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LRO-LAMP detection of geologically young craters within lunar permanently shaded regions

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ABSTRACT

The upper 25–100 nm of the lunar regolith within the permanently shaded regions (PSRs) of the Moon has been demonstrated to have significantly higher surface porosity than the average lunar regolith by observations that the Lyman-α albedo measured by the Lunar Reconnaissance Orbiter (LRO) Lyman Alpha Mapping Project (LAMP) is lower in the PSRs than the surrounding region. We find that two areas within the lunar south polar PSRs have significantly brighter Lyman-α albedos and correlate with the ejecta blankets of two small craters (<2 km diameter). This higher albedo is likely due to the ejecta blankets having significantly lower surface porosity than the surrounding PSRs. Furthermore, the ejecta blankets have much higher Circular Polarization Ratios (CPR), as measured by LRO Mini-RF, indicating increased surface roughness compared to the surrounding terrain. These combined observations suggest the detection of two craters that are very young on geologic timescales. From these observations we derive age limits for the two craters of 7–420 million years (Myr) based on dust transport processes and the radar brightness of the disconnected halos of the ejecta blankets.

1. Introduction

Geologically young, or "fresh", craters provide an important opportunity to calibrate space weathering processes (Denevi et al., 2014; Robinson et al., 2015). Observations of fresh craters within the permanently shaded regions (PSRs) of the Moon, however, are challenging due to the absence of direct sunlight. PSRs are of great scientific and exploration interest because of their expected ability to trap and retain volatiles, potentially for billions of years (Watson et al., 1961; Paige et al., 2010a) but little is known about their surface properties or space weathering rates compared to other regions of the Moon. Fortunately, various spacecraft instruments have managed to collect data from PSRs at a range of wavelengths and through particle detections. These observations provide information about the volatile content, surface properties and geological history of the PSR interiors. Reduced epithermal neutron fluxes (Feldman et al., 2001; Mitrofanov et al., 2010), elevated Circular Polarization Ratios (CPR; Nozette et al., 1996; Spudis et al., 2013) and surface reflectance at visible (Haruyama et al., 2008; Lucey et al., 2014) and ultraviolet wavelengths (Gladstone et al., 2012) provide limits on the amount of surface frost and subsurface ice present in the PSRs. At the same time, images of the interiors of south polar PSRs produced using sunlight scattered off of crater walls (Haruyama et al., 2008), radar (Spudis et al., 2013) and laser altimetry (Zuber et al., 2012; Lucey et al., 2014) provide details about the topography, surface features and material properties.

We describe here the detection of two geologically young craters within south polar PSRs using maps of the Lyman-α (121.57 nm) albedo of their interiors. These maps were produced using data taken by the Lyman Alpha Mapping Project (LAMP), a

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far-ultraviolet (FUV) imaging spectrograph (Gladstone et al., 2010) on the NASA Lunar Reconnaissance Orbiter (LRO; Chin et al., 2007). This work demonstrates a new method for detecting fresh craters on the Moon and provides observations that are useful for studying space weathering processes within the lunar PSRs.

Space weathering occurs through several processes, including impact gardening (Arnold, 1975), solar wind sputtering (Hapke, 1973) and possibly dielectric breakdown (Jordan et al., 2014, 2015). Impact gardening is the turnover of regolith by micrometeoroid impacts, which physically breaks down grains, buries more material than it exposes, and heats and vaporizes regolith material that is then deposited on the surrounding material (Hapke et al., 1975; Pieters et al., 2000; Noble et al., 2007). Exposure to the solar wind sputters atoms from the surface that are redeposited as a coating on the surrounding regolith (Hapke, 1973). Finally, dielectric breakdown, a proposed process that may be unique to the PSRs, occurs when large solar energetic particle events cause dielectric breakdown, or sparking, in locations where cold temperatures greatly lengthen the lunar regolith's electrical discharging timescale (Jordan et al., 2014, 2015). If effective in the PSRs, the impact of dielectric breakdown would be to (1) increase the percentage of fine-grained particles in the uppermost 1 mm of regolith within the PSRs, (2) increase evidence of weathering due to vaporization of material, and (3) increase surface porosity (because smaller particles can form "fairy castle" structures more easily; Hapke and van Horn, 1963). Surface porosity is an important parameter in albedo evaluations (Hapke, 2008). It is the fraction of free space between and inside individual grains in the upper few centimeters of the lunar regolith.

It is unclear which process dominates in the PSRs or if the space weathering rates from impact gardening and solar wind sputtering would be the same in the lunar PSRs as in other regions of the Moon. Latitudinal variation in the impact gardening rate is not expected (Arnold, 1975), but it is possible that the PSRs experience less exposure to solar wind than other areas of the Moon (Lucey et al., 2014). In any case, fresh craters provide a snapshot in time of space weathering conditions and are, thus, valuable tools for evaluating the influence of space weathering on lunar regolith.

Fresh craters are brighter at visible wavelengths due to the exposure of material not previously subjected to space weathering (Denevi et al., 2014; Robinson et al., 2015) and have high CPR due to increased surface roughness at centimeter to decimeter scale (Bell et al., 2012; Spudis et al., 2013). Observations of fresh craters in the near UV (300–400 nm) show that space weathering causes the spectrum of the regolith to mature faster at UV wavelengths than at visible or infrared wavelengths (VNIR – 400–1400 nm; Denevi et al., 2014), which means that fresh craters detected in the far UV (100–200 nm) could be significantly younger than those identified as fresh in the VNIR. Therefore, the use of starlight and sky-glow illumination by LRO-LAMP to map the PSRs (Gladstone et al., 2010, 2012) provides a unique tool for detecting fresh craters in these difficult-to-study regions.

Within its wavelength coverage of 57–196 nm, LRO-LAMP is sensitive to the surface reflectance of the uppermost 25–100 nm of the lunar regolith. Previous studies of the LAMP FUV albedo measurements indicate that the PSRs in the lunar south polar region contain between 0.3% and 2% surface frost and that the porosity of the regolith in the PSRs is >70% (Gladstone et al., 2012) while the lunar average is ∼52%. This is in good agreement with results from the Lunar Crater Observation and Sensing Satellite (LCROSS) which found that the regolith in the Cabeus crater PSR has a porosity of ∼70% (Schultz et al., 2010). Higher surface porosity will reduce the albedo across all wavelengths due to a greater absorption of photons (Hapke, 2008). Therefore, porosity is the best explanation for low Lyman-α albedo observed by LAMP (Gladstone et al., 2012; Lucey et al., 2014) within PSRs. However, maps of the normal albedo at 1064 nm (near-infrared) made using data from the LRO Lunar Orbiter Laser Altimeter (LOLA; Smith et al., 2010) show that the normal albedo at this wavelength within the PSRs is greater than the surrounding areas (Lucey et al., 2014), despite the higher porosity observed by LAMP (Gladstone et al., 2012). This higher normal albedo is interpreted to suggest either the presence of significant amounts of water ice or that the material within the PSR is not as weathered as material outside of the PSR (Lucey et al., 2014).

2. Observations

For this study we focus on two small, anomalously bright regions (A and B) within Faustini and Slater craters that otherwise exhibit low LAMP Lyman-α albedo, which has been shown to coincide with PSRs (Gladstone et al., 2012). These bright regions are shown in Fig. 1, are located in the south polar region highlighted in the inset.

These PSRs are located within the south pole Aitkin Basin, the largest impact crater on the Moon. Faustini has a diameter of 41.6 km and is more than 3 km deep. The material on its floor Faustini is estimated to be 3.50 billion years (Gyr) old (Tye et al., in press) and elevated CPR inside Faustini has been interpreted to indicate that the crater is filled with plains material related to the Orientale basin (Campbell and Campbell, 2006), although the elevated CPR is found to be patchy (Spudis et al., 2013).

2.1. Albedo and surface porosity

The bright regions (designated A and B in Fig. 1) correlate with what appears to be the ejecta blankets of small (<2 km) craters. The Lyman-α albedos of the polar region south of 80° latitude, south pole PSRs and the two bright regions are illustrated in Fig. 2 along with their modeled porosity (Hapke, 2008; Gladstone et al., 2012). It is clear from this figure that the Lyman-α albedos of the ejecta blankets of craters A and B are much higher than their surrounding PSRs, suggesting a 40–50% decrease in their porosity compared to the PSR. Moreover, the ejecta blanket Lyman-α albedos are higher than the average albedo for the south polar region, implying a porosity that is up to 5% lower than the south pole region.

2.2. Topography

Figs. 3 and 4 illustrate LOLA (Smith et al., 2010) shaded relief maps of the two PSRs. Sample topographic profiles of craters A and B are given in Figs. 3b and 4b. These are small craters: crater A has a maximum diameter of 1.4 km and a minimum of ∼1.0 km, while crater B is roughly circular with a diameter of 0.8 km. Their depth-to-diameter (d/D) ratios are 0.12 (A) and 0.21 (B). Based on the Lyman-α albedo map, crater A's ejecta blanket appears in Fig. 1 to extend to the right and above the crater while the ejecta blanket of crater B surrounds the crater symmetrically.

2.3. Observations at other wavelengths

The LOLA albedo, measured for the wavelength of 1064 nm (Lucey et al., 2014), is shown in Fig. 5. Unlike Lyman-α wavelengths, the ejecta blankets of craters A and B show no evidence of a substantially different normal albedo at 1064 nm than their surrounding PSRs.

Fig. 6a and b are composite images of the interior of Faustini and Slater craters taken by the Lunar Reconnaissance Orbiter Camera (LROC; Robinson et al., 2010) in visible wavelengths (390–700 nm) using sunlight scattered off crater walls as an