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High-priority lunar landing sites for in situ and sample return studies of polar volatiles

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ABSTRACT

Our understanding of the Moon has advanced greatly over the last several decades thanks to analyses of Apollo samples and lunar meteorites, and recent lunar orbital missions. Notably, it is now thought that the lunar poles may be much more enriched in H₂O and other volatile chemical species than the equatorial regions sampled during the Apollo missions. The equatorial regions sampled, themselves, contain more H₂O than previously thought. A new lunar mission to a polar region is therefore of great interest; it could provide a measure of the sources and processes that deliver volatiles while also evaluating the potential in situ resource utilization value they may have for human exploration. In this study, we determine the optimal sites for studying lunar volatiles by conducting a quantitative GIS-based spatial analysis of multiple relevant datasets. The datasets include the locations of permanently shadowed regions, thermal analyses of the lunar surface, and hydrogen abundances. We provide maps of the lunar surface showing areas of high scientific interest, including five regions near the lunar north pole and seven regions near the lunar south pole that have the highest scientific potential according to rational search criteria. At two of these sites—a region we call the “Inter crater Polar Highlands” (IPH) near the north pole, and Amundsen crater near the south pole—we provide a more detailed assessment of landing sites, sample locations, and exploration strategies best suited for future human or robotic exploration missions.

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1. Introduction

Following the establishment of the Vision for Space Exploration in 2004, NASA commissioned the National Research Council (NRC) to develop guidelines and a prioritized set of tasks for future lunar exploration missions. In 2007, the NRC published a report, entitled “The Scientific Context for Exploration of the Moon” (NRC, 2007), which provides a framework for continued robotic and human exploration of the Moon. This report identifies eight scientific concepts to be addressed: the bombardment history of the inner solar system (concept 1), the structure and composition of the lunar interior (concept 2), the diversity of lunar rocks (concept 3), the lunar poles and volatiles (concept 4), the lunar volcanism (concept 5),

the impact process (concept 6), the regolith processes and weathering (concept 7) and the processes involved with the atmosphere and dust environment of the Moon (concept 8). In this paper, we provide a detailed study of concept 4—“The lunar poles are special environments that may bear witness to the volatile flux over the latter part of solar system history”—and its five underlying science goals, as defined by the NRC (2007) (Table 1).

Our primary objective is to determine target sites where science goals 4a–4e can be addressed, i.e., where volatile chemical species (“volatiles”) are likely to be present on or near the surface of the Moon, such that they can be studied in-situ or via sample return. The science goals outlined in Table 1 (NRC, 2007) provide the structure in which we carry out this search. Such volatile deposits are most likely to exist near the lunar poles, in regions that are permanently shadowed due to the very low obliquity of the Moon relative to the ecliptic (Spudis et al., 2008). These permanently shadowed regions (PSRs) are prime targets for exploration of volatiles, as they

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Table 1
Science goals to be addressed while studying volatiles at the lunar poles (NRC, 2007).

Science goals	Definition
4a	Determine the compositional state (elemental, isotopic, mineralogic) and compositional distribution (lateral and depth) of the volatile component in lunar polar regions
4b	Determine the source(s) for lunar polar volatiles
4c	Understand the transport, retention, alteration, and loss processes that operated on volatile materials at permanently shaded lunar regions
4d	Understand the physical properties of the extremely cold (and possibly volatile rich) polar regolith
4e	Determine what the cold polar regolith reveals about the ancient solar environment

allow us to study the specific state and location of volatiles as they exist on the Moon (science goal 4a), the processes operating on these volatiles as they move in and out of PSRs (science goal 4c), the properties of the regolith in which they reside (science goals 4d and 4e), and potentially even the origin of volatiles (science goal 4b). We also provide case studies of the two most promising target sites as an example of how exploratory missions might be conducted to address concept 4.

Continued research into lunar volatiles and their special environment has important ramifications for both human exploration of the Moon and our understanding of volatiles in the Solar System. As an example, locating a local source of water ice on the lunar surface would allow future human explorers to perform in-situ resource utilization (ISRU), facilitating further lunar exploration and possibly the discovery of additional local resources. An understanding of the volatile content of the Moon could also help shed light on planetary formation and solar evolution processes (e.g., NRC, 2007).

2. Previous detections of lunar surface volatiles

Instruments, such as radars, neutron detectors, infrared and far-ultraviolet spectrometers, on spacecraft orbiting the Moon, as well as an impactor spacecraft, have produced data over the past several decades that collectively support enriched volatile abundances in lunar polar regions. In 1994, the *Clementine* mission measured coherent radar backscatter consistent with the presence of water ice at the south pole (Nozette et al., 1994, 1996), the first indication that there may be sizeable deposits of ice at the lunar surface. In 2009, the *Miniature Synthetic Aperture Radar* (Mini-SAR) aboard *Chandrayaan-1*, measured circular polarization ratios (CPR, the ratio of signal received in the same polarization as sent to the ground divided by the signal received in the opposite polarization) consistent with deposits of water ice which should be at least tens of wavelengths ($\sim 2\text{--}3$ m) thick, heterogeneously distributed within many of the small craters near the poles (Spudis et al., 2010). The *Mini-RF* radar instrument on the *Lunar Reconnaissance Orbiter* (LRO) spacecraft also measured CPR consistent with the presence of water ice within the upper couple of meters of at the surface of both poles (Spudis et al., 2013).

In 1998, the *Lunar Prospector* (LP) mission measured depressions in the epithermal-neutron (but not fast-neutron) fluxes close to permanently shadowed regions (PSRs) at both poles, evidence which has been interpreted to indicate deposits of hydrogen—possibly in the form of water ice—at depths of ~ 50 cm (Feldman et al., 1998). However, since the spatial resolution of the neutron data (~ 15 km at the equator) is much coarser than the size of the PSRs (meters to kilometers in diameter), a definite link between the two occurrences could not be established. Feldman et al. (2001)

improved the spatial resolution of the LP epithermal neutron data poleward of $\pm 70^\circ$ latitude by reducing the spatial integration time to 8 s, corresponding to a 13 km ground track. They found that the largest concentrations of hydrogen at the poles overlay PSRs. Elphic et al. (2007) also improved the spatial resolution of the LP neutron data by using a pixon reconstruction technique, and found enhanced concentrations of hydrogenous materials overlying some, but not all, PSRs. Neutron measurements by the *Lunar Exploration Neutron Detector* (LEND) onboard LRO suggest that some part of the depression in epithermal neutron fluxes might not be collocated with PSRs (e.g., Mitrofanov et al., 2010, 2012), although these results remain somewhat controversial (e.g., Lawrence et al., 2011; Teodoro et al., 2014). The exact link between H and PSRs remains unknown, however, and will likely remain so until investigated by future surface missions.

Pieters et al. (2009) analyzed data from the *Moon Mineralogy Mapper* (M^3), a spectrometer aboard *Chandrayaan-1* in the near infrared portion of the electromagnetic spectrum and found distinct absorption bands at 2.8 and $3.0\ \mu\text{m}$ that could be attributed to OH and/or H_2O present in the top 1–2 mm of the lunar surface. The strongest absorption features were found near the poles in cooler regions and at several fresh craters in feldspathic highland terrain. They observed a general lack of correlation with previous neutron measurements, suggesting that the formation and retention of OH and H_2O are on-going surficial processes. These results were vindicated by the *Moon Impact Probe of Chandrayaan-1* (Sridharan et al., 2010). The *High-Resolution Instrument-infrared* spectrometer (HRI-IR) aboard the *Deep Impact* spacecraft, which flew by the Moon en route to comet 103P/Hartley in 2010, independently confirmed the M^3 observations. The HRI-IR measured hydration features from 2.7 to $3.6\ \mu\text{m}$, consistent with stretching vibrations of surface or structural hydroxyls and hydrated minerals, over the entire lunar surface, during at least some part of the lunar day, which could be caused by a dynamic hydration process driven by solar radiation. These results also suggest that the formation, retention, and loss of some OH and H_2O are dynamic surficial processes (Sunshine et al., 2009). The Visual and Infrared Mapping Spectrometer (VIMS) aboard the *Cassini* spacecraft also measured absorption features from 2.8 to $3.0\ \mu\text{m}$, consistent with the presence of OH and H_2O at the surface during its flyby of the Moon in 1999 (Clark, 2009).

The orbital detection of putative water ice was part of what prompted the *Lunar Crater Observation and Sensing Satellite* (LCROSS) mission, in which a Centaur rocket impacted into a PSR within Cabeus crater. Cabeus was chosen for the mission because it displays the highest hydrogen concentration in the lunar south polar region: up to ~ 181 ppm at the surface according to *Lunar Prospector* data (which could be higher at depth), corresponding to an estimated content of 0.5–4.0% water ice by weight depending on the thickness of the overlying dry regolith layer, according to data from the *Lunar Exploration Neutron Detector* (LEND) (Mitrofanov et al., 2010). The LCROSS mission also included a *Shepherding Spacecraft*, which monitored the impact site and the resulting ejecta and revealed the presence of emission lines that could have been caused by Ag, CN, CO, CO_2 , H_2O , Na, NH, NH_2 and OH (Schultz et al., 2010). The presence of OH could be due to either the thermal dissociation of H_2O or desorption off of regolith grain surfaces. NH and NH_2 emission lines in LCROSS spectra are believed to come from the regolith. Na was also observed in the spectra and is interpreted to come from near, but not at, the surface (Schultz et al., 2010). Colaprete et al. (2010) reported a detection of $5.6 \pm 2.9\%$ water ice in the regolith at the LCROSS impact site, based on spectral measurements of the ejecta.

NASA's LRO observed a distinctive plume generated by the LCROSS impact which contained H_2 , CO, Hg, Ca and Mg with its *Lyman Alpha Mapping Project* (LAMP) far-ultraviolet (FUV) spectrometer (Schultz et al., 2010; Gladstone et al., 2010). As hydrogen

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