astrobiology/geology in extreme environment
- Assess global processes measured/studied specifically within PSRs
- Feed forward to missions/observations of other planetary environments
- Assess implications for operations on the Moon

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