SPACE WEATHERING AT THE LUNAR POLES: THE EFFECT OF TEMPERATURE ON REFLECTANCE OF MATERIALS WEATHERED BY LASER IRRADIATION.

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Introduction: The Lunar Orbiter Laser Altimeter (LOLA) measured increased brightness at 1064 nm in two ways: as an anomaly and a trend [1-3]. LOLA reveals a brightness anomaly, a sharp increase in reflectance by ~10% for permanently shadowed regions (PSRs), relative to polar surfaces that experience some illumination during the year [1, 2]. The reflectance increase for PSRs could be due to the presence of ice, however, increased reflectance at 1064 nm is also consistent with reduced space weathering [1, 2]. In addition, LOLA reveals an anticorrelation trend between temperature and reflectance poleward of 70 degrees latitude [3]. On this basis, Lucey et al. [2, 3] concluded there might be a temperature dependent relation on the production of space weathering effects.

Low surface temperatures of the polar regions and the extremely low temperatures of PSRs (as low as 50K) may affect the volume of impact melt/vaporization produced and subsequent development of submicroscopic iron. To test this hypothesis we compare spectra of materials laser space weathered at low temperature (~90 K) with spectra of the same materials laser space weathered at room temperature. We performed laser irradiation of olivine and a highlands-like mineral mixture at temperatures comparable to those of PSRs and measured the ultraviolet to near-infrared (UVVIS to NIR) reflectance, with specific attention to 1064 nm.

If temperature does indeed influence space weathering processes, the relevance extends beyond the lunar polar regions. Temperatures at the lunar equator fall below 100K at nighttime [4], meaning space weathering could be less effective half of the time. An environmental component to space weathering would also affect the poles of Mercury, where PSRs have biannual maximum surface temperatures as low as 50K [5]. In addition, there may also be a continuum of space weathering effects with distance from the Sun, affecting the interpretations of asteroid observations.

Methods: Laser irradiation experiments were performed on powdered (<75 μm) samples of San Carlos olivine and a highlands simulant, which is a mixture of 85% plagioclase, 10% pyroxene, and 5% olivine. For each experiment, 0.5 g of uncompressed sample was irradiated with a 1064-nm Nd:YAG, 5-7 nsec (20 Hz) pulsed laser, to simulate μm-sized micrometeorite impacts on the Moon. The samples were irradiated by rastering the laser across the entire surface of the sample. Each sample was irradiated at 30-sec intervals for 15 minutes, equivalent to 216 million years of space weathering on the lunar surface. In addition, an olivine sample was irradiated for 10 minutes at 295K. Samples were placed in a thermally controlled vacuum chamber that can be cooled to liquid nitrogen temperatures. Experiments were performed at 295K, 170K, and 88K, all under vacuum pressure of 10^{-5} to 10^{-7} mbar.

Reflectance measurements of all samples were taken at ambient temperature outside the thermal chamber with an Analytical Spectral Devices FieldSpec 4 spectrometer, which measures reflectance from the UVVIS to NIR (0.35-2.5 μm). Spectra were acquired with a 30° incidence angle and 0° emission angle. Reflectance was measured relative to Spectralon standards.

Results: Spectral changes were measured as a function of temperature and total irradiation. All irradiated samples exhibit darkening, reddening, and subdued absorption bands characteristic of space weathering. The olivine irradiated at 88K is brighter overall than the sample irradiated at 295K (Fig. 1), but it is specifically 5% brighter at 1064 nm. In addition, the 88K irradiated olivine exhibits slightly less reddening compared to olivine irradiated at 170K and 295K (Fig. 2). The spectrum of olivine irradiated at 295K for only 10 minutes is a close match to the 88K spectrum in overall reflectance, but it is darker at 1064 nm and redder than the 88K spectrum. Hapke radiative transfer modeling [7], with the modifications by [8] for larger microphase (~1μm), which darkens, and smaller nanophase (~10 nm), which reddens, provided abundance estimates for these two sizes of submicroscopic iron (Fig. 3). Based on these estimates, the olivine irradiated at 88K contained 70% the abundance of microphase iron and 65% the abundance of nanophase iron of olivine irradiated at 295K.

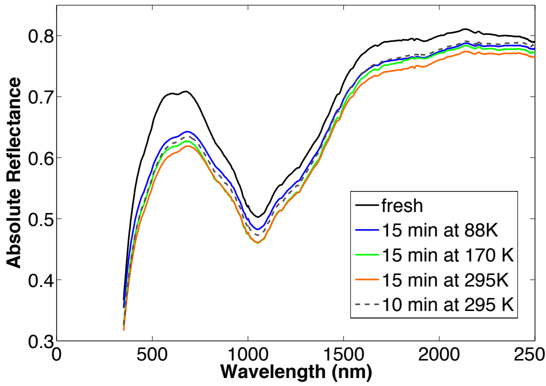

Fig. 1: Absolute reflectance of fresh and irradiated olivine.

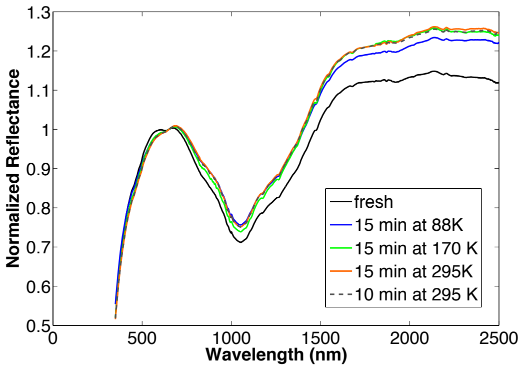

Fig. 2: Reflectance of fresh and irradiated olivine normalized to 650 nm.

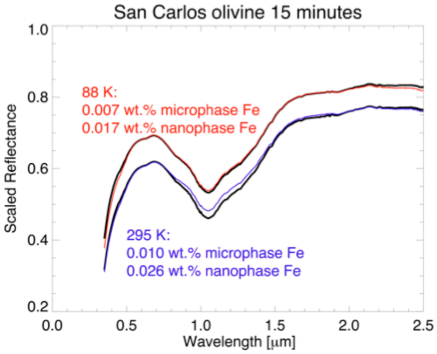

Fig. 3: Scaled reflectance showing the fits of the model to olivine samples irradiated at 88K and 295K. The 88K spectra are offset by 0.05 relative to the 295K spectra.

The highlands-like mineral mixture irradiated at 88K is slightly brighter than the mixture irradiated at 295K (Fig. 4a). At 1064 nm, the reflectance of the 88K sample is 1% brighter relative to the reflectance of the 295K sample. In addition, the 88K sample has a slope in the visible wavelengths that is less red than that of the 295K sample (Fig. 4b).

Discussion: Laser irradiation experiments performed at temperatures comparable to those in PSRs show that space weathering processes are influenced by temperature. The 5% greater reflectance at 1064 nm for the 88K olivine sample is consistent with the observed anticorrelation trend between temperature and LOLA albedo [3].

Radiative transfer modeling of our olivine samples reveals that olivine irradiated at 88K contains 65% the abundance of nanophase iron of olivine irradiated at 295K. This estimate is comparable to the prediction by [2], which suggested that if only differences in nanophase iron abundances are responsible for the LOLA brightness anomaly of PSRs, PSRs have between 50% and 80% the abundance of nanophase iron in mature lunar soil.

The highlands-like mineral mixture exhibited little temperature dependent spectral difference between low and high temperature. We predict that in order to characterize the effects of temperature on space weathering the sample requires longer irradiation, because it contains low FeO.

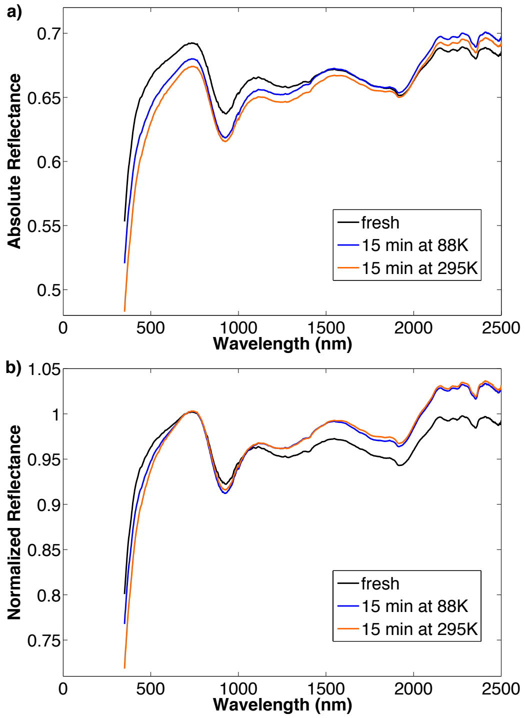

Fig. 4: (a) Absolute reflectance and (b) normalized reflectance (to 700 nm) of the fresh and irradiated mineral mixture.

Conclusions & Future Work: Previous work hypothesized that reduced space weathering contributes to increased brightness measured at polar regions by LOLA. Our results show that extremely low temperatures, comparable to those of PSRs, do influence space weathering and decrease the production of microphase and nanophase iron. These temperature effects should be measurable both with latitude for a given body and as a function of solar distance. We plan to use transmission electron microscopy to directly compare the rims and submicroscopic iron produced at 88-120K and 295K. In addition to reduced submicroscopic iron, the presence of ice may also contribute to the LOLA anomaly in PSRs. Future experiments will also examine how the addition of ice affects space weathering and whether it contributes to increased reflectance at 1064 nm.

Acknowledgements: This work was supported by NASA Headquarters under the NASA Earth and Space Science Fellowship Program – Grant NNX14AP20H.

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