**EVIDENCE FOR SURFACE WATER ICE IN THE LUNAR POLAR REGIONS USING REFLECTANCE MEASUREMENTS FROM THE LUNAR ORBITER LASER ALTIMETER AND TEMPERATURE MEASUREMENTS FROM THE DIVINER LUNAR RADIOMETER EXPERIMENT.**

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**Introduction:** The concept of volatiles accumulating on the surfaces of airless bodies via 'cold trapping', where volatile molecules are deposited and preserved on cold, permanently shadowed surfaces over geologic timescales, has been recognized for many years [e.g. 1]. Thermally driven sublimation strongly constrains where a volatile may plausibly survive on a planet's surface for extended time periods, because of the exponential relationship between temperature and sublimation rate in a vacuum; e.g. water ice cannot be preserved on surfaces that experience temperatures above ~100K due to rapid sublimation loss [2,3,4]. Water ice was identified on Mercury's surface by correlating surface material with high 1.064 μm reflectance, detected using the Mercury Laser Altimeter, with model biannual maximum temperatures that allow surface ice to be stable for billions of years (<100K) [4,5]. The Lunar Orbiter Laser Altimeter (LOLA) also measures 1.064 μm surface reflectance in the lunar polar regions [6,7,8,9], while the Diviner Lunar Radiometer Experiment measures surface temperature [10,11]. This study, published by Fisher et al., 2017 [12], assesses the behavior of LOLA reflectance as a function of Diviner derived maximum temperature, with the goal of determining if the lunar poles exhibit reflectance increases associated with maximum temperature thresholds (~110K) consistent with the presence of surface water frost.

**Methods:** Data used in this study includes recalibrated 1.064 μm LOLA derived normal albedo [9,13], and the Diviner derived maximum temperature experienced by each of the LOLA reflectance measurements' locations over the course of the LRO mission [14]. Supporting data includes surface slope (computed with Generic Mapping Tools' grdgradient program [15]) and illumination conditions (calculated using the numerical modeling tools of [16]). Data were spatially resampled to 500×500 m resolution to prevent biases introduced by increased sampling density at the poles.

*Analysis.* Study data were constrained to latitudes at or within 20° of each pole. The LOLA reflectance data set is affected by instrument challenges over cold surfaces [8], therefore comparisons among terrains were conducted statistically. We analyzed the average of albedo plotted as a function of maximum temperature, to visualize the relationship between 1.064 μm reflectance and maximum surface temperature. The Moon's reflectance is correlated with slope [8], due to mass wasting removing darkened space weathered material from steep slopes. To prevent this effect from biasing our analysis, we separated the data into low-slope (<10 degrees: little mass wasting), and high-slope (>20 degrees: strong control on reflectance by mass wasting) sets, and analyzed them separately. We also compared the reflectance distribution of PSRs (defined as 0% average incident solar flux) with maximum surface temperatures too warm to support stable surface water frost (>125K), with the reflectance distribution of PSR terrain cold enough to support surface water frost over geologic timescales (<~110K), to see if surfaces with the ability to retain frost are brighter than ice-free PSRs.

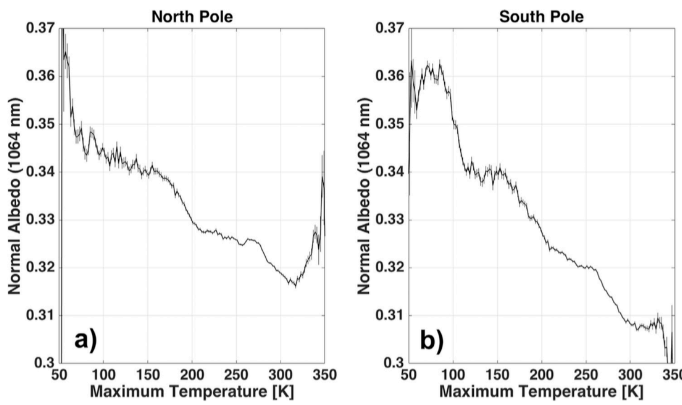
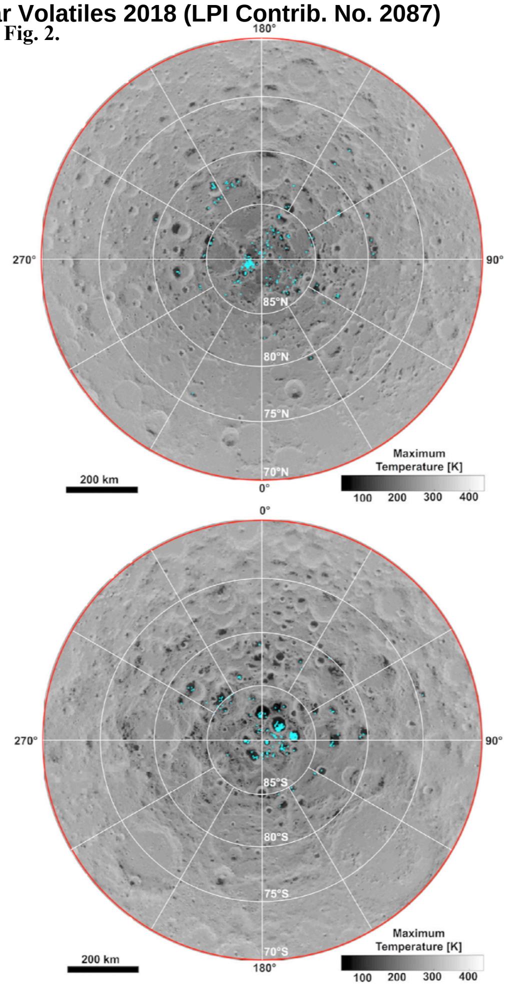



**Fig.1.** Average reflectance plotted as functions of maximum temperature for the **(a)** North and **(b)** South poles. Maximum temperature bin width = 1 K. Average reflectance curves are plotted with 2σ standard error of the mean [12].

**Results:** Fig.1 shows reflectance as a function of maximum temperature for the North (Fig.1a) and South (Fig.1b). In both polar regions, average reflectance generally increases with decreasing maximum temperature, and we observe breaks in trend at ~200K and ~300K (Fig,1a, 1b). At ~110K, South polar reflectance abruptly increases (Fig. 1b), accompanied by an upward shift (brightening) of the entire reflectance distribution [12]. High reflectance outliers such as Shackleton crater contribute little to this observed rise in reflectance [12]. No such abrupt increase occurs in the North polar region within that temperature range (Fig. 1a). Low-slope South-polar surfaces free of mass wasting bias also display an abrupt increase in average reflectance below ~110K, nearly identical to the ~110K reflectance peak observed in slope unconstrained data [12]. We also find the temperature-reflectance behavior of polar terrain varies significantly with proximity to the pole [12]. Within 5° of the South Pole, the reflectance of surfaces rapidly increases below maximum temperatures of 110 K; this 110 K feature is not observed at lower polar latitudes in the South polar region and is not observed at any latitude in the North polar region [12].

**Discussion:** The rapid reflectance increase observed at <110K maximum temperatures in the immediate South-polar region (−85°−90°) is consistent with the presence of surface water ice [Fig.1b;12]. This behavior mirrors observations made by [17], who showed that the ratio of UV wavelengths

**Fig. 2.**




within and adjacent to a water absorption feature, abruptly increases at maximum temperatures ~110K in the South pole, indicating the presence of surface water ice [12]. The North polar region does not show this behavior, nor do South polar surfaces at latitudes more than 5° from the pole. Reflectance-temperature behavior observed within South-polar PSRs is also consistent with the presence of surface water ice; PSRs surfaces capable of maintaining stable surface water frost typically show substantially higher reflectance than those incapable of sustaining stable surface water frost [12]. This difference is not noted in the North. Statistical modeling where reflective ice was randomly added to the South-polar high-temperature PSR reflectance distribution (an ice free surface), shows that 'ice-brightened' material heterogeneously distributed (some ice-free pixels) on a sub-pixel scale best reproduces the reflectance distribution of cold PSRs [12]. This agrees with findings of [17] which suggest that up to 10% of the surface they observe may host surface ice on a 250 m (sub-pixel) scale, and that the distribution of this ice within low-temperature areas is highly heterogeneous. We attribute the general trend of increasing reflectance with decreasing maximum temperature in the North and South to a temperature or illumination-dependent space weathering effect [e.g. 18, 19]. The pattern of 'trend breaks', superimposed on this general trend, which initiate at ~200K and ~300K in the North and South, is reminiscent of reflectance behavior near ~110K attributed to surface water frost (Fig. 1a, 1b); such features may result from deposition of additional volatile species. Candidate species with stability thresholds near ~200K include aromatic hydrocarbons, linear amides, carboxylic acids, and elemental sulfur [3]. Volatile species with stability thresholds near ~300K include complex polycyclic aromatic hydrocarbons such as coronene [20].

We identified areas that are so reflective that they are unlikely to be members of the background variation in reflectance due to ordinary lunar geologic processes. Assuming that the correlation between reflectance and temperature in areas with maximum temperatures greater than 125K is unrelated to processes involving surface water frost, we fit the reflectance-temperature data of ice free (>125K) areas at each pole with a linear trend, and remove that trend from the entire reflectance distribution of each pole. We then computed the statistics of the reflectance distribution of polar areas with maximum temperatures too warm to support the presence of surface ice (125-175K). Areas with maximum temperatures <110K that were 2-sigma more reflective than the mean reflectance of the ice-free distribution at each pole, and with surface slopes <10°, are mapped as potentially hosting surface water frost (Fig. 2);

**Conclusions:** We find that the reflectance of the lunar surface within 5° of latitude of the South Pole increases rapidly with decreasing temperature near ~110 K, behavior consistent with the presence of surface water ice. This distinction is not observed at the North Pole. The North polar region does not show this behavior, nor do South polar surfaces at latitudes >5° from the pole. South polar regions of permanent shadow show anomalous reflectance when their annual maximum surface temperatures are low enough to preserve water ice, also consistent with surface water frost. We note additional increases in reflectance with decreasing temperature at ~200K and ~300K, which may indicate the presence of additional volatile species. We identified and mapped surfaces with reflectances so high as to be unlikely to be part of an ice-free population (Fig. 2), and in the South we find a similar distribution to that found by [17] based on UV properties. Finally, unlike the North pole of Mercury, where all surfaces below about 100K exhibit reflectance anomalies [5], on the Moon not all surfaces cold enough to host surface ice show increased reflectance. This imperfect correlation between volatile signatures and temperature at the lunar poles stands in contrast with Mercury, where temperature accurately predicts ice distribution. Why this difference exists remains an important question in lunar science.

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