A tale of two poles: Toward understanding the presence, distribution, and origin of volatiles at the polar regions of the Moon and Mercury

David J. Lawrence

Abstract The Moon and Mercury both have permanently shaded regions (PSRs) at their poles, which are locations that do not see the Sun for geologically long periods of time. The PSRs of the Moon and Mercury have very cold temperatures (\(<120\,\text{K}\)) and as a consequence act as traps for volatile materials. Volatile enhancements have been detected and characterized at both planetary bodies, but the volatile concentrations at Mercury’s poles are significantly larger than at the Moon’s poles. This paper documents the study of PSR volatiles at the Moon and Mercury that has taken place over the past 60 years. Starting with speculative ideas in the 1950s and 1960s, the field of PSR volatiles has emerged into a thriving subfield of planetary science that has significant implications for scientific studies of the solar system, as well as future human exploration of the solar system. While much has been learned about PSRs and PSR volatiles, many foundational aspects of PSRs are still not understood. One of the most important unanswered questions is why the PSR volatile concentrations at the Moon and Mercury are so different. After describing the initial predictions and measurements of PSR volatiles, this paper documents a variety of PSR measurements, summarizes the current understanding of PSR volatiles, and then suggests what new measurements and studies are needed to answer many of the remaining open questions about PSR volatiles.

1. Introduction

Permanently shaded regions (PSRs) are locations on planetary bodies that do not see the Sun for geologically long periods of time and therefore have unique properties compared to other locations on planetary bodies. If PSRs exist on airless planetary bodies, they will have very cold temperatures (\(<120\,\text{K}\)) because they radiate directly to space with no source of heat input other than residual interior heat from the body itself and small amounts of multibounce thermal photons from nearby sunlit locations. The low temperatures that exist for long durations within PSRs can result in a variety of interesting effects. One of the most intriguing is that volatile materials, especially water ice, can become trapped within PSRs as a direct consequence of the cold temperatures. Thus, while the residence time of volatiles for non-PSRs is short with timescales of days to weeks, the residence time of volatiles within PSRs can be geologically long (millions to billions of years).

The type examples of PSRs within the solar system are those that exist on the Moon and Mercury. The axes of rotation for both these bodies are nearly perpendicular to their orbital plane around the Sun (1.5° for the Moon, 0.034° for Mercury, where 0° would be exactly perpendicular) [Siegler et al., 2015; Margot et al., 2012]. Because the Moon’s and Mercury’s rotational orientation has been stable for billions of years [Siegler et al., 2013, 2015], there are craters near the poles of both bodies that are sufficiently deep such that their interiors do not see the Sun, and they are therefore PSRs.

The existence of PSRs does not guarantee they will accumulate volatiles over time, but only makes such accumulation possible. There is a range of possible volatile sources that can include sources interior (endogenous) or exterior (exogenous) to the planet. Endogenous sources could be residual volatiles from ancient volcanism as well as more recent volatile releases or outgassing events [Crotts and Hummels, 2009]. There is a large variety of exogenous sources that can include comets, asteroids, interplanetary dust particles, solar wind, and even occasional giant molecular clouds that may pass through the solar system [Lucey, 2009]. In terms of their time of delivery, all sources can in principle be continuous and/or episodic. In a broader sense, it is now being recognized that “dry,” airless planetary bodies have a volatile transport system [Lucey, 2009; Lawrence, 2011], and when there are PSRs, such as on the Moon or Mercury, the PSRs are a key sink in such a transport system. It is for these reasons (and others explained below) that PSRs have become a topic of intense study and interest within planetary science. Because PSRs are so different than other planetary environments, they contain a
wide range of fascinating effects, processes, and targets of scientific study. In addition to volatile enhancements, other interesting attributes about PSRs include unique surface charging and space plasma physics effects [Zimmerman et al., 2013; Jordan et al., 2015; Farrell et al., 2015], potentially distinctive geotechnical properties of the persistently cold and volatile-rich regolith [Schultz et al., 2010], and the possible organic synthesis that may take place within PSR volatiles due to long-term cosmic ray bombardment [Crites et al., 2013]. Because of their unique nature, PSRs can be difficult to study, and even now in the early 21st century there are many fundamental aspects of PSRs that are not understood. Nevertheless, current and future studies of PSRs hold great promise. PSRs are a significant scientific resource, not only for what they can reveal about their host planetary bodies but because they have been trapping volatiles for up to billions of years, they are a storehouse of solar system volatile materials, and they are therefore a resource for future studies of solar system history. As an analogy, it has been stated: “As Antarctica concentrates and stores solar system refractory materials in the form of meteorites, PSRs concentrate and store solar system volatiles.” (Originally heard by the author from Paul Lucey at a now, unrecalled planetary science meeting.) Finally, for at least the Moon, the existence of volatile enhancements, and especially water ice, can enable future human exploration to the Moon and elsewhere beyond in the solar system [Spudis, 2016].

The purpose of this paper is to review the scientific history of PSR volatiles by describing the early predictions of PSR volatiles and the evidence that has accumulated over the last six decades that support these early predictions. The exploration of PSRs has been carried out in three main epochs as illustrated by the time line in Figure 1. These epochs are initial predictions (1952–1992), initial measurements (1992–2001), and detailed measurements (2002 to present).

A fundamental result that has emerged from these studies is that in spite of similar PSR environments, the quality and quantity of volatile enhancements at the Moon and Mercury are very different. At Mercury, there is strong evidence from many types of measurements that its PSRs contain large amounts of volatiles. In contrast, while the Moon shows evidence of volatile enhancements within its PSRs, the volatile abundances are much less than at Mercury and appear nonuniform across different PSRs. Trying to understand these Mercury/Moon differences directly leads to trying to understand how the volatiles reached the PSRs and their time history within the PSRs. Much understanding has been gained, but many fundamental facts and
properties of PSRs are not yet known. As a consequence, there is still significant information and data that need to be gathered about PSRs to enable further understanding. While some of these data can be obtained remotely from orbital spacecraft, measurements will ultimately need to be acquired inside PSRs from the surface of Mercury and the Moon.

The structure of this paper contains three main sections. First, in section 2 the timeline of Figure 1 is used as an outline to describe the three epochs of PSR exploration. Section 2 provides the bulk of the review, as there is a wide and diverse history of predictions, measurements, and characterizations. Section 3 provides a brief review of the current understanding of the origin and time history of PSR volatiles, especially in regard to how this understanding relates to the differences between Mercury and the Moon. Finally, section 4 provides some perspective for the next 50 years by giving a brief summary of plans and thoughts for future studies of PSR volatiles.

2. Timeline of PSR Exploration

2.1. Initial Predictions

The initial predictions of volatile enhancements within PSRs were carried out sporadically for almost 40 years starting in 1952. Harold Urey provided the first tangential suggestion that “condensed volatile substances” might be present at the Moon’s poles in his book “The Planets: Their Origin and Development” (Urey, 1952). Specifically, Urey stated in Chapter 2, pages 17–18:

“The moon has no detectable atmosphere and none could be expected because of the low gravitational field and the high temperature of its surface during the day. Near its poles there may be depressions on which the sun never shines, where condensed volatile substances might be present, but if they ever evaporated they would be rapidly lost”; (italics not in original)

The first study to investigate details of lunar polar water ice was carried out by Watson et al. [1961a]. Using lunar nighttime temperatures of 120 K measured 30 years prior by Pettit and Nicholson [1930] and estimates of possible water liberated from the surface, Watson et al. [1961a] suggested that there might be concentrations of water ice within PSRs. Soon thereafter, Watson et al. [1961b] presented more detailed calculations of water transport across the Moon and retention at the poles to show that water could indeed be trapped in polar PSRs. In regard to sources, Watson et al. [1961b] primarily considered endogenous water from the Moon suggesting that external water from meteorites would be small compared to internal lunar water trapped at the poles. While Watson et al. [1961b] did not make quantitative predictions of the possible amount of polar water, Opik [1962] estimated that solar wind alone hitting the Moon could result in water deposits up to 100 m at the lunar poles, a prediction that has not proven correct. Nearly 20 years after these initial studies Arnold [1979] made detailed predictions of the amount of ice within lunar PSRs by accounting for various factors such as PSR lifetimes, temperatures, and areas, as well as volatile migration and possible endogenic and exogenic sources. Arnold [1979] found that when these sources were considered, the total mass of polar water ice could be in the range of \(10^{16}–10^{17}\) g. Arnold [1979] also predicted a water concentration in the range of 1–10 wt %, although this estimate was highly dependent on various parameters, such as area of permanent shade and depth of water ice enrichment. It is interesting to note that the amount of water ice at Mercury’s poles estimated by Moses et al. [1999] and later by Lawrence et al. [2013] is \(10^{16}–10^{18}\) g, which is within the same range estimated by Arnold [1979] for the Moon.

In contrast to the study by Arnold [1979], Lanzerotti et al. [1981] claimed that a significant accumulation of water ice was unlikely to be present in lunar PSRs; they estimated that water losses due to solar wind and Earth magnetospheric ions is comparable \((10^{6}–10^{8}\) protons/cm\(^2\)/s) to the deposition estimated by Arnold [1979] of \(~10^7\) molecules/cm\(^2\)/s.

During this period, the Moon attracted the most attention of initial studies of polar volatiles. However, water ice at Mercury’s poles was briefly discussed in a paper by Thomas [1974]. This paper was focused on the possibility of water within Mercury’s atmosphere but had the following statement: “If model ii [a model of Mercury’s atmosphere] prevailed on Mercury for a significant period in its history, ice could have accumulated in the polar regions in permanently shaded areas, as suggested for the Moon by Watson et al.” While some other studies parenthetically mentioned the possibility of volatiles within
Mercury’s poles [e.g., Kumar, 1976; Gibson, 1977], in general, Mercury was not a focus for studies of polar volatiles during this time. In summary, during the years of 1952 to 1992, there were relatively few studies of planetary PSRs. However, despite the few number of studies, the ones published demonstrate good physical insight and set the stage for the first round of planetary PSR measurements.

2.2. Initial Measurements of Polar Volatiles at Mercury and the Moon

The initial measurements that investigated polar volatiles at Mercury and the Moon took place during the last decade of the twentieth century using both Earth- and spacecraft-based instrumentation. The disparate measurement techniques of radar (Mercury and the Moon) and neutron spectroscopy (Moon) provided an initial confirmation of volatile enhancements at both bodies. The radar and neutron measurements at the Moon were supported by illumination and topography studies from Earth-based radar and spacecraft-based measurements.

2.2.1. Radar Measurements of Mercury and the Moon

Despite the fact that most attention regarding polar volatiles was focused on the Moon, the first measurements of PSR volatile enhancements were acquired from Mercury using Earth-based radar. Water ice has distinctive radar reflection properties such that it is highly radar reflective and it has a high circular polarization ratio (CPR) (i.e., same-sense to opposite-sense polarization of the radar echo) [Hapke, 1990], although other effects such as rocky surfaces can cause high CPR (see below and section 2.3.1). Prior to measurements at Mercury, these radar properties were used to characterize icy surfaces on Jupiter’s Galilean satellites [Campbell et al., 1978; Goldstein and Green, 1980; Ostro and Shoemaker, 1990], as well as Mars’ south polar ice cap [Muhleman et al., 1991].

The first radar measurements of Mercury and interpretations of these measurements were reported in a trio of papers [Slade et al., 1992; Harmon and Slade, 1992; Paige et al., 1992] followed by a more detailed analysis and discussion by Butler et al. [1993]. The initial radar measurements described by Slade et al. [1992] and Butler et al. [1993] (at a radar wavelength of 3.5 cm and a spatial resolution of 165 km) were carried out on 8 August 1991 and 23 August 1991 from the Very Large Array (VLA) radio telescope in Socorro, NM, which received signals transmitted from the 70 m radio transmitter in Goldstone, CA. These data showed that Mercury’s north pole had a high CPR (Figure 2) indicative of water ice. In a complementary set of
measurements conducted during 1991 and 1992 from Arecibo Observatory in Puerto Rico, Harmon and Slade [1992] reported radar reflection enhancements from both poles of Mercury that were consistent with the VLA measurements. The fact that Arecibo data showed radar properties at Mercury’s south pole (within the vicinity of the 150 km diameter Chao Meng-Fu crater) similar to what was seen at Mercury’s north pole further supported the idea that materials unique to Mercury’s polar environment were responsible for the detected radar properties [Butler et al., 1993]. The study of Paige et al. [1992] provided context for the radar measurements by showing that the likely thermal environment within PSRs at Mercury’s poles would be cold enough to retain water ice for geologically long periods of time. Butler et al. [1993] carried out a comprehensive analysis and interpretation of the radar data and thermal models and concluded that “ices (at least H2O) do exist at the poles of Mercury but not in the form of totally exposed, uniform coverage ice caps. The ice deposits are at least tens of meters in depth, probably formed relatively rapidly in permanently shaded regions, and were subsequently covered over by a shallow layer of dust or soil. Other ices may also collect in the same way and contribute our observed signal, depending on how cold it really is where the ices are being deposited.”

In a follow on study a couple of years later, Harmon et al. [1994] refined the analysis of the previously collected radar data and obtained new data to show that the radar-bright enhancements were indeed within craters near Mercury’s polar regions, further supporting the idea that PSRs at both poles contained enhanced water ice. The first attempt to measure volatiles in the lunar polar regions was conducted from the Clementine spacecraft that orbited the Moon for 71 days in 1994 [Nozette et al., 1994]. Instead of making a direct measurement of radar reflection, Nozette et al. [1996] carried out a bistatic measurement, where the radar transmitter was on the Clementine spacecraft and the radar signals were detected at Earth by the Deep Space Network (DSN) antennae. The purpose of the bistatic measurement was to enhance possible reflection effects from water ice and minimize effects caused by other surface features such as roughness and/or blocky material. Nozette et al. [1996] reported an enhancement of CPR for one orbit (orbit 234) over the Moon’s south pole, where there were likely PSRs, while other orbits not over likely PSRs showed no such effect (Figure 3). These results were interpreted as possibly due to water ice, though Nozette et al. [1996] stated that other effects such as surface roughness could in principle explain the measurement. In addition, due to the large footprint of the measurement, Nozette et al. [1996] stated that their measurement did not necessarily imply there were large expanses of water ice but that the possible ice could be mixed as patches within the polar regolith as “dirty ice.”

A number of other lunar radar studies followed. Stacy et al. [1997a] reported results from Earth-based Arecibo radar where large portions of the Moon’s south pole were imaged with radar backscatter and CPR data. Stacy et al. [1997a] found multiple radar enhancements associated with impact features, many of which were in sunlit regions. Based on these results, they concluded that there was little evidence in the Arecibo data for large expanses of ice at the Moon’s south pole. Subsequently, short reports by Weidenschilling [1997], Nozette et al. [1997], and Stacy et al. [1997b] made various points regarding the validity of the respective ice/no-ice claims based on the Clementine and Arecibo data. Simpson and Tyler [1999] produced a detailed reanalysis of the Clementine bistatic radar data concluding that they
could not reproduce the Nozette et al. [1996] results but that small amounts of water ice (1 wt% H₂O) were not inconsistent with the Clementine data. Finally, Nozette et al. [2001] reported a data integration study of multiple data sets, concluding that their original claim of water ice enhancements at the Moon’s south pole was consistent with all data but that ambiguities still remained, which needed better data to resolve.

2.2.2. Neutron Measurements of the Moon

Hydrogen abundances can be remotely measured on planetary surfaces using the technique of neutron spectroscopy [e.g., Feldman et al., 1991]. The principle of this technique starts with the fact that high-energy (~1 GeV per nucleon) galactic cosmic rays (GCRs) hit airless planetary bodies and create spallation neutrons from the surface nuclei. These neutrons are emitted with energies, Eₙ, of ~1–10 MeV and lose their energy (down to fractions of an eV) through various scattering processes. Planetary neutrons are typically divided into three energy ranges: fast (Eₙ > 0.5 MeV), epithermal (0.5 eV < Eₙ < 0.5 MeV), and thermal (Eₙ < 0.5 eV). The energy boundaries demarcate different types of neutron transport and lost processes. Hydrogen has the unique ability to moderate neutrons because hydrogen atoms and neutrons have the same mass, which allows for an efficient momentum transfer between the two. Of the three energy ranges, epithermal neutrons are most sensitive to the presence of hydrogen and are strongly depressed in the presence of hydrogen within planetary materials.

Lingenfelter et al. [1961] first recognized the possibility of using neutrons to remotely measure hydrogen on planetary surfaces. Feldman et al. [1991] later applied these ideas to the case of lunar PSRs and predicted that hydrogen abundances within the lunar PSRs could be measured with simple neutron sensors in orbit around the Moon. One aspect of orbital neutron data that has particular relevance for measurements of polar hydrogen abundances is that the spatial resolution of these data is roughly the altitude of the spacecraft making the measurement. This relatively broad spatial resolution is a consequence of the fact that the sensors generally used to detect neutrons are omnidirectional detectors and observe neutrons out to the horizon seen by the sensor (attempts to improve the spatial resolution have been made; see section 2.3.2).

The idea for using GCR-induced neutrons to measure hydrogen within the lunar PSRs was implemented on NASA’s Lunar Prospector (LP) mission [Binder, 1998], which orbited the Moon from 18 January 1998 to 19 December 1998 at an altitude of 100 ± 20 km, and from 19 December 1998 to 31 July 1999 at an altitude of 30 ± 15 km. Using the first 5 months of collected data from the Lunar Prospector Neutron Spectrometer (LP-NS), Feldman et al. [1998] reported count-rate decreases of epithermal neutrons at both lunar poles, which provided strong evidence for enhanced hydrogen abundances in and around the lunar PSRs. Assuming that the enhanced hydrogen reaches a depth of 2 m, which is the depth of lunar regolith thought to be gardened in 2 billion years [Arnold, 1979], Feldman et al. [1998] estimated that the total equivalent water at each pole was 3 × 10⁸ t (or 3 × 10¹⁵ g). This value is roughly an order of magnitude less than the lower value predicted by Arnold [1979]. Later studies using the full 18 month data set refined the location and abundance of the lunar polar hydrogen enhancements (Figure 4). With the higher spatial resolution data from the low-altitude portion of the mission, Feldman et al. [2000] and Feldman et al. [2001] concluded that the hydrogen enhancements were generally located in and around PSRs, although the spatial resolution of the low-altitude data (30–45 km) [Maurice et al., 2004] was sufficiently broad to preclude identification of specific PSRs with hydrogen enhancements. At the south pole, which has larger PSRs, the neutron data were combined with measurements of PSR area (see section 2.2.3) to estimate that the hydrogen concentration within PSRs was 1670 ± 890 ppm, or 1.5 ± 0.8 wt% water equivalent hydrogen (WEH), if this hydrogen is in the form of water ice. The primary source of uncertainty in these estimates is uncertainties in the area of permanent shade and how much of each PSR contains the enhanced hydrogen. At the north pole, where there are many small PSRs, Feldman et al. [2000] reported that the average hydrogen concentration over the full-area LP-NS footprint was 100 ppm higher than the hydrogen seen at more equatorial latitudes. Based on various arguments from location, abundance, and thermodynamics, Feldman et al. [2001] argued that the most likely form of the enhanced hydrogen was water ice.

In a response to the Feldman et al. papers, Hodges [2002] questioned the conclusions that the LP-NS data uniquely identified hydrogen at the lunar poles and suggested that abundance variations from other elements (e.g., Si and Ca) could explain the epithermal neutron data. Lawrence et al. [2006] carried out a more detailed modeling analysis than was done for the Feldman et al. studies and concluded that enhanced hydrogen abundances best explained the polar neutron data.
2.2.3. Illumination and Topography Studies of the Lunar Poles

One more collection of measurements related to the lunar poles in this time period of initial measurements was that of topography and polar illumination. The Clementine spacecraft carried a laser altimeter from which mostly global lunar topography measurements were obtained [Smith et al., 1997]. Due to the nature of the Clementine spacecraft’s orbit, direct topography measurements poleward of 82°N and 79°S were not obtained [Cook et al., 2000]. Nevertheless, using long- and short-wavelength topography close to the south pole, it was inferred that possible crater-shaped PSRs were no larger than 80 km at the pole and likely no larger than ~30 km for locations 2° off the pole [Zuber and Smith, 1997]. Data from Clementine images enabled the derivation of lunar topography maps using stereo imaging [Cook et al., 2000], although the resulting maps had a number of gaps.

The first detailed maps of lunar polar topography were obtained with Earth-based radar interferometry data where range differences between points on the Moon’s surface and two receivers on Earth were used to derive lunar elevation information [Margot et al., 1999]. With these topography data from both poles, Margot et al. [1999] used ray tracing algorithms to derive locations in permanent shade (Figure 5). One limitation to this technique is that locations on the Moon’s farside cannot be mapped, so PSR areas in unmapped areas were estimated based on modeling of expected topography. Margot et al. [1999] estimated areas of 2650 km² and 5100 km² for the north and south poles, respectively. These values were used as input data for estimates of total polar hydrogen from the LP-NS neutron data [Feldman et al., 2000, 2001]. Finally, using Clementine images taken at a range of local times, Bussey et al. [1999] quantified the illumination conditions at the Moon’s south pole, and in a subsequent study [Bussey et al., 2003] found larger PSR areas of 7500 km² and 6500 km² at the north and south poles, respectively.

2.2.4. Summary of Initial Measurements

The general conclusion from this first round of measurements at Mercury and the Moon is that the poles of both bodies have enhanced volatiles. However, the exact amount and form of the volatiles remained uncertain. While the evidence for water ice at Mercury’s poles was strong, alternate explanations for the radar data were put forward to explain the radar data, ranging from enhanced sulfur abundances [Sprague et al., 1995] to unusual thermal effects in silicate materials [Starukhina, 2001]. For the Moon, arguments were made that the most likely form of enhanced hydrogen was water ice [Feldman et al., 2001], but due in part to the

Figure 4. Maps of epithermal neutrons for the north and south poles measured by the Lunar Prospector Neutron Spectrometer. Data are originally from Feldman et al. [2001], and the figure is taken from Lucey et al. [2006] (figure courtesy of Reviews of Mineralogy and Geochemistry).
relatively small hydrogen concentrations, other studies suggested that the PSR hydrogen enhancements could be explained by the long-term deposition of solar wind hydrogen [Crider and Vondrak, 2000; Starukhina and Shkuratov, 2000]. Thus, this situation set the stage for the large number of new Earth- and spacecraft-based measurements that are explored in the next section.

**Figure 5.** Locations of cold traps at the lunar (top) north and (bottom) south poles (figure from Margot et al. [1999]). Areas that were visible to the radar and are in permanent shadow from solar illumination have been marked with white pixel values. Several other regions, which were not visible to the radar (that is, in radar shadow), have been depicted with gray pixels to indicate that they are predicted, on the basis of the topography of the surrounding terrain, to also be in permanent shadow (figure courtesy of Science magazine).
2.3. Detailed Measurements of PSRs

Starting midway between 2000 and 2010, a large number of measurements and analyses of Mercurian and lunar polar regions were carried out. The primary measurements came from six spacecraft as well as additional Earth-based data. Of the six spacecraft, one was flown by India (Chandraayan-1), one by Japan (Kaguya renamed from SELENE), one by China (Chang’E-1), and the remaining were flown by NASA. The NASA missions are the Lunar Reconnaissance Orbiter (LRO) [Chin et al., 2007], the Lunar Crater Observation Sensing Satellite (LCROSS) [Colaprete et al., 2012], and the Mercury Surface, Space Environment, Geochemistry, and Ranging (MESSENGER) mission [Solomon et al., 2007]. The data from the Earth-based measurements and six spacecraft provided large amounts of new information about PSR environments and have provided a significantly enhanced understanding of PSRs and their volatile enhancements. In addition, analyses and interpretation of prior and newly collected data provided further understanding of PSRs. Because there is a large number of PSR or PSR-related studies from 2006 to the present, only the highlights can be summarized here. The general categories of these studies are new results based on radar, neutron, and topography measurements, as well as new measurements of temperature, reflectance from different photon wavelengths, and an in situ impact measurement of a lunar PSR.

2.3.1. New Information From Radar Measurements of Mercury and the Moon

This period of detailed measurements saw many types of radar measurements of both the Moon and Mercury. For Mercury, a number of measurement campaigns from the Arecibo and Goldstone radio telescopes were carried out from 1999 to 2005. The results from these campaigns are summarized by Harmon et al. [2011]. Specifically, using improved measurements and analysis techniques, detailed radar maps were produced for both Mercury’s north and south poles (Figure 6). Based on these data, Harmon et al. [2011] concluded that many craters at both poles are completely covered with radar reflective materials, and many other craters are partially covered. The 112 km diameter crater Prokoviev (86°N, 296°W) is a particularly dramatic example of a partially covered radar-bright crater. Comparison of the 12.6 cm radar data from Arecibo with shorter wavelength (3.5 cm) data from Goldstone was interpreted by Harmon et al. [2011] to indicate that for many locations, a dusty, less water-rich layer that is tens of centimeter thick covers pure water ice layers. Radar reflective signatures were detected in many small craters down to a latitude of 67°; the locations of these craters are biased toward Mercury’s longitudinal cold poles. While providing more details, these comprehensive radar data continued to be consistent with the initial conclusions of Slade et al. [1992] and Harmon and Slade [1992] that Mercury’s PSRs are filled with water ice.

In contrast to the reasonably clear conclusions drawn from Mercury radar data, radar measurements of the Moon have continued to be more challenging to interpret. In 2006, Campbell et al. [2006] reported new radar reflection data of the Moon’s south pole using the Arecibo radio telescope. With particular attention to Shackleton crater, which is located almost directly at the pole, Campbell et al. [2006] concluded that there were no large expanses of water ice at Shackleton or elsewhere in the Earth-visible vicinity of the pole. Radar polarization signatures normally associated with ice were seen at various latitudes and often correlated with rocky surfaces. These results, however, did not rule out small amounts of water ice (<10 wt %) disseminated within grains in the lunar regolith.

Orbiting radar instruments were included on the payloads of the Chandraayan-1 and Lunar Reconnaissance Orbiter (LRO) missions and acquired data from the lunar poles. Results from the Mini-SAR on Chandraayan-1 and Mini-RF on LRO were published by Spudis et al. [2010] and Spudis et al. [2013], respectively (Figure 7). The conclusions from both these studies are that many craters across the Moon have high CPR values and that these high values can be due to either large amounts of surface roughness and/or the presence of water ice. In both studies, two classes of high CPR craters were identified, where one class has high CPR both inside and outside the craters, whereas the other class, known as anomalous craters, has high CPR mostly inside the respective craters. A number of characteristics led Spudis et al. [2013] to conclude that water ice is the likely cause of the high CPR for the anomalous craters. First, most of these craters are also PSRs and could therefore host water ice. Second, a significantly larger number of these craters exist in the small-area polar regions than in the rest of the larger nonpolar area across the Moon, which suggests that there is something special about the polar regions to enhance the number of anomalous craters. Finally, application of radar scattering models [Thompson et al., 2011] suggests that water ice provides a good explanation of the polar anomalous craters compared to other types of craters where roughness could be the cause of the high CPR signatures.
In contrast to these results, separate studies investigated the possibility that factors other than water ice may be causing the high CPR in the anomalous polar craters. Fa and Cai [2013] studied anomalous craters in nonpolar regions, where water ice would not be present, and using topography data from these craters, they concluded that a relatively high rock abundance was likely responsible for their high CPR, a conclusion also reached by Spudis et al. [2013]. Based on additional statistical studies and a good match of their data with a two-component mixed radar scattering model, Fa and Cai [2013] concluded that the high CPR within anomalous polar craters might also be due to roughness. In a complementary study, Eke et al. [2014] analyzed Mini-SAR data and found that when these data were corrected for look-direction effects, the resulting CPR maps were significantly changed from the originally published data. With these corrected

Figure 6. Radar images of Mercury’s (a) south and (b) north polar regions (figure taken from Harmon et al. [2011]). For the south pole, the mean radar illumination direction (arrow) is from the bottom and the dark blank area at the top is the region that is beyond the radar horizon (figure courtesy of Icarus).
data, Eke et al. [2014] showed that the CPR values did not correlate with surface temperatures as might be expected if water ice was causing the high CPR values and that higher CPR values were found in craters with steeper slopes, which may have more rocky surfaces. Thus, Eke et al. [2014] also concluded that other factors, such as surface roughness, may be responsible for some portion of the elevated CPR within polar anomalous craters.

Finally, in a different use of the Mini-RF instrument, Patterson et al. [2016] reported on the results of a bistatic measurement where radar signals from Arecibo were aimed at the Moon and detected at LRO, a reverse configuration of the original Clementine bistatic radar experiment of Nozette et al. [1996]. In this study, multiple locations on the Moon, both polar and nonpolar, were observed at various bistatic phase angles between the radar source and receiver. For such a configuration, water ice is expected to show an “opposition surge” such that for very small bistatic angles, there should be a CPR enhancement. While a prior study did not find enhanced CPR within Cabeus crater [Neish et al., 2011], Patterson et al. [2016] found an opposition surge within sunlit portions of Cabeus crater nearby parts of the crater that are within permanent shade (Figure 8). Given the unique nature of the signature, Patterson et al. [2016] concluded that there might be water ice beneath the surface where temperatures could be sufficiently cold to inhibit the release of water ice.

**2.3.2. New Information From Neutron Data at the Moon and Mercury**

Additional analyses of prior neutron measurements and new neutron measurements from both the Moon and Mercury took place in the time period after 2006. As described in section 2.2.2, the primary limitation of the LP-NS data is that its spatial resolution was sufficiently broad to prevent a definitive identification of
hydrogen enhancements with specific PSRs. One way to provide higher spatial resolution information of lunar polar hydrogen measurements is to apply spatial deconvolution algorithms to the neutron data. A sequence of such analyses was carried out by Elphic et al. [2007], Eke et al. [2009], and Teodoro et al. [2010], where it was concluded (1) that the enhanced hydrogen at the lunar poles was preferentially located within PSRs, (2) that the PSRs did not contain uniformly enhanced hydrogen, and (3) that the inferred hydrogen concentrations within PSRs ranged from 300 ppm to as high as a few weight percent WEH. In addition to these spatial deconvolution studies, Miller et al. [2014] carried out a combined analysis of LP epithermal and fast neutron data. Based on the knowledge that these different neutron energy ranges are sensitive to different hydrogen burial depths, Miller et al. [2014] concluded that hydrogen enhancements of ~1 wt % WEH at Shackleton crater were possibly located at the surface, whereas the hydrogen enhancements at other south polar locations were likely buried by tens of centimeters of drier material. Finally, Eke et al. [2015] carried out a global analysis of LP epithermal neutron data and found that the geometry of bowl-shaped craters in the size range of 20 to 60 km could cause a subtle enhancement of epithermal neutrons. Based on this analysis, Eke et al. [2015] suggested that the inferred hydrogen abundances within the relatively deep Cabeus crater could have been underestimated at 1 wt % WEH and may be as high as ~4 wt % WEH.

A second way to provide improved spatial resolution information of orbital neutron data is to use new detection techniques. To this end, the LRO spacecraft carried the Lunar Exploration Neutron Detector (LEND) [Mitrofanov et al., 2010b], which used a collimator made from neutron-absorbing materials to narrow the field of view of a standard $^3$He neutron sensor. In principle, such a collimated sensor can provide measurements with a spatial resolution that is up to a factor of 4 better than the LP-NS measurements. Initial results from LEND were reported by Mitrofanov et al. [2010a] and claimed to have a spatial resolution small enough to

![Figure 8. Plots of mean CPR (solid lines) versus bistatic angle (figure taken from Patterson et al. [2016]). Data are shown for (a) highland materials, (b) radar-facing slopes, and (c) Cabeus floor materials sampled in five bistatic observations targeting Cabeus. Uncertainty is represented by the 3σ standard deviation of the mean for the measurements in each bistatic angle bin (dashed lines). (d) Summary plot shows results of all sampled regions (thick solid line is Cabeus) (figure courtesy of Icarus).](image-url)
resolve individual PSRs. As part of these results, Mitrofanov et al. (2010a) stated that hydrogen enhancements were likely located both inside and outside PSRs and had concentrations in the range of 0.5 to 4.0 wt% WEH, results generally consistent with the prior analyses of LP-NS data by Elphic et al. (2007), Eke et al. (2009), and Teodoro et al. (2010). The spatial resolution performance claims of Mitrofanov et al. (2010a) and Mitrofanov et al. (2010b) were disputed by Lawrence et al. (2010) and Lawrence et al. (2011a). The disputes were based on arguments that background epithermal neutrons which penetrate the collimator were significantly underestimated by the LEND analyses and that these uncollimated background neutrons were also sensitive to hydrogen, but in an uncollimated manner. As a consequence, the Lawrence et al. studies concluded that the LEND spatial resolution was significantly broader than claimed by the Mitrofanov et al. studies. Following these initial reports, a large number of additional studies were published that provided disparate conclusions of whether the LEND instrument either achieved [Mitrofanov et al., 2011, 2012; Boynton et al., 2012; Litvak et al., 2012; Sanin et al., 2012] or did not achieve [Eke et al., 2012; Miller, 2012; Miller et al., 2012; Teodoro et al., 2014] its original spatial resolution claims. While this author contends the evidence conclusively shows that the LEND instrument did not achieve its original performance goals and thus did not spatially resolve individual PSRs (as grounded upon multiple independent and complementary analysis techniques described in the above-referenced studies), to date, the respective claims of the two different interpretations of LEND data have not reached a public uniform agreement. The interested reader is referred to the above mentioned papers and references therein for more information.

The first neutron measurements at Mercury were conducted using the Neutron Spectrometer (NS) [Goldsten et al., 2007] on board the MESSENGER mission. The primary goal of these measurements was to either confirm or refute the hypothesis that water ice is the dominant species present in Mercury’s PSRs. In contrast to the lunar neutron measurements that collected neutron data at low altitudes (30–100 km) relative to the Moon’s radius of 1737.4 km, the MESSENGER mission had a highly eccentric orbit about Mercury (2439.7 km radius), with orbit altitudes that ranged from 400 to ~20,000 km. Since robust planetary neutron measurements can only be made from distances of ~<1 planetary radius, the primary MESSENGER NS measurements were made in Mercury’s northern hemisphere where the spacecraft had altitudes in the range of 400–800 km. Even at these high altitudes, neutron measurements of Mercury’s PSRs were challenging, as the broad spatial resolution of these measurements (hundreds of kilometers) competed with the need to detect hydrogen signatures from craters with sizes generally less than 50 km in diameter. Because of this broad spatial resolution relative to the size of the PSRs, the decrease in epithermal neutron signal from 100 wt% water ice within north pole PSRs at Mercury was expected to be a few percent or less [Lawrence et al., 2011b]. In comparison, the decrease in epithermal neutrons due to 1 wt% WEH at the Moon was around 7–10% [Feldman et al., 2000]. Nevertheless, based on the first 10 months of orbital data, Lawrence et al. [2013] reported a decrease in the polar epithermal neutron count rate that closely matched the expected count rate decrease if the north pole PSRs were filled with large amounts (50–100 wt% WEH) of water ice (Figure 9). In addition, measurements of higher-energy fast neutrons suggested that this water ice was likely buried beneath tens of centimeters of drier material, consistent with similar suggestions from Earth-based radar data [Harmon et al., 2011]. Thus, the Mercury neutron data were consistent with the idea that Mercury’s radar-bright enhancements were most likely due to water ice.

2.3.3. Orbit-Measured Topography and Temperature Information

The time period after the year 2006 saw the advent of many new types of measurements of the poles of the Moon and Mercury. These include topography and temperature measurements (discussed in this section), as well as new reflectance measurements at a variety of wavelengths (discussed in section 2.3.4).

Lunar polar topography measurements were carried out by the Chinese Chang’E-1 [Ping et al., 2009], the Japanese Kaguya [Araki et al., 2009], and the U.S. LRO [Smith et al., 2010] spacecraft. These topography data were used to construct models of polar illumination from which full-coverage PSR locations and areas were derived. Noda et al. [2008] used data from the Kaguya laser altimeter (LALT) instrument to obtain PSR areas that were updated and within 20% of those of the partial-coverage results of Margot et al. [1999]. Full polar coverage data from the LRO Laser Orbital Laser Altimeter (LOLA) were also used to construct illumination models of PSRs at both lunar poles [Mazarico et al., 2011]. Of all these studies, Mazarico et al. [2011] found the largest PSR areas of 12,866 km² for the north pole and 16,055 km² for the south pole. Compared to the
prior studies of Noda et al. [2008] and Bussey et al. [2003], Mazarico et al. [2011] attributed these larger areas to a better identification of small craters (<10 km) in the north and a more regular digital elevation model (DEM) in the south. In general, these studies confirmed that PSRs in the north are smaller but more numerous, whereas the PSRs in the south are larger but fewer in number.

Direct temperature measurements were made of the lunar surface—and specifically the south pole—using LRO’s Diviner instrument [Paige et al., 2010]. These measurements showed a wide range of temperatures within PSRs from ~120 K to less than 40 K (Figure 10). As a result, there are large expanses around the Moon’s south pole that are cold enough to trap water ice at the surface. Using these measured surface temperatures as a tie point, Paige et al. [2010] then derived a three-dimensional thermal model of the Moon’s south pole (Figure 10c) and identified depths down to 1 m where water ice is stable (Figure 10d). These results showed that there are large areas of stability for subsurface water ice near the PSRs that can act as a “permafrost.” Siegler et al. [2016] reported updates of the water ice stability depths for the south pole, as well as the first water ice stability depths for the north pole. Paige et al. [2010] also showed that the lunar PSRs are cold enough to trap other volatile species, such as sodium, mercury, and other compounds (e.g., CO2). Such species were found in the first in situ measurements of lunar south pole material (section 2.3.5). The Chang’E-1 mission carried a four-channel microwave radiometer that obtained subsurface temperature measurements in the polar regions that are complementary to the Diviner measurements [Gong and Jin, 2012].

As with the different lunar spacecraft, NASA’s MESSENGER mission carried a laser altimeter—the Mercury Laser Altimeter (MLA)—from which topography measurements of Mercury were obtained. Because of MESSENGER’s eccentric orbit, and the need for the MLA to obtain measurements from within ~1500 km of the surface, Mercury’s polar topography was only gathered from its northern hemisphere. The MESSENGER spacecraft did not have an instrument to directly measure surface temperature, but using the topography data, a high fidelity thermal model was constructed for Mercury’s north pole (Figure 11) [Paige et al., 2013] grounded upon the same measurement-validated model of the Moon’s south pole. Based on these modeled temperatures, a number of important new aspects of Mercury’s PSR’s were revealed. First, while Mercury’s PSRs are cold enough to trap water ice, they are nevertheless warmer than the Moon and do not reach the very low temperatures seen at the lunar poles (<~50 K). Second, based on these thermal models, it was found that locations of water ice stability match well the locations of radar-bright regions, which further supports the idea that the radar-bright regions are composed of water ice. In an unexpected finding, different locations of surface and subsurface water ice stability match locations where the surface reflectance is anomalously bright and dark, respectively (see section 2.3.4). Paige et al. [2013] interpreted these results to imply...
Figure 10. Maps of measured and model-calculated surface and subsurface temperatures in the lunar south polar region (figure taken from Paige et al. [2010]). The outer circle on all maps is 80° south latitude. Observations were acquired between 6 September and 3 October 2009 as the Moon approached southern summer solstice. (a) Diviner-measured daytime bolometric brightness temperatures acquired between 11.4 and 13.6 h local time. (b) Diviner-measured nighttime bolometric brightness temperatures acquired between 21.41 and 1.66 h local time. (c) Model-calculated annual average near-surface temperatures and the location of the LCROSS impact in Cabeus Crater. (d) Model-calculated depths at which water ice would be lost to sublimation at a rate of less than 1 kg m$^{-2}$ per billion years. The white regions define the locations where water ice can currently be cold trapped on the surface, the colored regions define the upper surface of the lunar ice permafrost boundary, and the gray regions define locations where subsurface temperatures are too warm to permit the cold trapping of water ice within 1 m of the surface (figure courtesy of Science magazine).
that the bright regions are surface water ice and that the dark regions are composed of a less water-rich but more carbon-rich (organic) material that may be a sublimation lag deposit left over from the original material deposited in the PSRs. Finally, MLA data have been used to place limits on the maximum thickness of radar-bright deposits. Specifically, Talpe et al. [2012] examined the morphology and depth of many north polar craters and found no detectable difference between craters hosting deposits and those not hosting deposits. Based on this observation and the statistical limits of the analysis, Talpe et al. [2012] concluded that the radar-bright deposits have an upper limit thickness of <170 m.

2.3.4. Reflectance Measurements of PSRs

Reflectance measurements—passive and active—were made of PSRs at both the Moon and Mercury from orbiting spacecraft. These measurements, some of which were not part of the original mission plans, have yielded important new information about volatiles and PSR environments at both bodies.

2.3.4.1. Reflectance Measurements: At the Moon

At the Moon, PSR reflectance measurements have been carried out in three broad categories: passive reflectance in the visible wavelengths, passive reflectance in ultraviolet (UV) wavelengths, and active (laser) measurements at the near-infrared (IR) wavelength of 1064 nm. The first direct passive image of a PSR was reported by Haruyama et al. [2008], where the interior of Shackleton crater was imaged using the Terrain Camera on the Japanese Kaguya spacecraft (Figure 12). Haruyama et al. [2008] showed that there were no anomalous or unusual materials within Shackleton crater and concluded that there was no evidence for exposed water ice on its surface. In a follow-up study, Haruyama et al. [2013] used additional data from the Kaguya multiband imager to infer that bright features near Shackleton’s inner wall close to its rim may be rich in anorthosite as opposed to water ice, as was suggested from LRO LOLA reflectance data [Zuber et al., 2012] (see more below). Even though surface ice was not detected at Shackleton, Haruyama et al. [2013] stated that 1 to 2 wt% water ice mixed within the soil at Shackleton [Miller et al., 2014] would be consistent with their observations. Visible wavelength images using the LRO Lunar Reconnaissance Orbiter Camera (LROC) were taken of the inside of multiple lunar PSRs [Koeber et al., 2014]. In contrast to the PSRs at Mercury [Chabot et al., 2014] (see also below), the lunar PSRs showed no anomalous features or terrains at visible wavelengths, but CPR-anomalous craters [Spudis et al., 2013] showed indications of being younger than their “nonanomalous” counterparts.

A second type of passive reflectance measurement was carried out in UV wavelengths using data from the LRO Lyman Alpha Mapping Project (LAMP) instrument. The LAMP instrument detects reflected UV photons from interplanetary Lyman alpha radiation (121 nm) as well as from UV-bright stars. Using the first 18 months
of data accumulation of LAMP data, Gladstone et al. [2012] reported UV measurements of south pole PSRs and found that all PSRs are darker compared to non-PSR regions and that most PSRs have stronger reflectance at longer wavelengths (i.e., they are "redder"). From these results, Gladstone et al. [2012] inferred that the surfaces of PSRs have higher porosities than non-PSR regions and that the preference for redder reflectance was consistent with the presence 1 to 2 wt % water frost at the top surface of the PSRs.

Hayne et al. [2015] carried out a more extensive modeling and analysis of both LAMP and polar temperature data measured by the Diviner instrument. In this study, Hayne et al. [2015] made a number of key observations and conclusions regarding lunar PSR volatiles and environments. First, by separately delineating the UV spectra for temperatures above and below the water sublimation temperature of 110 K, Hayne et al. [2015] found that the UV spectral characteristics strongly changed for temperatures below 110 K, which provided compelling evidence for the presence of surface water frost. Second, based on the UV spectral characteristics within PSRs, Hayne et al. [2015] concluded that high porosities could not fully explain the PSR observations. Third, a bimodal distribution of UV spectral water features at the south pole was found such that one population of PSR locations was grouped just below the water sublimation temperature of 110 K, and another, larger population of PSR locations had temperatures near 65 K. This distribution could be explained by either a different type of temperature-dependent vertical mixing from impact gardening at low temperatures and water-diffusion-based migration at temperatures near 110 K, and/or possible CO2 enhancements at the colder locations. This author notes, however, that if there are CO2 enhancements in the few wt % range similar to the inferred water frost abundance [Hayne et al., 2015], and if such enhancements extended to centimeter-type depths (as do the inferred hydrogen enhancements based on neutron data), then such CO2 enhancements would be detectable with thermal neutron data as has been done in nonpolar locations at Mercury [Peplowski et al., 2016]. That such thermal neutron enhancements are not detected in the vicinity of any of the cold PSR regions [Miller et al., 2014] argues against the CO2 hypothesis. Finally, Hayne et al. [2015] delineated a spatially heterogeneous distribution of water frost (Figure 13) and as a consequence suggested that the destruction of water frost by impact gardening and space weathering is itself spatially heterogeneous.

Active reflectance measurements of lunar PSRs were made using the near-IR 1064 nm laser from LRO’s LOLA instrument [Zuber et al., 2012; Lucey et al., 2014]. With these actively interrogated reflectance measurements, it was found that all PSRs have systematically higher reflectance values at 1064 nm than non-PSR regions [Lucey et al., 2014], with Shackleton crater showing a particularly high reflectance [Zuber et al., 2012; Lucey et al., 2014]. These high reflectances can be partially accounted for by mass wasting on steep-walled craters revealing new and brighter material. After accounting for steep-slope mass wasting, Lucey et al. [2014] ruled out enhanced porosity as the sole explanation for the increased reflectance but suggested that either
enhanced water frost and/or reduced space weathering might explain the higher PSR reflectances. If surface water ice is responsible for the increased PSR reflectance, then possible abundances would range from 3 to 14 wt%; if reduced space weathering causes the enhanced reflectances, then the PSR regions would have between 50% and 80% less nanophase iron than mature lunar soil.

2.3.4.2. Reflectance Measurements: At Mercury

Passive and active measurements of Mercury’s PSRs were carried out with instruments on the MESSENGER spacecraft. Active reflectance measurements were made with the 1064 nm laser from MLA in a manner similar to the LOLA measurements of the Moon. Passive reflectance measurements were obtained using MESSENGER’s Mercury Dual Imaging System (MDIS), which used a broadband clear filter (700 nm central wavelength; 600 nm bandwidth) to gather images at pixel scales ranging from ~100 m to almost as small as 20 m. The MDIS measurements characterized the PSR illumination conditions as well as imaged the permanently shaded portions of Mercury’s north pole craters.

As for the Moon, active reflectance measurements at Mercury are particularly useful for PSRs where there is no direct illumination from sunlight. The first reflectance measurements of Mercury’s PSRs were reported by Neumann et al. [2013]. In contrast to the Moon that showed moderate PSR brightness enhancements, the MLA data clearly revealed anomalous dark and bright regions in almost all the PSRs that were interrogated (e.g., Figure 14 shows dark regions). In general, these anomalous regions were located on poleward facing slopes and showed a high degree of spatial correlation with locations of radar-bright enhancements. When these data were compared with the polar thermal models [Paige et al., 2013], the optically bright regions (the most prominent being Prokofiev crater) were found in places where water ice is stable at the surface. A large number of dark regions were found in locations of thermal stability for subsurface water covered

![Figure 13. Locations of anomalous UV albedo consistent with water ice (figure taken from Hayne et al. [2015]). Colors indicate points with off-/on-band albedo ratio values >1.2 and Lyman α albedo <0.03, increasing from deep orange (1.2) to white (>3.2). The average Moon outside of the cold traps has a ratio of ~0.9. Ratio values in the range 1.2–4.0 are consistent with water ice concentrations of ~0.1–2.0% by mass. If patchy exposures of pure water ice are mixed by area with dry regolith, the abundance could be up to ~10% (figure courtesy of Icarus).](image)
by a layer (tens of centimeters thick) of less water-rich material. In addition, these locations were thermally stable at the surface for materials rich in carbon-bearing materials, many of which happen to have a dark reflectance. These thermal and reflectance results combined with the neutron and radar data made a very strong case that Mercury’s PSRs were indeed filled not only with water ice but also more complex volatile materials. In a recent study, Delitsky et al. [2016] suggested that the dark, carbon-rich material may be dominantly formed by energetic protons and electrons focused to the polar regions by Mercury’s magnetic field.

The first illumination maps of Mercury’s south [Chabot et al., 2012] and north [Chabot et al., 2013] poles were constructed using imagery from MESSENGER’s MDIS. These maps confirmed that all radar-bright regions are located within PSRs but that not all PSRs contain radar-bright materials. For craters farther than 10° from the poles, the illumination maps confirmed the bias for radar-bright regions to be within PSRs at Mercury’s cold longitudes of 90°E and 270°E rather than 0°E and 180°E. In a more extensive analysis of illumination conditions, Deutsch et al. [2016] found that ~45% of PSRs hosted radar-bright materials. Some of the craters lacking radar-bright materials are located within 10° of the pole (e.g., Sapkota and Burks; see Figure 15) and, as a consequence, should have a similar thermal environment to nearby craters that do not host radar-bright deposits. Deutsch et al. [2016] investigated the possibility that nonuniform coverage of the Earth-based radar data caused radar-bright materials to be “missed.” Simulations of the radar illumination conditions showed that if these craters contained radar-bright materials, they should have been detected. This conclusion therefore leaves open the possibility that whatever process deposited the volatile materials at Mercury’s north pole did so in a spatially nonuniform manner.

The interior of Mercury’s north polar PSRs were directly viewed using MDIS imagery in a manner similar to the PSR images of the Moon. In contrast to the Moon, Mercury’s PSRs show striking and distinctive features [Chabot et al., 2014, 2016]. Dark deposits identified by MLA were also easily identified as dark in the MDIS images (Figure 16). The center of Prokofiev crater shows up as bright in the image data as it did in the MLA data (Figure 17). Various textures within the deposits (e.g., small craters, and hills) do not appear to be obscured by either the bright or dark deposits. As described by Chabot et al. [2014], the boundaries of the dark deposits are very sharp and distinct and, in most cases, are colocated with permanent shade boundaries as well as radar-bright enhancements when present. In many instances, the dark regions are uniformly dark across large expanses, but as revealed in the highest spatial resolution data, there are sometimes smaller bright patches that appear to be associated with temperature variations within the larger dark regions. The existence of the underlying textures in dark and bright deposits indicates that these PSR deposits were emplaced after the formation of such textural features. The existence of the sharp boundaries indicates that the deposits may be young, having been emplaced either in the geologically recent past and/or supplied by an ongoing process.

2.3.5. Ground Truth Measurements of a Lunar PSR

The final set of measurements described in this section is from the LCROSS mission that flew in 2009 [Colaprete et al., 2012]. The goal of the innovative LCROSS experiment was to investigate lunar PSRs by exercising a controlled impact into a PSR and observe the resulting effects. The LCROSS spacecraft was colaunched with LRO on 18 June 2009 and carried a payload of cameras and reflectance spectrometers. The concept of operations was that the LRO Centaur upper stage shell, which flew to the Moon with the...
Figure 15. Shadowed regions displayed on a mosaic of MESSENGER images from 80°N to 90°N in polar stereographic projection (figure taken from Deutsch et al. [2016]). (a) Areas shadowed in all MDIS images are shown in cyan, radar-bright deposits are in yellow, and areas with both shadow and radar-bright materials are in coral. Sapkota, Burke, and Yamada craters are outlined in magenta. (b) Areas shadowed in the MLA model are shown in cyan, radar-bright deposits are in yellow, and areas with both shadow and radar-bright materials are in coral. Radar data are from Harmon et al. [2011] (figure courtesy of Icarus).
Figure 16. Low-reflectance material in 31 km diameter Berioz crater; the rim of the crater is outlined in pink. All images are in stereographic projection about the north pole; north is to the top (figure taken from Chabot et al. [2014]). (a) Radar-bright (yellow) [Harmon et al., 2011] and persistently shadowed (red) regions are collocated. (b) Illumination conditions ~20 h prior to acquiring the image in Figure 16c. (c) Wide-angle camera broadband image reveals low-reflectance material. (d) Low-reflectance area extends to the edge of the radar-bright and persistently shadowed regions. (e) Reflectance values measured by the Mercury Laser Altimeter (MLA) [Neumann et al., 2013]. (f) Calculated maximum surface temperatures [Paige et al., 2013] (figure courtesy of Geology).
LCROSS spacecraft after separating from the LRO spacecraft, would impact a PSR and be closely followed by the LCROSS spacecraft. In the time between the impact of the Centaur and LCROSS spacecraft, LCROSS instrumentation would make measurements of the impact and resulting ejecta plume. At the same time, it was planned that the orbiting LRO spacecraft would also make measurements of the impact event.

The LCROSS experiment was successfully carried out on 9 October 2009 when both it and the Centaur upper stage impacted into Cabeus crater at the Moon’s south pole (Figure 18). The initial results from the experiment were described by Colaprete et al. [2010], Gladstone et al. [2010], Hayne et al. [2010], and Schultz et al. [2010]. Spectral measurements of the ejecta plume detected the presence of water along with the presence of a number of other volatile species, including light hydrocarbons, sulfur bearing species, and CO2 [Colaprete et al., 2010; Schultz et al., 2010]. The total amount of water detected using near-IR spectra was estimated to be 155 ± 12 kg [Colaprete et al., 2010]. Based on this measurement and other information from the impact event, it was estimated that the water concentration at the impact site was 5.6 ± 2.9 wt % H2O, which is larger than that estimated based on original values from neutron data [Feldman et al., 2001] but is closer to revised estimates of hydrogen enhancements within Cabeus crater [Eke et al., 2014]. Diviner observations of the impact event showed a clear thermal signature, and based on these observations, Hayne et al. [2010] suggested that up to 300 kg of water could have been liberated in the event, which is consistent with the LCROSS observations. Finally, LRO LAMP also saw a clear signature from the impact event in UV wavelengths and inferred the presence of a variety of species in the ejecta plume, including molecular hydrogen, carbon monoxide, and the elements calcium, magnesium, and even mercury [Gladstone et al., 2010], which was predicted to be present in PSRs based on the presence of and expected thermodynamic behavior of mercury in lunar samples [Reed, 1999].

2.4. Interpretation and Explanation of PSR Volatiles

As is the case in any broad scientific topic, studies of interpretation and explanation interact contemporaneously with studies that make predictions and present measurement results. Thus, to provide context for
the measurement investigations described in sections 2.2 and 2.3, broad categories of interpretation studies are described. In mentioning specific papers, there is no attempt to provide an exhaustive description of all such studies; rather, the investigations mentioned here are illustrative of the types of interpretation studies of PSR volatiles that have been conducted.

There are three broad categories of PSR volatile interpretation studies: the delivery of water and volatiles to PSRs, the stability of delivered volatiles within PSRs, and the modification of volatiles within the PSRs. Moses et al. [1999] provides a good type example of a study that investigates the delivery of various volatiles to Mercury's PSRs. In this study, Moses et al. [1999] investigated the delivery of water from interplanetary dust particles, water-rich asteroids, and Jupiter family and Halley-type comets. It was concluded that all these sources could possibly supply the estimated water to Mercury's PSRs but that Jupiter family comets were particularly promising because of their water content and orbital characteristics. The delivery of water to the Moon via comet impact has been studied through the simulation of the impact process and resulting time evolution of the impact products [e.g., Ong et al., 2010; Stewart et al., 2011; Prem et al., 2015]. In some cases, it was determined that such impacts could create a transient, collision-dominated atmosphere around the Moon thus enhancing the amount of water that could reach the polar PSRs [Prem et al., 2015]. No such similar impact-simulation studies have been carried out for Mercury. Other studies have investigated the migration of water to lunar PSRs in the noncollisional, exospheric regime. A recent study by Moores [2016] suggests that spatially heterogeneous water deposition in south polar PSRs may be a natural result of such water migration.

A study that investigated the stability of volatiles within PSRs was carried out in a classic investigation by Vasavada et al. [1999]. This study derived thermal stability requirements for simple, flat-floored, bowl-shaped craters at Mercury and the Moon. While actual craters are more complicated than those assumed by Vasavada et al. [1999], this study nevertheless provided useful constraints from which to assess the volatile...

Figure 18. Image from LRO/CTOP visible camera showing sunlit ejecta about 20 s after impact of the LRO Centaur upper stage shell (figure taken from Schultz et al. [2010]). Inset shows a close-up with the direction of the Sun and the Earth (indicated by arrows). Asymmetry of the ejecta reflects, in part, the projected shadow over the crater (from the edge of Cabeus) and across the ejecta cloud. Dotted circle represent the fields of view of the visible and near-infrared spectrometers (figure courtesy Science magazine).
stability of real craters at actual locations on the Moon and Mercury. Additional studies have investigated volatile stability within Mercurian and lunar PSRs across geologic time periods [Siegler et al., 2011, 2013, 2015]. These studies accounted for effects such as time-dependent obliquity, and the results suggest there are fundamental differences in volatile stability between the Moon and Mercury due to such effects.

Finally, studies have investigated the modification of volatiles due to various surface and environmental processes. As an example, Crider and Vondrak [2003], Crider and Killen [2005], and Hurley et al. [2012] investigated how surface volatiles will be buried, destroyed, and spatially modified due to space weathering processes on the Moon and Mercury. As another example of volatile modification at the Moon, Siegler et al. [2016] extended prior volatile stability analyses to show that the current lunar-polar-hydrogen distribution may be explained in part by the modification of a geologically old volatile deposit that has been systematically changed by time-dependent lunar obliquity changes due to lunar polar wander.

### 2.5. Summary of PSR Measurements

When all the PSR measurements from the Moon and Mercury are summarized (Table 1), a consistent picture emerges that the poles of Mercury have large amounts of water ice, and the Moon’s poles, while enriched in volatiles, have a much lower concentration of volatiles than Mercury. The radar data strongly support this conclusion by showing large radar-bright enhancements at Mercury that are all within PSRs. In contrast, while radar data from the Moon show evidence for water enhancements, these data do not show the same clear PSR-filling signatures that are seen at Mercury. Hydrogen measurements support this conclusion such that all lunar neutron measurements indicate a hydrogen concentration no greater than a few wt % WEH within PSRs, while hydrogen concentrations at Mercury’s PSRs are in the range of 50 to 100 wt % WEH. The thermal environments at both bodies enable the retention of water ice and other volatiles. Imaging and reflectance measurements show clear differences. At the Moon, there is evidence for surficial frost of water and possibly other species, but the presence of such frost is not uniform in all locations, and there is not uniform and unambiguous evidence that PSR lunar volatiles have been emplaced in large and thick contiguous areas. At Mercury, the reflectance data show clear evidence for bright and dark deposits that closely follow thermal stability for surface and subsurface water ice, respectively. Further, the clearly delineated reflectance features within Mercury’s PSRs imply the presence of large and contiguous volatile deposits. Finally, even with the apparently smaller amount of water at the lunar PSRs, the in situ LCROSS data reveal the presence of a complicated mixture of volatile materials. Based on the clear dichotomy between the nature and quantity of volatiles at the PSRs of Mercury and the Moon, a fundamental question that immediately arises is why is there such a difference between the two bodies? While there are no clear answers yet to this question, potential explanations can be offered, and these explanations are discussed in the next section.

### 3. Why Are the Moon and Mercury’s PSR Volatiles So Different?

Gaining understanding for why the lunar and Mercurian PSR volatiles are so different requires looking for specific differences that can explain this dichotomy. While not exhaustive, broad categories of explanation are provided in Table 2. These explanations are not intended to cover every conceivable scenario, as there are explanations that might not yet have been considered. Nevertheless, these explanations are intended to be broad and illustrative and provide a summary of what might be possible. The four broad explanatory categories are differences between the Moon and Mercury in delivery time of volatiles, type and

### Table 1. Summary of Types of PSR Measurements at the Moon and Mercury

<table>
<thead>
<tr>
<th></th>
<th>Moon</th>
<th>Mercury</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water (from radar)</td>
<td>Spotty; not one-to-one correlated with PSRs.</td>
<td>Fills PSRs and radar-bright regions always in PSRs.</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>&lt;few wt % H2O; not one-to-one correlated with PSRs.</td>
<td>50–100 wt % H2O; spatially correlated with PSRs.</td>
</tr>
<tr>
<td>Temperature</td>
<td>Cold temperatures can trap volatiles.</td>
<td>Cold temperatures can trap volatiles; slightly warmer than Moon.</td>
</tr>
<tr>
<td>Reflectance/imaging</td>
<td>Consistent with frost in some places; not uniform within all PSRs; no clear “deposits” within PSRs.</td>
<td>Consistent with surface water and carbon-rich organics; PSRs show dark regions with sharp boundaries.</td>
</tr>
<tr>
<td>In situ</td>
<td>Multiple volatile species; few wt % H2O.</td>
<td>NA</td>
</tr>
</tbody>
</table>

*NA: not applicable.*
Table 2. Possible Explanations and Tests for Understanding the Difference Between the PSR Volatile Contents of Mercury and the Moon

<table>
<thead>
<tr>
<th>Explanation</th>
<th>Description</th>
<th>How to Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Differences in delivery time</td>
<td>Recent delivery to Mercury and not to the Moon.</td>
<td>Find recent crater on Mercury; model recent comet impacts; characterize layering and stratigraphy.</td>
</tr>
<tr>
<td>Differences in impactors</td>
<td>Mercury impacted by water-rich comet(s); Moon impacted by less water-rich asteroid(s).</td>
<td>Measure isotopic abundances (D/H, oxygen and nitrogen isotopes).</td>
</tr>
<tr>
<td>Differences in processes</td>
<td>Do slight temperature differences cause significant difference in processes that trap and remove volatiles? Does the space environment cause different processes to operate?</td>
<td>Measure the composition within PSRs and three-dimensional stratigraphy; correlate volatiles with temperature inside and outside PSRs; characterize environmental effects by making in situ measurements of environmental factors (charged particles, solar wind, etc.).</td>
</tr>
<tr>
<td>Differences in planetary compositions</td>
<td>Can Mercury’s volatile-rich composition make substantial contribution to PSR volatile inventory?</td>
<td>Measure in situ compositions at Mercury; better understand Mercury volatile composition and volatile release mechanisms.</td>
</tr>
</tbody>
</table>

The differences in volatile contents between Mercury and the Moon are likely due to differences in delivery times, processes, impactors, and planetary compositions. It is likely that the complete explanation may involve some combination of any number of these explanations.

**Differences in delivery time.** One straightforward explanation is that Mercury may have had a recent impact fill up its PSRs, whereas the Moon simply has not had any recent impacts. While this explanation might provide a good prima facie understanding of the Mercury/Moon difference, there is a sense that it is a “too easy” and ad hoc explanation. In order for this to be a robust explanation, there needs to be multiple lines of independent evidence that would point to a recent delivery of volatiles to Mercury. It turns out there is such evidence. First, as described in section 2.3.4, Mercury’s PSR deposits are clearly delineated with sharp boundaries in the reflectance data. These boundaries suggest the deposits may be geologically young. No such features exist on the Moon. Second, there is clear evidence that in many locations within Mercury’s PSRs, relatively pure water ice is covered by tens of centimeters of drier material. Given that pure water ice may be buried by drier material due to space weathering [Crider and Killen, 2005], this possible drier top layer suggests Mercury’s deposits may be geologically young (<70 Myr) [Lawrence et al., 2013]. Third, the relative purity of Mercury’s polar ice, especially compared to the Moon, suggests that it is a recent deposit, as modification processes will tend to dilute the water purity over time [Hurley et al., 2012]. Fourth, if a recent impact deposited the volatiles in Mercury’s PSRs, then one might expect to see evidence on Mercury’s surface of such an impact. A recent study by Ernst et al. [2016] suggests that a candidate source crater is Hokusai crater, which is located in the north central portion of Mercury (100 km diameter, 17°E, 58°N). Hokusai crater is one of the youngest craters on Mercury, has an extensive ray system that stretches very large distances across Mercury, and has almost no small, superposed craters. Ernst et al. [2016] carried out a preliminary analysis of the type of impactor that could have created Hokusai and concluded it is not unreasonable for the Hokusai impactor to have delivered the necessary volatiles to Mercury’s poles. There is additional information from neutron-based composition measurements that the Hokusai region may be enriched in lower mass materials indicative of a possible volatile enhancement [Lawrence et al., 2016a, 2016b]. In contrast to a recent delivery of volatiles to Mercury, at the Moon there is evidence for the ancient presence of enhanced hydrogen that has been modified by long-term obliquity changes [Siegler et al., 2016], which supports the idea that the Moon has not had a recent delivery of large amounts of volatiles.

While there is therefore some evidence to support a recent impact at Mercury and not at the Moon, more work, including analyses, modeling, and new measurements can be done to test this explanation. Specific tasks include the following: carry out new analyses of Mercury composition data, conduct better models of comet impacts at Mercury, and make in situ measurements at either or both bodies that could characterize the composition and soil properties and compare these measurements with expectations for recent or ancient volatile deposition.

**Differences in impactors.** The difference between the Moon’s and Mercury’s PSR water content may be due to the original water content contained in different types of impactors, such that water delivered to Mercury may be from high-water-content comets, while water delivered to the Moon is from lower-water-content asteroids. While not directly applicable to the lunar PSRs, recent studies of trapped lunar water in Apollo
volcanic glass samples have shown that this water is indistinguishable from that of bulk water in carbonaceous chondrites [Saal et al., 2013]. Given that isotopic measurements of various species (e.g., D/H, $^{15}$N/$^{14}$N) [Saal et al., 2013] can discriminate between these different sources, a key test of this explanation is to measure these and other isotopic abundances within the PSRs at both the Moon and Mercury. If such measurements could be made as a function of depth into the surface (down to tens of centimeters), these data could provide information for the time history of volatile deposition from different sources.

*Difficulties in processes.* There are different environmental factors operating on PSRs at the Moon and Mercury, and as a consequence, there may be different processes that act within PSRs to modify the volatile concentrations and distributions. As mentioned in section 2.3.3, the PSR temperatures in the lunar PSRs are notably colder than those in Mercury’s PSRs. Thus, temperature-dependent processes, such as diffusion and/or thermal cycling [e.g., Schorghofer and Aharonson, 2014] may have significantly different effects on one body compared to the other. Environmental differences are not restricted to temperature, as the space environment is different between the two bodies. The Moon has no intrinsic magnetic field and only passes through the far portion of Earth’s magnetosphere for a portion of its orbit. In contrast, Mercury has a magnetic field, which can shield the planetary surface from solar energetic particles, but is also the source of internally generated energetic particles [e.g., Lawrence et al., 2015a], some of which might modify PSR materials [Delitsky et al., 2016]. Finally, Mercury’s closer distance to the Sun causes differences in the amount of solar wind and charged particles that reach its surface, as well as the number of impactors that can reach its orbit and hit the planet.

There is little understanding about how differences in these and other processes may result in different volatile contents at the two sets of PSRs. Additional understanding about such processes can be obtained by gathering new information about the three-dimensional hydrogen distribution at the lunar PSRs, and how this distribution relates to the thermal environment. More studies to investigate charged particle effects can be carried out. Finally, in situ measurements of various environmental factors (e.g., magnetic field, charged particles, solar wind, and hydrogen deposition and removal) would provide important constraints on the level to which differences in processes might play a role in the overall difference between the two sets of PSRs.

*Difficulties in planetary compositions.* Until the MESSENGER mission, it was not considered that differences in composition between the Moon and Mercury might help to explain the difference between the PSR volatile content of the two bodies. However, MESSENGER compositional measurements show that Mercury is more enriched in volatile elements (K, S, Na, Cl, and C) than was expected for a supposedly volatile-depleted body [e.g., Peplowski et al., 2011, 2014, 2016; Nittler et al., 2011; Evans et al., 2015]. In addition, a geologic feature now known as hollows was discovered to be ubiquitous across Mercury’s surface. Hollows are relatively small (less than tens of kilometers across), geochemically young, rimless depressions that are mostly located within impact features [Blewett et al., 2011]. The best current explanation for the existence of hollows is that they are formed through the relatively rapid loss of volatile material [Blewett et al., 2013]. These observations of Mercury therefore suggest it may be possible that some portion of Mercury’s PSR volatiles could be due to the release of volatile material that finds its way to the poles and gets trapped. Interestingly, this idea is similar to the original idea proposed by Watson et al. [1961b] of lunar endogenous material supplying water to the lunar poles. In contrast to Mercury, the Moon has low abundances of volatile materials and therefore would not likely contribute large concentrations of endogenous volatile material to the lunar PSRs.

The idea that endogenous volatiles might supply a substantial portion of water to Mercury’s PSRs is currently only a speculation; thus, much work needs to be done to test if it is a viable hypothesis. One argument against this idea is that an endogenous delivery of volatiles would need a special means to keep the PSR water relatively pure, which may not be easy for a presumably continuous process that takes place over long periods of time. Progress for testing this idea can be made by better understanding the nature of Mercury’s volatile materials, how they are released, and then how they are trapped and possibly accumulated within PSRs. As with the other explanations, in situ composition measurements, both within and outside PSRs, would provide key constraints and enable tests of specific hypotheses.

*Combination of explanations.* The final explanation for the difference between the Moon and Mercury may of course be some combination of different explanations given above. For example, the water at Mercury may have been supplied by a recent comet impact, and no such comets may have hit the Moon in the geologically
recent past. Further, even if there is recent and/or ongoing volatile deposition, different processes could still be affecting the resulting deposits in different ways [Delitsky et al., 2016]. So while there is information pointing at all these explanations as possible explanations, we currently do not have enough information to definitively resolve why there is the difference between the PSRs at the Moon and Mercury.

4. PSR Exploration in the Next 50 Years

Much has been learned in the first half century of PSR exploration. The field started with a few speculative studies and has reached a well-bounded understanding of the nature of PSR volatiles. As is almost always the case when initial speculation and prediction gives way to “finding things out,” reality is more complicated (and interesting) than could have been envisioned at the beginning. So it is with studies of PSR volatiles.

While a broad understanding is now known, there are still many basic and fundamental aspects of PSRs and PSR volatiles that are still not understood. The nature of the soil and layering (mechanical, detailed composition) are still largely unknown. Models have been generated and predictions have been made about processes that operate within PSRs, but actual knowledge of such processes is limited. The major question of why the PSR volatiles are so different at the Moon and Mercury is still not resolved.

Predictions about what might take place in the next 50 years of PSR exploration is challenging at best, as it has been noted “Prediction is very difficult, especially about the future” (This quote has been attributed to various people, but often it has been stated as a quote from Niels Bohr.). Nevertheless, there are broad categories of future exploration that will likely be accomplished in the next 50 years. Below is a brief survey of these categories.

The next spacecraft scheduled to go to Mercury is the Bepi Colombo mission, which is being jointly built and operated by the European Space Agency (ESA) and the Japanese Space Agency JAXA [Benkhoff et al., 2010]. Bepi Colombo will orbit two spacecraft around Mercury, and the ESA-built Mercury Planetary Orbiter will orbit Mercury with increased global coverage compared to MESSENGER, especially of Mercury’s south pole, which was not studied up close by MESSENGER due to its eccentric orbit with periapsis in the northern hemisphere. One instrument that can make a new type of measurement of Mercury’s PSRs is the Mercury Radiometer and Thermal Infrared Spectrometer (MERTIS) [Hiesinger et al., 2010], which will obtain measurements of Mercury’s surface in the spectral range of 7–40 μm. MERTIS will enable direct measurements of the PSR thermal environment as well as characterize the sulfur content and mineralogy of Mercury’s surface including the PSR regions. Neutron data from Bepi Colombo should provide the first characterization of hydrogen abundances of Mercury’s south polar PSRs [Mitrofanov et al., 2010c].

At the Moon, a number of new orbital measurements could be accomplished that would provide key new information. Measurements of hydrogen concentrations with improved spatial resolution can be made by flying neutron sensors at very low altitudes (<10 km) near PSRs to isolate the hydrogen concentrations to individual PSRs. A pathfinder mission to make this measurement from a CubeSat platform is currently planned [Hardgrove et al., 2015]. A full-coverage, high-statistics measurement that could carry out high spatial resolution measurements, as well as provide spatially resolved, hydrogen burial-depth information, likely requires a larger instrument and more spacecraft resources than can be provided by a CubeSat [Lawrence et al., 2015b]. New multiwavelength spectral data at the Moon, either active or passive, could provide additional details about volatiles and frost within lunar PSRs.

A new leap in knowledge will require landed measurements from within a PSR. Such measurements are essential but challenging. One of the biggest challenges is the need to operate a landed spacecraft in the very cold PSR environment, which is difficult for engineering (power, thermal, and mechanical) and operational reasons. At Mercury, there is the additional challenge of safely landing a spacecraft in the deep gravitational well at Mercury’s location near the Sun. Nevertheless, such missions would reveal fundamentally new information about PSRs (composition, stratigraphy, and processes) that would likely challenge and expand our current understanding of PSRs.

While there are no currently planned PSR-landed missions, NASA is currently studying a lunar polar rover called Resource Prospector that would carry out investigations in sunlit regions near south pole PSRs [Elphic et al., 2015]. While the RP rover will not be designed to survive in large, deep PSRs, it may still investigate small shaded regions in which enhanced volatiles might be present and PSR-like process might be
operating. There are also reports that the Russian and Chinese space agencies are planning lunar polar missions, although details of PSR-specific missions are unclear. In any case, an in situ PSR mission (or series of missions) will likely be accomplished by some or multiple space agencies and will provide significant changes in our understanding of PSR volatiles.

Finally, the Moon and Mercury do not necessarily contain the only PSRs in the solar system but are only the best known examples. A recent study has reported that the asteroid Ceres has craters near its poles that may approximate PSRs [Schorghofer et al., 2016]. Given that Ceres is much more volatile rich than either the Moon or Mercury, it likely represents another end-member of PSR environments with interesting and unique qualities.

Acknowledgments
The author would like to thank Dr. William C. Feldman for generously providing me with the initial opportunity at Los Alamos National Laboratory to carry out work in this exciting field of PSR volatiles; I am exceedingly grateful for the long and fruitful relationship (both scientific and personal) with Dr. Feldman. The material in this paper was originally presented as a seminar in November 2014 at Brown University, which was supported by the NASA Solar System Exploration Research Virtual Institute (SSERVI). The work to complete the paper was supported by different grants from NASA including the MESSENGER Participating Scientist program (grant NNX08AH30G), the NASA Lunar Advanced Science and Exploration Research program (grant NNX13AJ61G), and a NASA SSERVI grant to Johns Hopkins University Applied Physics Laboratory (grant NNA14AB02A). All data presented in the paper either reside in the NASA Planetary Data System and/or can be found via the referenced papers. The author thanks Wenzhe Fa and Richard Elphic for providing helpful reviews that improved the scope and quality of this manuscript.

References


Icarus (2005), L13204, doi:10.1016/j.icarus.2015.03.032.


