Evidence for surface volatiles on the Moon and Mercury: A Planetary Comparison

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Introduction: The Moon and Mercury both have cold, permanently shadowed regions featuring temperatures low enough to preserve water ice and other volatiles. With data from the Lunar Reconnaissance Orbiter (LRO) and MESSENGER missions, we can now begin to make detailed comparisons between comparable data sets to look for evidence of polar volatiles on these two solar system bodies.

Background: Both LRO and MESSENGER carried 1064 nm wavelength laser altimeter instruments that provide a unique, zero-phase measurement of surface reflectance. Surfaces measured by the Mercury Laser Altimeter (MLA) showed higher than average surface albedo within some shadowed craters near the North Pole [1]. Modelling surface temperatures with MLA topography, these same areas were found to provide thermally stable environments for surface water ice to survive for geologic time (with loss rates less than 1mm per Gyr) [2].

Areas where ice was modeled to be stable only if covered by a low thermal conductivity surface material (such as Mercury regolith) showed an unusually dark MLA reflectance [2, 1]. This material is hypothesized to be one or more compounds less volatile than water ice, plausibly an organic material originating from comet impacts. Both bright and dark areas showed high circularly polarization ratio returns from earth based radar [3,4] and neutron spectrometer detections consistent with near surface concentrations of water ice [Lawrence, 2013]. Reflectance data from the the Lunar Orbiting Laser Altimeter (LOLA) show that the lunar permanently shadowed regions are anomalously bright compared to areas that receive illumination, but direct comparisons of temperature and LOLA reflectance has not been carried out [6,9]. These reflectance variations can be affected by many things, including soil composition, space weathering, geology and roughness. Comparing the data sets between these two bodies can help differentiate these processes and potentially strengthen any claims volatile presence.

This study: Here we further the MLA reflectance vs. temperature study of Paige et al. [2] and apply a similar technique to newly available data from LOLA. In the previous studies for Mercury [2,1] MLA data was unavailable at latitudes northward of 84^o (due to the MESSENGER orbit). Since this time, a campaign of off-nadir measurements has extended both MLA topography and reflectance measurements to colder areas nearer to the North Pole (southern polar data is not available due to MESSENGER's elliptical orbit). Thermal model comparisons to be extended to much lower temperatures than previous work, which featured surfaces generally exceeding 100K.

These colder environments on Mercury are more comparable to those found in the permanent cold traps on the Moon. This allows for a direct comparison between the two bodies within areas whose surface maximum temperatures are roughly 50-100 K. These environments, water and other volatiles should be stable at the surface over geologic timescales.

Impact gardening should mix and bury ice, causing these surface features to slowly disappear [e.g.14]. We would like to test an hypothesis that deeply buried, thermally mobile volatiles would then rise to the ice table, outpacing loss by gardening. Conversely, at colder temperatures, gardening will again dominate, causing a surface to return to the average regolith albedo.

As some gardened material is mixed from below a thick layer should stay volatile dominated longer than a thin layer. Therefore, surface brightening found at temperatures far below the "volatility temperature, T_v", where thermal migration could outpace gardening, could imply thick ice deposits. Cold areas smaller than the resolution of the thermal models/data, so a brightening above the volatility temperature should also be expected. The presence of a surface volatiles should therefore result in characteristic "bumps" and "dips" in brightness as a function of maximum surface temperature, a *volatility spectrum*.

Results: Figures 1 and 2 show the volatility temperatures of several volatile materials plotted as dashed lines on top of a point cloud (grey) of all available MLA (Fig 1) and LOLA (Fig 2) data as a function of MLA modeled/Diviner data maximum surface temperature. Maximum surface temperature controls the abundance of surface ice perceptible to laser altimeters.

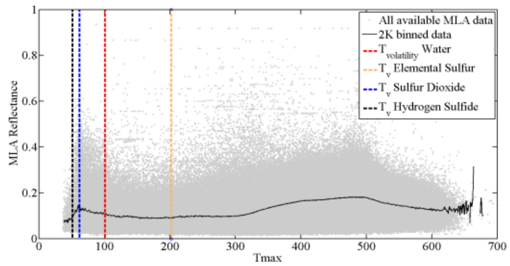

Figure 1: MLA reflectance vs maximum modeled surface temperature [updated models from Paige et al., 2013].

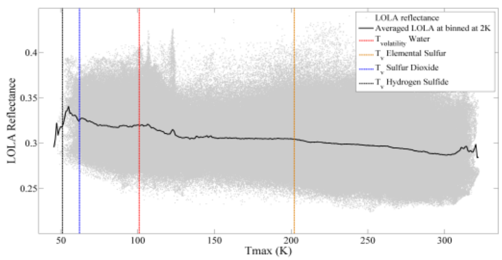

Figure 2: LOLA reflectance vs maximum Diviner measured surface temperature.

We note that both the Moon and Mercury show substantial brightening of their surfaces below roughly 120K. This could be indicative of surface water frost on both bodies. Water has a volatility temperature of about 100K (seen in figures 1-4), so one might expect a dark surface to brighten around 100K if water is present. If the water layer were thin one might expect a decreased brightness below 100K due to impact gardening. LOLA data shows a clear dip near 80K, which could imply a thin water frost layer that is being mixed into the regolith by impact gardening. In MLA, this dip is more subdued, potentially pointing to a thicker volatile layer.

Both also show a second increase in brightness at lower temperature. This lower peak could be evidence for a second bright volatile. Candidates for this peak are SO_2, with a T_v of about 62K, or CO_2 with a T_v of about 54K. Mercury appears to have brightening closer to SO_2, while the Moon favors CO_2.

Rather than being a separate volatile, this lower peak could also be indicative of either a very thick water ice layer (as might be supported by radar evidence on Mercury, but not the Moon), or a very freshly deposited layer (as theorized in [15])

Noted in Paige et al. [2], MLA data showed substantial darkening between ~150 and 350K. In Figure 3, we see enhanced darkening within this temperature range at ~200K, as might be expected from elemental Sulfur or a family of complex organics (such as linear amides or carboxylic acids), especially when processed by Mercury's high radiation environment [16,17]. This could be explainable by volcanic activity on Mercury or by delivery of organics from a comet. Such a dip is not present in the LOLA measurements, implying an absence of this dark material (which should show an even stronger contrast with higher albedo lunar regolith) is not present.

These comparisons hint that both of these planetary bodies may have evidence for surface stable volatiles, but that that these volatiles are not the same on the two planets and may have different source materials. Understanding these potential volatile materials and their sources can substantially impact our understanding of the delivery and retention of volatiles in the inner solar system.

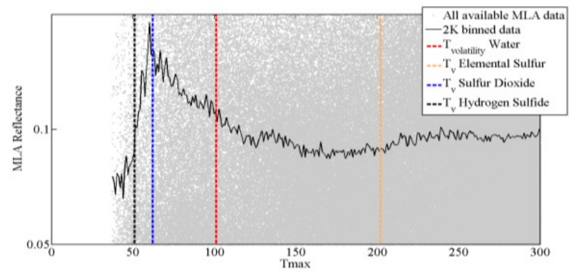

Figure 3: Close up of MLA reflectance vs maximum modeled surface temperature [updated models from Paige et al., 2013].

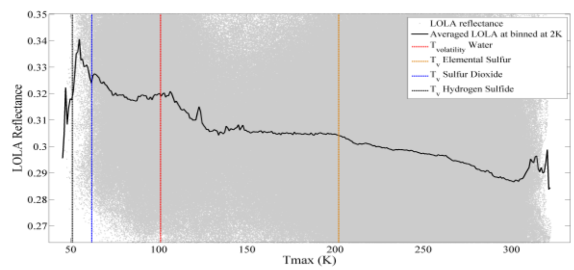

Figure 4: Close up of LOLA reflectance vs maximum Diviner measured surface temperature.

References:[1] Neumann et al. 2013, Science [2] Paige et al. 2013, Science [3] Slade et al., 1992, Science [4]Harmon et al, 2011, Icarus [5] Lawrence et al, 2013, Science [6] Lucey et al, 2013 AGU [7] Campbell et al, 2006, Nature [8] Feldman 2001, JGR[9] Lucey et al., 2014, JGR in press [10] Schorghofer 2007, JGR [11] Siegler et al. 2011, JGR [12] Siegler et al., 2014, Icarus, in press [13] Paige et al., 2010, Science [14] Crider and Killen, 2005, GRL [15] Hayne, et al. 2014, Icarus, In press [16] Zhang and Paige, 2010, GRL.[17] Delensky et al. Icarus, in review.