EVIDENCE FOR WATER ICE AND TEMPERATURE DEPENDENT SPACE WEATHERING AT THE LUNAR POLES FROM LOLA AND DIVINER.
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Introduction: LOLA measurements of zero phase reflectance of the Moon have revealed that polar regions in permanent shadow are significantly brighter at 1064 nm than equivalent surfaces that experience some illumination during the year [1,2]. Zuber et al. [1] outlined several hypotheses for this brightening including water frost and a polar effect on space weathering. Inclusion of Diviner temperature measurements to LOLA reflectance observations adds a physical chemical dimension to aid interpretation because of the exponential temperature dependence of surface frost lifetime against sublimation. In this abstract we present the results of LOLA measurements of surface reflectance in the polar regions, and assess the validity of the various hypotheses to explain the observations with special attention to temperature.

LOLA Surface Reflectance Observations: The Lunar Orbiter Laser Altimeter (LOLA) [3] aboard the Lunar Reconnaissance Orbiter (LRO) is principally a laser altimeter used for quantitative topography and related cartographic and geodetic applications. But in addition to measuring the range of the spacecraft to the lunar surface, LOLA measures the energy and width of the returned laser pulse from the surface [3], a method [4] pioneered from the Mars Orbiter Laser Altimeter [5,6,7]. LOLA samples the lunar surface with a 5-spot laser pattern with 5-m individual footprints, and a 28 Hz laser pulse gives rise to a net 10-12 meter sampling of the lunar surface below the LRO ground track. Over many months of observations these longitudinal profiles have yielded a high density of measurements of lunar reflectance.

The physical quantity that LOLA reports is the normal albedo, the reflectance of a spatially resolved surface element observed where the angle between the illumination source, surface element and detector is zero, relative to a Lambert surface viewed normally observed at the same geometry [8].

With passive imaging using the Sun as the light source, at high latitudes normal albedo can only be observed at oblique angles that become more extreme as the poles are approached. Because of the rugged lunar topography, some portions of the poles are permanently obscured from this measurement. LOLA's unique contribution is that it carries its own light source, and has measured the normal albedo for the entire lunar surface viewed normally below the LRO spacecraft, enabling unprecedented views of the lunar polar regions (Figure 1).

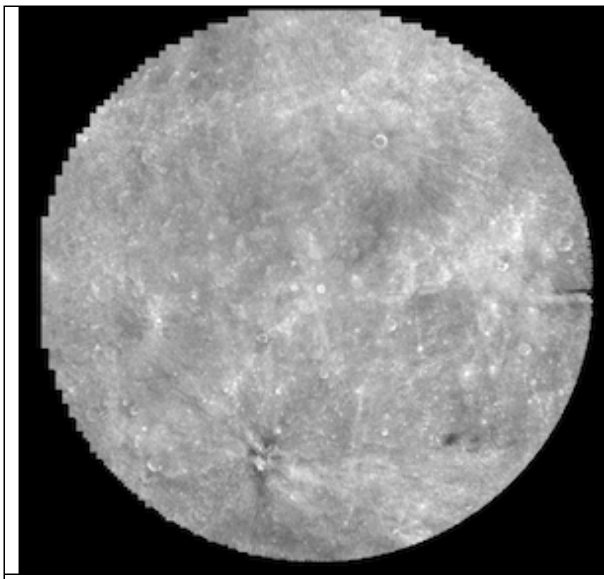
Figure 1. The normal albedo of the south pole of the Moon, orthographic projection 70-90S. The bright spot at the center is the polar crater Shackleton. The dark pattern in the lower left is the 57 km crater DeForest.

Reflectance Properties of Permanent Shadow: The normal albedo of surfaces in permanent shadow are significantly higher than those of polar locations that receive some sunlight. The width of the distribution is causes by brightness variations due to lunar mass wasting and cratering properties; similar distributions are observed at the equator.

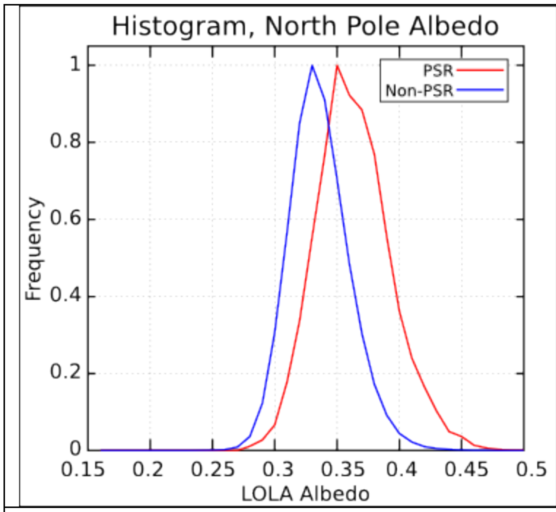

Figure 2. The distribution of normal albedos for areas in permanent shadow (PSR) and areas sometimes illuminated (Non-PSR) in the north pole (70-90N). The two populations are significantly offset, though considerable overlap persists.

Temperature Reflectance Integration: Integrating temperature provides new insight into polar reflectance. Mercury provides the type example for this analysis. Data taken by the Mercury Laser Altimeter (MLA) on MESSENGER were found to show brightening at specific temperatures [9,10]. Many surfaces on Mercury modeled to have maximum biannual temperatures below ~120K often were nearly twice as reflective as average Mercury regolith. These bright surface features, which correlate with Earth-observed radar bright deposits [e.g.11] are most likely due to the presence of surface water ice [10].

In Figure 3, we plot LOLA reflectance versus Diviner yearly maximum bolometric temperature. Across all temperatures there is a slight anticorrelation of maximum temperature and reflectance. There is a clear anticorrelation of temperature and reflectance. Because most of the surfaces we observe are mature we hypothesize that trend is due to an influence of temperature on space weathering. The optical effects of space weathering are fundamentally a physical chemical process of vapor phase reduction of ferrous iron to native iron, accompanied by evolving native iron grain sizes in microscopic impact melts and either of these processes could be influenced by temperature. This hypothesis is amendable to experimental investigation.

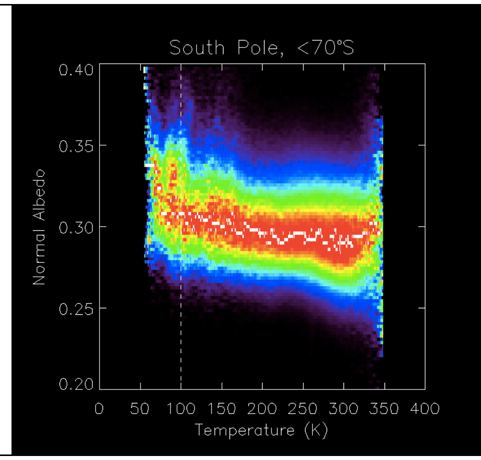

Figure 3. Distribution of normal albedo with temperature for the South Polar region. Values within each temperature bin are normalized to their peak value.

However, superimposed on the general trend are clear excursions above the main trend at temperatures below 120K; these, like on Mercury, may be due to surface frost.

Shackleton Crater appears to expose pure anorthosite [12] so it is possible that the bright excursions are due to bright anorthosite. However, inspection of craters in the polar regions generally show that the pole facing walls are brighter than the equator-facing walls; mass wasting would not show this preference.

Conclusions: We conclude that many of the high reflectance anomalies at Tmax < 120 are due to the presence of a thin layer of water frost, and the general trend is due to temperature influence on space weathering.

References [1]] Zuber, M.T. et al. Nature 486, 378-382, 2012., [2] Lucey et al. JGR submitted; [3] Smith, D.E, et al, 2010. Geophy. Res. L. 37, p. 18204, [4] Sun, X., G. A. Neumann, J. B. Abshire, and M. T. Zuber (2006), Appl. Opt., 45(17), 3960; [5] Smith, D. E. (1999), Science, 284(5419), 1495–1503;[6] Smith, D. E. et al. (2010), Space Sci. Rev., 150(1-4), 209–241; [7] Zuber, M. T., D. E. Smith, S. C. Solomon, D. O. Muhleman, J. W. Head, J. B. Garvin, J. B. Abshire, and J. L. Bufton (1992), J. Geophys. Res., 97(E5), 7781; [8] Hapke, B. (1993), Theory of reflectance and emittance spectroscopy, 1st ed., Cambridge University Press, Cambridge, UK, [9] Neumann, G.A. et al. Science, 339, 296-300, 2013, [10] Paige, D.A. et al. Science, 339, 300-303, 2013, [11] Slade, M.A., B. J. Butler, D.O. Muhleman. Science, 258:635-640, 1992, [12] Haruyama, J., S. Yamamoto, Y. Yokota, M. Ohtake, and T. Matsunaga (2013), Geophys. Res. Lett., 40(15), 3814–3818.