Lunar Polar Volatile Resources:
Obtaining Their Origins Prior to Extraction

Submitted by

William Farrell, NASA/Goddard SFC, 301-286-4446, William.M.Farrell@nasa.gov
Esther Beltran, University of Central Florida, 407-823-6306, Esther.Beltran@ucf.edu
Parvathy Prem, Johns Hopkins University/Applied Research Laboratory
Michael Poston, Southwest Research Institute
Ariel Deutsch, Brown University
Dana Hurley, Johns Hopkins University/Applied Research Laboratory
Kurt Retherford, Southwest Research Institute
Paul Hayne, University of Colorado
Mihaly Horanyi, University of Colorado
Thomas Orlando, Georgia Institute of Technology
Jeffrey Gillis-Davis, Washington University
Gerardo Dominguez, California State University, San Marcos
Shashwat Shukla, Univ. of Twente, The Netherlands
Jamey Szalay, Princeton University
Debra Needham, NASA/Marshall Space Flight Center
Margaret Landis, University of Colorado
Kathleen Mandt, Johns Hopkins University/Applied Research Laboratory
Christopher Bennett, Univ. of Central Florida
Cesare Grava, Southwest Research Institute

1. **Motivation**

There has been much recent interest in planetary mining - especially extracting the resources found in lunar polar craters to enable longer duration missions at the Moon and to provide resources for missions to Mars. In early April 2020, the US Administration signed an executive order entitled 'Encouraging International Support for the Recovery and Use of Space Resources' (https://www.govinfo.gov/app/details/FR-2020-04-10/2020-07800/summary) advancing larger scale extraction of space-based resources.

From the dawn of the space age, lunar polar craters were thought to entrap and sequester water and other volatiles in the cold, sun-shielded environment (Watson et al., 1961). Intriguing evidence came from the Lunar Prospector Neutron Spectrometer (LPNS) that sensed a suppression in the epithermal neutron flux associated with large quantities of hydrogen (**Figure 1**) in the top ½ meter of polar regolith (Feldman et al., 2000). If all of this hydrogen is bound as water molecules, then it weighs close to 400 million metric tons - about the same amount of water in Lake Erie. Instruments onboard Lunar Reconnaissance Orbiter (LRO) also sensed neutron suppressed regions pointing to subsurface hydrogen deposits (Mitrofanov et al., 2010). In addition, FUV reflectance spectroscopy and IR LIDAR reflections revealed evidence of large patches of exposed surface frost – up to a few percent ice-regolith mix - scattered within persistently shadowed regions (Hayne et al., 2015; Fisher et al, 2017).

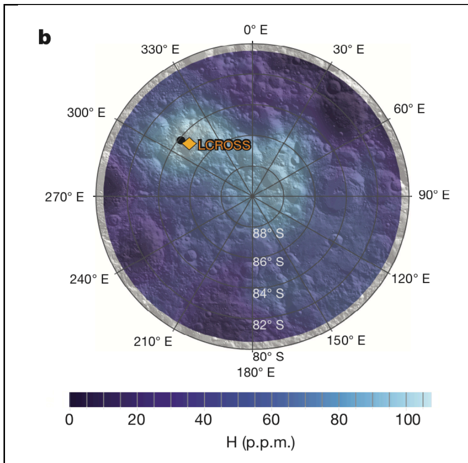

Figure 1- The hydrogen content in the south pole from the LPNS (from Siegler et al., 2016)

Direct evidence for water in lunar polar craters came in 2009 with the Lunar CRater Observation and Sensing Satellite (LCROSS) plume-creating mission. A shepherding satellite examined the dust and gas plume created by a Centaur booster impact into the floor of Cabeus crater. The plume contained about 6% water vapor and ice, and also possibly contained light hydrocarbons, sulphur-bearing species and CO_2 that may have a cometary/asteroid origin (Colaprete et al., 2010; Schultz et al., 2010) or possibly a volcanic origin (Lucey et al., 2020).

While the remote-sensing LCROSS suggests a complex deposit composition, to date, the isotopic information, subsurface concentrations, distribution, and physical form of the deposit remains shrouded. The exact origins of the polar crater volatile deposits remain unknown. Since the origin is unknown, it cannot currently be assessed if the resource is renewable – which impacts any strategy on resource extraction.

We thus recommend, from a scientific perspective, that NASA and our international colleagues assess the origin and renewability of the lunar polar deposits, first, before the fragile environment is irreversibly altered by resource extraction via mining.

The environmental information obtained in this 'Origins-first' strategy then feeds forward to prospecting and extraction strategies. As described herein, the proposed Origins-first approach is in the spirit of the Outer Space Treaty and consistent with the new Artemis accords. A determination of the deposit origin should be made prior to final planetary protection classification for the lunar polar deposit.

2. **Polar Deposits: A Potential Astrobiology Treasure Trove**

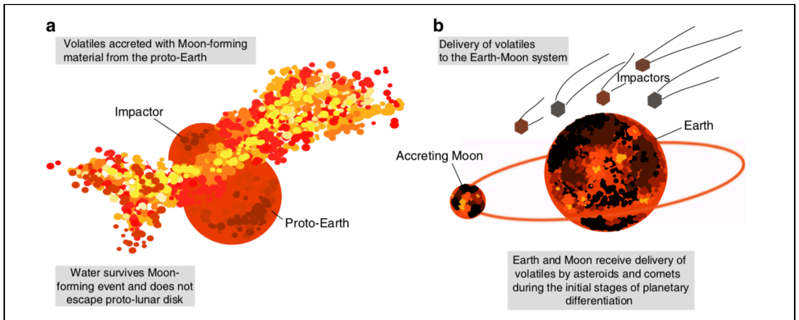

Figure 2- Illustrations of two possible origins of lunar mantle water (from Barnes and Kring, 2016)

The large amounts of LPNS-inferred hydrogen may represent a vast resource to utilize in future human and robotic exploration. However, the LCROSS findings of more complex species leaves open the possibility that the polar deposits contain critical astrobiological information such as chemical and isotopic markers that might reveal the state of the early solar system, the origins of our own oceans, and possibly hold clues to origins of our own life (David, 2019). The astrobiological value of polar deposits depends upon their origin – which still remains unknown. It is possible that the volatiles are sourced from indigenous sources (i.e., volcanic outgassing) or exogenous sources (i.e., volatile-rich impacts or solar wind bombardment).

Regarding an indigenous source, there is an existing hypothesis that the deposit could have resulted from past volcanic outgassing of mantle material. The origin of mantle volatiles has been reexamined in the last ten years. **Figure 2** shows two scenarios. In the first, volatiles might have been implanted into lunar material at the initial Moon-forming impact event ~ 4.5 Ga. Lab crystallization studies suggest that the Moon was water-rich at its origin, and outgassed water during the subsequent ~200 Myr lunar magma ocean period following the Moon's formation (Lin et al., 2016). However, in the second scenario, analysis of lunar samples suggests that mantle volatiles were accreted by the Moon as delivered by asteroids (comets contributing < 20%) during this Lunar Magma Ocean period (Barnes et al., 2016). This asteroid water delivery also would have been ongoing simultaneously at Earth between 4.5-4.3 Ga.

In either scenario, these interior volatiles would remain in the mantle, but were possibly outgassed later in large quantities during the Lunar Mare Volcanism period near 3.5 Ga (Needham and Kring, 2017). During this time, the lunar atmosphere may have been relatively thick - at 1% of the current terrestrial surface atmospheric pressure. Released mantle volatiles might then have been retained at the poles and exist now in the form of the polar deposits. Thus, the polar deposits may retain a record of the early inner solar system asteroid volatile delivery – connecting to the origins of our own oceans and the origin of water at Mars and Venus.

Added evidence for an ancient source to the polar deposits was presented by Siegler et al., (2016), who noted that the distribution of the polar hydrogen deposits is not symmetric about the north and south lunar poles (Miller et al., 2012), and that the asymmetry in the two polar distributions is antipodal. They found that the antipodal hydrogen deposits are consistent with a period of true polar wander associated with lunar mare volcanism in the Procellarum KREEP terrain. Thus, the Seigler model suggests that the asymmetric portion of the deposit, which includes the LCROSS experiment site, could have formed during the early (~ 3.5Ga) period of the Moon's history and thus possibly contain mantle material that might reveal the volatile history in the early solar system.

However, exogenic sources for the polar deposit cannot be ruled out. Such soruces may contribute all or in part as a primary source. Atmosphere-exosphere models indicate that transient collisional atmospheres can form during volatile-rich impact events at the Moon and such events should deliver volatiles to the polar cold traps (Prem et al., 2019). For example, a 2 km diameter comet, impacting at 30 km/s, would result in 1 mm of water ice added to the polar cold traps (Stewart et al., 2011). Added up over geologic time, either comets or asteroids could deliver enough water to account for Lunar Prospector hydrogen abundances, with asteroids likely contributing six times as much water as comets (Ong et al., 2010,). The presence of water, CO_2 and hydrocarbons as observed by LCROSS could be evidence to support a comet or asteroid delivery, although the S-bearing species could also implicate a volcanism source.

Another hypothesized exogenic source for the polar deposits is a modern-day, ongoing surface conversion of solar wind to water and the subsequent water migration to the poles (Crider and Vondrak, 2000). The observations of a 3-μm OH feature in IR reflectance spectra (**Figure 3**) have provided evidence for solar wind implantation and hydroxyl formation in the mid-latitude surface (Li and Milliken, 2017). LRO LAMP observations suggest that water is migrating (Hendrix et al., 2019). However, LADEE Neutral Mass Spectrometer observations place a lower limit to the water exosphere at a very low value of 0.62/cm^3 (Benna et al., 2019). Thus, it remains an outstanding question whether solar wind generated water is capable of migrating poleward in large quantities to continually feed the deposits.

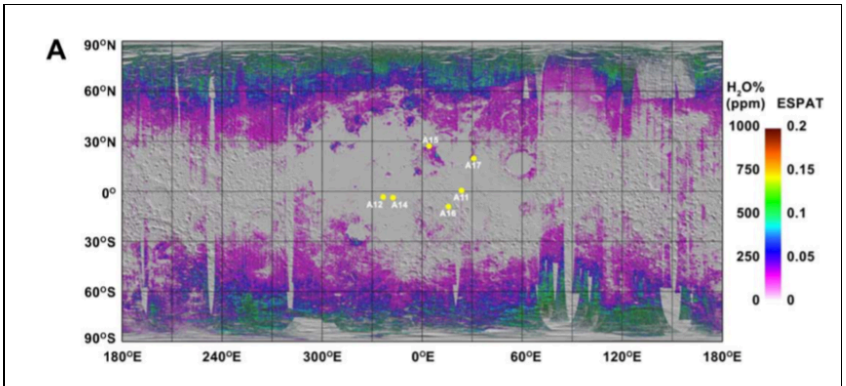

Figure 3- Map of the lunar OH content from the 3-micron absorption feature as measured by Chandraayan-1 M^3 IR instrument (from Li and Milliken, 2017)

We note that while we address individual possible indigenous and exogenous sources above, there could be combination of these sources that operated/operating, yielding a complex deposit revealed in the layers. In other words, there may not be one source but multiple sources revealing themselves with depth and location.

If the deposit ultimately connects to the history of the solar system, careful consideration is likely required before disrupting the local surface and exosphere environment so as not to permanently lose any critical chemical markers. Volatile extraction from a deposit along a crater floor is an irreversible process. Once drilling commences, the temperature in and near the drill site increases, possibly releasing the most easily desorbed molecular species (CH_4, O_2, N_2, CO_2, H_2S, & SO_2) into the exosphere. While in mining applications these volatiles might not be deemed important, in astrobiology scientific assessments, these easily desorbed species might be regarded as critical. We know once these areas are altered, they will never go back to their original state to thoroughly study and understand them. Finally, any refinery will itself release processed extracted gases (like extracted mercury that is known to be in the deposit) and processed grains/particulates that will affect the local/regional environment.

Due to the inevitable and irreversible disturbances that extraction will bring to the lunar polar deposits, we recommend to first assess the state, composition, origin and fragility of the polar deposits prior to mining – the 'Origin-First' strategy

3. Renewability: A Key Factor in Resource Utilization

The PSRs may be a significant scientific reserve, since they have been trapping a portion of any volatiles that crossed their path for billions of years. They thus may be a depot of solar system volatile materials. However, these same volatiles could be used to advance the needs of space exploration. A possible key factor in assessing the intrinsic value of the deposit as a science reserve vs an exploitable resource is the 'renewability' of the deposit. Why are the resources there? Are these resources produced in a constant or semi-constant fashion? Or, are these elements deposited there as a novel event with a very low probability of happening again and therefore finite in their existence?

Thus, in the broad area of resource utilization, resource renewability is a key element that is intrinsically scientific because it is linked to the origin of the volatiles. We note that the mere existence of PSRs as cold traps does not guarantee they will accumulate volatiles over time, but only makes such accumulation possible. There is thus a large range of possible volatile sources that can include sources interior (indigenous) or exterior (exogenous) to the Moon (see also Prem et al., 2020 Decadal WP).

If it can be demonstrated that the water origin is modern via volatile migration from lower latitudes, then polar deposits may be a renewable asset. However, if resources are of cometary origin or from past lunar volcanism, these will not be renewable. We note that any renewable resources to the deposit does not automatically mean they do not hold astrobiological significance. There could be a case where the resource is renewable, but still holds key science interest and thus reserved from extraction. There is a large variety of exogenous sources, these can be from comets, asteroids, interplanetary dust particles, solar wind, micrometeoroids, and even occasional giant molecular clouds that may pass through the solar system (Lucey, 2009).

Only with a thorough understanding and analysis of the origin is there an assessment of the renewability. Once the renewability of the resource is established, a consistent strategy for large scale extraction/mining can occur.

We would expect a special Polar Deposit Analysis Group (PDAG) (like that proposed in the recommendations) to assess the significance and strategy. We suggest that the group include members of International Space Exploration Coordination Group (ISECG, 2020) who are already conducting coordination of international lunar exploration efforts to increase scientific knowledge, to determine the viability of potential resources, and to use the Moon as a proving ground for Mars ISRU technologies. Certainly, any determination of the polar deposits as renewable or non-renewable should be considered by this expert group to plan for future resource extraction activities.

4. Planetary Protection and the Outer Space Treaty

The objective of this white paper is to provide a scientific context to an 'Origins First' approach to the lunar polar deposits. However, the topic itself cannot avoid migration into areas of planetary protection and international law. While the focus is on a science rationale, it should be pointed out that the scientifically-based 'Origins First' strategy presented here is consistent with the spirit of the Outer Space Treaty of 1967 (OST).

Specifically, Article IX of the OST states that "Parties to the treaty shall pursue studies of outer space, including the moon and other celestial bodies, and conduct exploration of them so as to avoid their harmful contamination…". Here, the treaty is addressing forward contamination by any Party that would disallow the site to be used for future studies.

Even though "harmful contamination" is a broad term, to date there has not been intense dispute over its meaning due, in part, to existing strong international collaboration provided by COSPAR (NAS 2018).

With international involvement in a determination of deposit origins (see Recommendations below), all Parties could assess for themselves any astrobiological potency lying within the deposit prior to mining and large-scale excavation. By taking a scientific approach to the Origins question, and including our international colleagues in answering the question, there can be the needed consultation and consideration on the value of the deposit, thereby providing remediation for one Party's concerns about another Party's mining.

The scientifically-based 'Origins-First' approach is aligned with the spirit of the Outer Space Treaty and should reduce potential disputes between Parties of the Treaty.

The Artemis accords were recently released in mid-May 2020 by NASA to better-define the relationship between NASA and its international partners. These accords emphasize transparency, sharing of scientific data, protecting heritage sites, and especially underscoring that any space resource extraction and utilization will be conducted under the auspices of the OST (see https://www.nasa.gov/specials/artemis-accords/index.html). All of these components are specifically designed to reduce potential conflicts. **Thus, involving our international partners on the Origin-first strategy, described herein, is also consistent with these new accords.**

5. Recommendations

We include a set of recommendations for consideration by the Decadal study team:

SSERVI-coordinated environmental impact statement. SSERVI and its community partners have numerous teams that possess modeling, experimental, and field expertise on the lunar polar environment, resource mining, spacecraft-surface interactions, etc. These assets should be brought together, along with appropriate community members from outside SSERVI, to consider how this environment might be altered by small, medium, and large-scale human extraction efforts. This environmental impact study would then provide an initial assessment of the fragility of polar cold traps.

Flagship 'Origins-First' Mission to the Lunar Polar Craters. We recommend that the Planetary Science Division (PSD) fast-track a lunar lander/rover mission to the floor of a larger polar crater (e.g, Cabeus crater, **Figure 4**) to determine the structure, composition, origin, and renewability of lunar polar deposits. In 2008, NASA's Science Mission Directorate leadership fast-tracked the LADEE mission to determine the composition of the native, fragile lunar exosphere prior to planned human activity under the Vision for Space Exploration initiative (LADEE SDT report, 2008). Using a parallel argument, we recommend that a polar deposit 'Origins-first' mission be fast-tracked to assess the native polar deposit environment before large scale mining/excavation alters the polar regions.

The current Flagship missions include MSR and Europa Clipper, both slated for completion in the 2030's. We recommend fast-tracking a Flagship PSR mission since lunar polar mining activities by commercial entities could commence prior to the completion of these other Flagship missions.

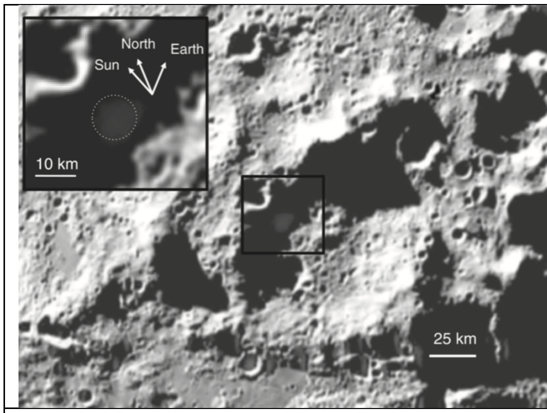

Figure 4- Cabeus crater as imaged by the LCROSS satellite with the Centaur-created impact plume visible - see inset (from Schultz et al. 2010).

We note that the CLPS/VIPER mission will prospect in a small permanently shadowed crater. This mission is not specifically designed to determine the origin and renewability of the deposits. However, VIPER findings will likely further constrain the origin. A white paper is submitted to the Decadal committee on a lunar polar mission to specifically derive the origin/source of the deposit (Hurley et al. 2020 Decadal WP). This mission might serve as the needed Origin-finding mission. However, a cryogenic sample may also be required to be returned to perform more complex compositional analysis using larger laboratory systems that are too massive to fly. An SDT for the Origin-finding mission will determine the *in situ* vs returned sample analysis strategy.

An 'Origins-first' mission should also include active participation from our international colleagues in mission design, operations, and subsequent analysis so that all parties are involved in any conclusions drawn about the origins of the deposits.

In NASA's planetary protection classification, the lunar polar regions were recently reclassified as Category II-L: "Of significant interest relative to the process of chemical evolution but only a remote chance that biological contamination by spacecraft could compromise future investigations." (NID 8715.128). We suggest that a final classification occur once the Origin-first mission is complete and a full environmental assessment on the fragility of the deposit can be determined. There is a possibility that commercial mining may compromise future science investigations carried out by the US or our international partners. This possibility might require that the polar crater deposits be moved to a more protected category in the special case of intense excavation/mining. We note that both COSPAR and NASA classifications are applicable to missions having a light-to-mild contact with the lunar surface. These categories likely need to be reassessed and redefined to consider the case of commercial mining activity, depending upon the activity being performed.

PSD Polar Deposit Analysis Group (PDAG). Once the Origin-finding mission has gathered its key measurements, PSD should then stand-up a science, technology, and mining committee to consider strategies for mining. The group would incorporate ISECG members who are also stakeholders in any mining/extraction decisions. PDAG would decide the extraction strategy based on the origin findings. PDAG would answer questions like: Should mining occur at all? Could we plan to extract from one crater but leave another alone as an astrobiological reserve? Could we extract from one pole and leave the other as a reserve? If the committee agrees that mining is harmful to the polar deposit (and nearby adjacent deposits in other craters), what are alternatives for longer term lunar stays? PDAG could recommend a determination of the protection classification in the case of large-scale extraction and mining which would be forwarded to NASA's Planetary Protection Office and COSPAR for approval.

The environmental science obtained about the lunar polar deposit by the 'Origins-First' analysis would then become a key input in mining and extraction strategies.

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