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Lunar space weathering at ultraviolet wavelengths

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Abstract

The Lunar Reconnaissance Orbiter Camera (LROC) Wide Angle Camera (WAC) images nearly the entire Moon each month through two ultraviolet (UV) filters (bandpasses centered at 321 and 360 nm) and five visible filters (415, 566, 604, 643, and 689 nm) [1]. Global coverage at UV wavelengths provides a fresh opportunity to examine the rate and causes of space weathering on the Moon. We find that UV observations provide a new tool to more confidently identify the least weathered material. Only the youngest craters (<~100 My) appear fresh in the UV, and the UV reflectance of lunar swirls is consistent with limited space weathering.

1. Space weathering

Our understanding of the effects of exposure to space weathering is based on lunar samples and remote sensing observations at visible (Vis) and near-infrared (NIR) wavelengths [e.g. 2-6]. Past work suggests reflectance at ultraviolet wavelengths may be especially sensitive to space weathering effects [7]. In the UV, light penetrates to a relatively shallow depth within a particle and its reflectance includes a larger fraction of photons scattered from grain surfaces, as opposed to from within their interiors [e.g. 8]. Thus vapor-deposited coatings on grain surfaces have a greater effect on light reflected in the UV than at longer wavelengths.

Silicates typically have a strong decrease in reflectance toward UV wavelengths (<~450 nm) due to strong bands at 250 nm and in the far UV. Metallic iron is relatively spectrally neutral, and laboratory spectra suggest that its addition to mature soils in the form of submicroscopic iron (SMFe, also known as nanophase iron) flattens silicate spectra, significantly reducing spectral slope in the ultraviolet [7]. This effect is in contrast to space weathering trends at Vis and NIR wavelengths, where weathered materials have a steeper positive ("redder") slope than their immature counterparts [3-6]. We assess the effects of space weathering on the slope of the UV spectrum using global WAC mosaics (400 m/pixel) that were photometrically normalized to a standard viewing geometry [9]. In particular, we focus on the ratio of the 321/415 nm filters to assess changes in UV slope.

2. UV slopes of immature material

Global observations show that variations in UV slope due to differences in maturity are greatly reduced in comparison to the effects at longer wavelengths. Rays that are readily apparent in longer wavelengths of many large Copernican craters are not easily distinguished from background mature material in UV ratio images. Distal rays of large Copernican craters have 321/415 nm ratio values <1% to 3% higher than surrounding mature highlands terrain, vs. 6-10% higher for 415/689 nm. Near the rims of these large craters and in the ejecta blankets of some small craters we observe areas with lower 321/415 nm ratio values (i.e., less mature) as compared with their surroundings. (Because FeO and TiO_2 also have a strong effect on this region of the spectrum [10], the reflectance of immature materials must be compared with that of mature material within the same unit.)

In comparison with a model of maturity based on Vis-NIR wavelengths (optical maturity or OMAT) [5], much of the material that is considered fresh according to OMAT shows no corresponding reduction in 321/415 nm ratio values. For fresh craters, OMAT has been shown to increase with increasing distance from the crater rim [11]. Ejecta blanket thickness decreases with distance, thus subsequent impact gardening is more efficient at mixing the fresh ejecta with mature material from below as radial distance increases, meaning maturity indices as a function of distance from the rim can be used as a proxy for time [11]. Average radial crater profiles are calculated by binning like distances and calculating their mean reflectance and OMAT values (higher OMAT indicates a fresher surface). Profiles for large rayed craters show that while OMAT continues to decrease for large distances, 321/415 nm ratios increase quickly to match mature background levels (Fig. 1). For Giordano Bruno (22 km diameter), one of the youngest large impact craters on the Moon, 321/415 nm ratio values reach those of mature material <40 km from the rim (<1.8 crater diameters), compared to >150 km (>6.8 crater diameters) for OMAT. A similar trend is observed for smaller craters: only craters with the highest OMAT show a decrease in the 321/415 nm ratio of their ejecta.

3. Immaturity vs. impact glass

While the observed spectral trends are consistent with flattening of the UV spectrum due to the addition of SMFe, glass also has strong UV charge-transfer absorptions [12, 13] and is produced through shock heating in impact events. We examine the possibility that low 321/415 nm ratios are due to the presence of glass produced during the primary impact, as opposed to the exposure of unweathered silicates. Using LROC Narrow Angle Camera high-resolution images, we find that most of the lowest 321/415 nm ratios are associated with blocky, high-reflectance ejecta. The presence of impact melt deposits, which could be expected to have a high glass content, do not appear to be the main cause of the drop-off in reflectance at short wavelengths. However we cannot rule out the possibility of fine particles of impact glass dispersed throughout the ejecta.

Lunar swirls, sinuous high albedo markings associated with crustal magnetic anomalies [e.g. 14] exhibit low 321/415 nm ratio values. The origin of lunar swirls has long been enigmatic; proposed formation mechanisms include reduced space weathering due to magnetic shielding from the solar wind, the deposition of fine-grained plagioclase dust, or the scouring of the surface by cometary impacts [see 15, and references therein]. The low UV ratio values in LROC WAC observations are consistent with the exposure of fresh material on the surface; none of the proposed formation mechanisms would result in higher glass abundances.

4. Discussion

Among the regions studied, lunar swirls like Reiner Gamma appear to be the least mature. Even UV spectra of Giordano Bruno appear to be affected by some degree of space weathering. Tycho, with an age of ~100 My, is approaching UV maturity, and if glass is responsible in part for the UV absorption near its rim [16], this would imply an even faster rate of spectral maturation in the UV (i.e., the area may already be mature, but glass-rich). WAC UV observations suggest that by this measure, nearly the entire lunar surface has saturated in UV maturity, with only material on the order of 100 My or younger considered immature. These short time scales are consistent with rapid space weathering due to exposure to the solar wind [17]. Since swirls are the least UV-mature materials on the Moon, the idea that local magnetic fields deflect the solar wind is attractive, and/or that these are very recent features.

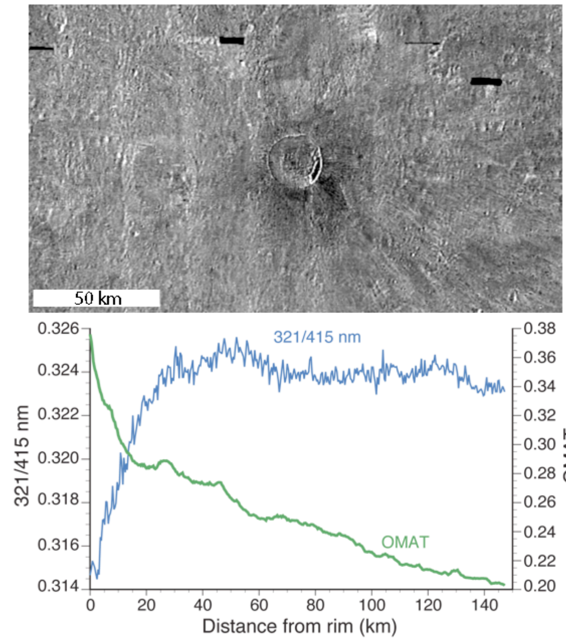

Fig. 1. Top: 321/415 nm image of Giordano Bruno crater (35.9°N, 102.9°E). Ejecta has a lower ratio value near the rim, further away the rays are indistinguishable from background material. Bottom: Corresponding 321/415 nm ratio and OMAT radial profiles.

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