SPECTRAL AND MORPHOLOGICAL VARIATIONS RESULTING FROM SPACE WEATHERING EXPERIMENTS ON PRISTINE LUNAR SOILS. H. M. Kaluna¹, J. P. Bradley², H. A. Ishii³, and J. J. Gillis-Davis⁴, ¹Department of Physics and Astronomy, University of Hawai‘i at Hilo, Hilo-HI-96720 USA (kaluna@hawaii.edu) ²Hawai‘i Institute for Geophysics and Planetology, University of Hawai‘i at Mānoa, Honolulu-HI-96822 USA

Introduction:  Space weathering is a complex, multi-component process that occurs on atmosphere-less bodies and results in both optical and physical alterations in the surface regolith of these bodies. Although limited, the retrieval of samples from Solar System bodies such as the Moon and Itokawa has greatly illuminated our understanding of the various processes and products that constitute space weathering. Complementing the insights gained from these returned samples are space weathering experiments, which range from pulsed laser irradiation [1,2], ion bombardment [3,4] and kinetic energy experiments [5]. These experiments allow us to examine space weathering effects for a variety of compositions and controlled experimental conditions beyond those represented by returned samples. This work examines the efficacy of laser simulated micrometeorite impacts reproducing the lunar spectral maturity trends and morphological features (i.e. npFe and vesicle production). To assess the effectiveness of these experiments, we use TEM and spectral analyses to compare the spectra of laser irradiated pristine soils derived from rocks collected during the Apollo 12 and 16 missions to lunar soils of varying maturity levels.

Methods:  The soil samples were produced from the interior components of lunar Mare and Highland rocks, 12002 and 68416 respectively. 12002 is a Mare basalt rock consisting predominately of pyroxene (~49 vol.%), with accessory olivine (17%), plagioclase (16%) and minor amounts of ilmenite and chromite [6]. 68416 is a Highlands balsatic impact melt predominately composed of plagioclase (~80 vol.%), with accessory pyroxene (12-16%), minor amounts of olivine, ilmenite and metallic iron (<5%) [7]. Each sample was crushed and dry-sieved to <75 µm, producing a pristine lunar soil that had little to no interactions with the solar wind.

We used a Nd:YAG, 1064 nm, pulsed laser to simulate micrometeorite impacts on ~0.2g of each soil sample. A laser spot size of 0.25 mm, an incident energy of 30mJ, a frequency of 20 Hz and a 6-8 nanosecond pulse duration was used to simulate timescales of 10 µm sized micrometeorite impacts [8]. Each of the sample soils were irradiated at intervals of 5, 5, 10, 10, 10 and 10 minutes for a total of 60 minutes. Each of the samples were irradiated as uncompressed powders and under vacuum pressures of $10^5$ to $10^6$ mbar.

Spectral data were taken using a Vis/NIR (350-2500nm) ASD FieldSpec 4 spectroradiometer. Bidirectional reflectance spectra were acquired at a viewing geometry of $i=30^o$ and $e=0^o$, and measured relative to a 99% reflectance LabSphere Spectralon Standard.

Spectral Variations:  As seen in Figure 1, the 12002 and 68416 soils have distinctly shallow spectral slopes and pronounced absorption features. Although there are slight mineralogical differences between the prepared soil samples and the NASA RELAB samples [9], the stark contrast between the spectra demonstrate the pristine nature of the samples used in this work. Also evident in Fig. 1 is the stark contrast between even the most immature soils collected during the
Apollo missions and the soils irradiated in this work. After ~60 minutes of irradiation, the 12002 and 68416 begin to achieve slopes that are consistent with these immature soils. It is clear that while the pulsed laser irradiation modifies the continuum slopes of the samples, this method is less efficient at reproducing the suppression of absorption features, particularly for 68416.

**TEM Analyses:** After irradiation, samples were carbon-coated to ensure conductivity for SEM and TEM analyses. Electron-transparent sections were prepared using the UH FEI Helios 660 dual beam FIB-SEM with a 30 kV Ga+ ion beam and a Pt protective strap. Sections were FIB-polished at low kV to reduce amorphous kerf and implanted Ga. Sections were then analyzed at ~200 kV in the UH FEI 80-300 kV Titan dual Cs-corrected and monochromated TEM/STEM. Brightfield and darkfield images were collected using STEM mode, compositions were analyzed with a Si(Li) energy dispersive x-ray detector.

**npFe inclusions.** The production of npFe particles was ubiquitous in both the 12002 and 68416 samples, occurring in both melt rims as well as large glassy melt spherules (~500 nm in diameter), which adhered to the host grains. Electron diffraction patterns of Fe-rich inclusions were found to be consistent with oxidized npFe. It is possible that the oxidation occurred after irradiation because diffraction patterns were taken several months after the FIB sections were made. The size distribution of npFe particles is shown in Fig. 3. The larger particle tail resembles the tail that is observed in naturally weathered lunar soils [10].

**Vesicle occurrence and size distribution.** Vesicle formation is widespread in both the glassy melt spherules as well as the glassy melt rims in both the 68416 and 12002 samples. The size distribution of vesicles in the 68416 appear to occur in two populations, with the smaller size ranging from ~5 - 20 nm, and the set ranging from ~30 – 50 nm, with several as large as ~100 nm. The size range of vesicles observed in this work is comparable to those observed in both naturally space weathered lunar and Itokawa soils [11-14]. The observed large vesicles (20 nm – 50nm) are associated with the melt spherules and not typically accompanied by the presence of npFe. In contrast, the smaller vesicles appear to form primarily in the glassy rims containing npFe particles. Several vesicles also appear to have npFe particles.

The size distribution of the vesicles in both lunar samples well approximate those of naturally weathered soils, however, both samples originate from the interior of lunar rocks, implying little to no exposure to solar wind and H and He ions, an expected component of vesicle formation [15]. It is possible that adsorbed water on the surface of the ground 12002 and 68416 soils may provide a source of volatile material that could lead to vesicle formation. It is possible that the H and O released during irradiation may also serve to oxidize the npFe particles as they are forming, affecting the spectral modification of the soils. While npFe inclusions are ubiquitous in the soil rims, it is unclear why they are less efficient at absorption band suppression than expected. It is possible agglutinates may be an important mechanism in reducing spectral contrast.