LRO LAMP FAR ULTRAVIOLET INVESTIGATION OF COLD SPOTS ON THE MOON AND IMPLICATIONS FOR SPACE WEATHERING RATES ON AIRLESS BODIES.

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Introduction: The Moon is a prominent location for studying crater formation processes and regolith modification. Extensive modification has been observed around some fresh craters, extending to tens of crater radii or more [1-3]. The Diviner Lunar Radiometer Experiment, an instrument on-board NASA's Lunar Reconnaissance Orbiter (LRO), has observed thermal anomalies in rayed profiles around these fresh craters, known as cold spots [1] (**Figure 1**). Cold spots have been observed around the new impact crater captured by paired observations of LRO Narrow Angle Camera (NAC) [3], and they are likely the result of mixed/reworked *in-situ* regolith due to the impact. Mixing/reworking likely cause cold spot surfaces to be immature at formation time despite little evidence of that being found in visible and near infrared. Maturity evaluates the degree to which the regolith has accumulated space weathering products such as nanophase iron (npFe) over time [4]. Cold spots represent a sort of physical immaturity in the upper few cm, whereas UV/Vis observations are sensitive to both physical (e.g. packing/roughness) and chemical (e.g. npFe) immaturity possibly in the upper mm. As the regolith is processed over time, signs of immaturity over cold spots seem to disappear based on depth of sensitivity of the measurement [1, 3, 5].

In this study, we investigated the cold spots using observations from the far ultraviolet (FUV) spectrograph on-board LRO known as the Lyman Alpha Mapping Project (LAMP). Preliminary results from our previous FUV analysis of several of the largest cold spots showed that the cold spot surfaces tend to be less mature than the surrounding regolith [6]. These large cold spots correspond to higher H-parameter values (i.e., a measure of the rate of regolith density increase with depth) and younger surface age [3, 7]. Cold spot features fade over time, thus the smaller cold spots with lower H-parameter values correspond to older surfaces. The age of the cold spots with varying H-parameters has been investigated and determined by [3], which allows FUV analysis of the link between maturity change as function of the fading of the cold spots over time. The results can therefore provide constraints on space weathering rates on the Moon and other airless bodies which is currently a matter of debate [8].

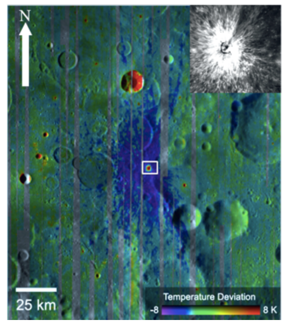

Figure 1: Diviner nighttime regolith temperature map of a cold spot near 90.8°E, 5.4°S around a fresh crater, adapted from Figure 4 of [1]. The cold spot regions are shown blue. The white square indicates the region shown in the top right grayscale LROC image.

Methodology: The primary dataset used in this study is the FUV data from the LRO LAMP instrument. LAMP is nadir pointing and provides global coverage of both nightside and dayside of the Moon in the wavelength range 57-196 nm, with a spatial sampling of ~250m/pixel. It has two observation modes: lunar nightside, when the aperture door is open and faint Lyman alpha sky glow and UV bright stars are used for illumination; and lunar dayside, when the aperture door is closed and reflected sunlight is viewed through a pinhole [9]. We use LAMP dayside data for this analysis. The dayside observations measure bidirectional reflectance, which depends on the incident, emission, and phase angles, as well as soil properties. Given the different viewing geometries, photometric corrections are required to normalize the reflectance to a common viewing geometry. The data used in this work are all photometrically corrected using the method of Liu et al., 2018 [10]. To improve the signal-to-noise ratio, data collected between the beginning of the mission (i.e., September 2009) and December 2015 were summed and averaged. For the cold spot analysis, a comparison was performed between the spectral slopes of the cold spot regions, the surrounding areas, and the center young crater associated with the cold spot. Shape files based on Diviner temperature maps were used to map cold spot surfaces, which allows us to extract the average FUV spectra over the cold spot terrain more accurately, as shown in **Figure 2**.

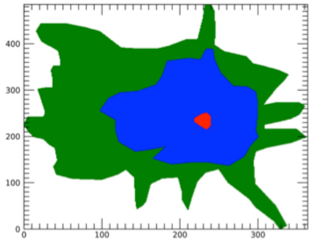

Figure 2: Cold spot extent derived from Diviner temperature map. Red area: crater and continuous ejecta region, blue area: intense cold spot region, and green area: largest extent of the cold spot. Surrounding terrain: areas in white color.

Results and Discussion: Four example cold spots with ages spanning from 0.22 to 0.99 Ma were investigated [3] (**Table 1**). For each cold spot, the spectra of the crater region (area in red in **Figure 2**), intense cold spot region (area in blue) and surrounding terrain (area in white color) were all plotted and compared. The surrounding terrain includes areas outside the area in green (i.e., largest extent of the cold spot) shown in **Figure 2**. **Figures 3a-c** show example spectra for three cold spots, T6, T9, and T1, respectively. For the younger cold spot T6 with higher H-parameter value, the spectrum over the cold spot surface shows a bluer spectral slope compared to the fresh crater (**Figure 3a**), but a clearly redder slope than the surrounding terrain. The spectral slope in FUV between 170 and 190nm is indicative of space weathering, and therefore regolith maturity [11]. The longer the regolith is exposed at the surface, the more space weathering it endures, and therefore the region appears more mature. Space weathering results in a bluer spectral slope in FUV wavelengths due to the formation of opaque nanophase iron particles [11]. Similar results were observed for another extensive and younger cold spot T2 (**Table 1**).

In contrast, for the more faded cold spot such as T9 (**Table 1**), the spectral slope over cold spot surfaces is only slightly redder (i.e., immature) than the surrounding terrain, with both the regions being more mature than the center fresh crater (**Figure 3b**). This is more evident for the most faded cold spots such as T1 (**Figure 3c**), where the spectral slope show no difference between cold spot surfaces and surrounding terrains.

The results have important implications for the space weathering rates on the Moon. Cold spot surfaces appear to be immature in FUV measurements after their initial formation during impact events. They fade over time and become mature due to space weathering.

Cold spot	Longitude, Latitude (°)	Diameter (km)	H parameter	Age (Ma)	Terrain type
T1	144.4504, -17.7153	2.286	0.01586	0.99	Highland
T2	151.6411, -3.9815	1.759	0.05322	0.22	Highland
T6	120.2339, -29.8857	1.039	0.04400	0.38	Highland
T9	-125.9853, 5.8210	1.074	0.03975	0.42	Highland

Table 1: Table showing properties of cold spots investigated. H parameter values were derived from fitting modeled nighttime temperatures to Diviner nighttime temperatures, and ages were derived from crater counting by [3].

Our results show that cold spot surfaces became as mature as surrounding terrain after ~0.4-1 Ma, indicating the space weathering time scale of ~10^5 years.

Conclusion: In this study, several cold spots in the FUV wavelengths were investigated, and distinct spectral differences between cold spot surfaces and surrounding terrains were found depending on the age of the associated crater. FUV spectra show that cold spot regions are more mature than the center fresh crater but less mature than the surrounding regolith and this trend is more clearly seen in the younger cold spots. For the older cold spots the maturity of the regolith between the cold spot area and surrounding terrain was similar. This means that for more faded cold spots space weathering effects have processed the regolith to the extent that they are not much different from their surroundings in FUV measurements. Due to the age differences between these older and younger cold spots, we can constrain the space weathering rates, for example, ~0.4-1 million years of exposure to space weathering will result in the regolith being as mature as the surrounding terrain in the FUV.

References: [1] Bandfield et al. (2014) Icarus 231 pp.221-231. [2] Speyerer et al. (2016) Nature 538 pp.215-218. [3] Williams et al. (2018) JGR Vol. 123 pp.2380-2392. [4] Lucey et al. (2000) JGR Vol. 105. [5] Powell et al. (2018) LPSC, LPI Contrib. No. 2083. [6] Liu et al. (2018) EPSC Vol. 12 492. [7] Hayne et al. (2017) JGR Vol. 122 pp.2371-2400. [8] Pieters et al. (2016) JGR Vol. 121 pp.1865-1884. [9] Gladstone et al. (2010) Space Science Reviews 150.1, pp.161-181. [10] Liu et al. (2018) LPSC. Vol. 49. p. 2089. [11] Hendrix et al. (2016) Icarus 27.

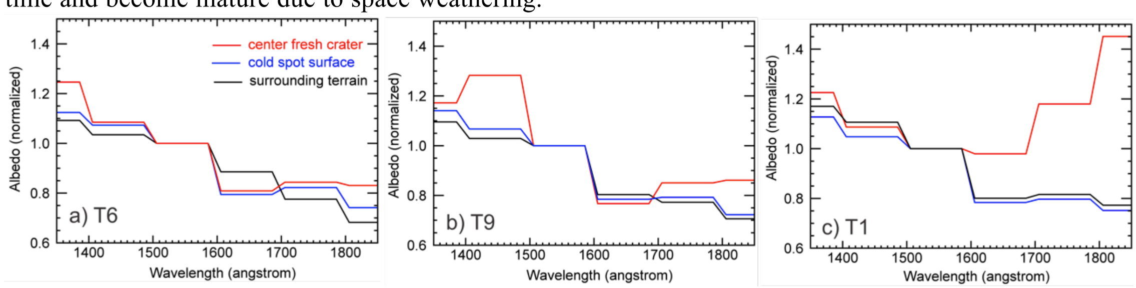

Figure 3: Far UV reflectance spectra normalized at 154 nm for cold spots T6 (youngest), T9 and T1 (oldest). Redder spectral slope over 170-190 nm wavelength range indicates less mature regolith.