OLIVINE AND PLAGIOCLASE SPECTRA LARGELY UNAFFECTED BY LUNAR-LIKE SPACE WEATHERING IN THE "CROSS-OVER" REGION.

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Introduction: Recent work has demonstrated that infrared spectra measured in the 4-8 µm "cross-over" range are a useful tool for determining the Mg# of olivine [1]. Olivine has two strong, distinct bands at 5.6 and 6.0 µm (Fig. 1) that shift systematically to longer wavelengths with increasing Fe content, allowing Mg# to be determined for reflectance spectra of pure olivine samples in a laboratory setting within +/-10 mol% [1]. In order to assess opportunities for "cross-over" spectroscopy in the lunar context, we investigate samples that are analogous to space weathered materials on the Moon.

Although space weathering has been demonstrated to have a strong influence on spectra in the visible-near infrared (VNIR, 0.5-3 µm) range [e.g., 2–4], the effect of space weathering in the 4-8 µm range remains largely unexplored. In the VNIR, space weathering is a major complication in the determination of Mg# [e.g., 4], and so understanding the influence of space weathering on Mg# determination in the "cross-over" range is crucial for assessing potential applications of "cross-over" spectroscopy. Since olivine is expected to occur in plagioclase-bearing rocks and regolith on the Moon [5, 6], it is also necessary to investigate the influence of space weathering on mixtures of olivine and plagioclase. We examined cross-over spectra of experimentally laser-weathered olivine and describe ongoing investigations of laser-weathered anorthite and olivine-anorthite mixtures in order to constrain the expected spectral character of olivine-bearing rock materials in the lunar environment.

Background: Space weathering is pervasive on the Moon and other airless bodies, producing nanophase metallic iron ($npFe^0$) and micro-phase iron, which cause darkening and reddening of spectra, and loss of diagnostic absorption features [e.g., 2,3]. These effects can significantly hamper remote compositional analysis. While the spectral effects of space weathering have been thoroughly characterized in the VNIR range, study of its effects in the midinfrared (MIR, 8-15 µm) has been limited [7,8], and essentially non-existent in the "cross-over" region.

The "cross-over" region is the wavelength range of the infrared where the volume scattering of photons in the visible-near infrared transitions to the surface scattering of photons in the MIR. In the inner Solar System, the "cross-over" region for silicate minerals also generally coincides with the transition between the dominance of reflected solar photons in VNIR and thermally emitted photons in the MIR. Spectral bands of silicate minerals in the "cross-over" region are hypothesized to arise as combination-overtones of fundamental vibrations at longer wavelengths in the MIR [9], where space-weathering effects are more modest than in the VNIR [7,8]. While olivine has two strong distinct bands at 5.6 and 6.0 µm, anorthite has relatively weak broad bands at ~5.3 and ~6.2 µm [10]. Olivine and plagioclase co-occur in lunar rocks such as troctolites, troctolitic anorthites, and basalts [6].

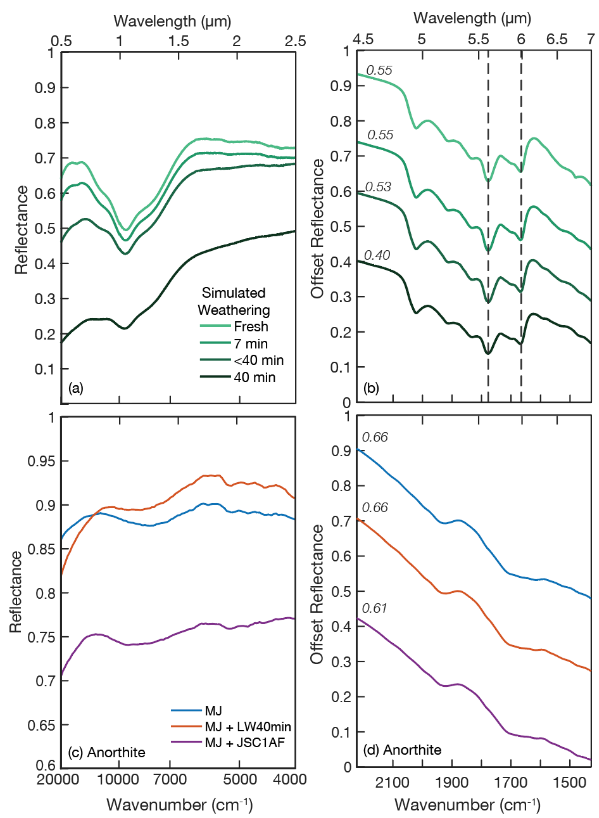

Figure 1. *(a) VNIR and (b) "cross-over" spectra of laser weathered San Carlos olivine. Dashed vertical lines indicate 5.6 and 6.0 µm diagnostic bands [1]. (c) VNIR and (d) "cross-over" reflectance spectra of Miyake-jima anorthite. Samples include laser-weathered anorthite (red), pure anorthite (blue), and anorthite + 5 wt% JSC-1AF (purple). Absolute reflectance at 4.5 µm of offset spectra given in italics.*

Methods and Materials: We examined spectra measured from a suite of 1) experimentally weathered San Carlos olivine and 2) samples of pure Miyake-jima anorthite, pure anorthite that had been laser-weathered, and anorthite that had been mixed with 5 wt% lunar simultant JSC-1AF. Miyake-jima (MJ) anorthite is a highly calcic (An_{95}) plagioclase [11] that closely approximates the calcium content and "cross-over" spectral character of lunar anorthite [10].

Olivine with a particle size of <45µm was laser-weathered by exposing the sample to nanosecond pulsed laser irradiation, which approximates the micrometeorite component of space weathering. Experiments were conducted at the University of Hawai'i using methods described in [12]. Experiment durations were: 0 min, 7 min, 40 min, and an unspecified duration between 7 and 40 min (Fig. 1). MJ anorthite with a particle size of <25 µm was also laser-weathered using the same method as the olivine for the maximum duration (~40 min). This technique has been shown to produce $npFe^0$ and micro-phase iron observed in space-weathered materials and to simulate accurately the spectral reddening and darkening caused by space weathering in the VNIR [13].

We also examined extraterrestrial olivine containing pervasive inclusions of $npFe^0$ (Fig. 1), as described by [14,15]. Although this olivine comes from the Martian meteorite NWA 2737 and the $npFe^0$ in this sample likely formed as the result of impact shock [14], the abundant inclusions of $npFe^0$ cause significant spectral reddening in the VNIR, similar to spectra of space-weathered olivine, allowing the sample to be used as a natural analog to space-weathered lunar olivine.

Coordinated spectral measurements of all samples were made in the NASA/Keck Reflectance Experiment Laboratory (RELAB) at Brown University [16]. Specific measurements include bidirectional reflectance (BDR) measurements for the VNIR, "quick-look" ASD measurements for the VNIR, and FTIR measurements for the "cross-over" region and MIR. Emissivity spectra of the plagioclase samples were also collected under a simulated lunar environment (SLE) in the Planetary Analogue Surface Chamber for Asteroid and Lunar Environments [17].

Results: Laser-weathering and $npFe^0$ development have a small influence on the reflectance character of olivine in the "cross-over" region. Laser-weathered olivine exhibits strong, distinct 5.6 and 6.0 µm bands, while also exhibiting increased reddening and darkening in the VNIR range that is characteristic of progressive space weathering. In the "cross-over" region, the strengths of the 5.6 and 6.0 µm bands are similar in the fresh, 7 min, and intermediate-duration sample, while they are somewhat weaker in the 40 min sample. The positions of the diagnostic 5.6 and 6.0 µm band centers across the sample suite do not change with duration of laser irradiation.

The notable red slope of the VNIR spectra of the laser-weathered MJ anorthite compared to the pure, non-weathered anorthite indicates that experimental weathering produced minor $npFe^0$ iron on the surface of grains that is detectible in the VNIR. However, effects at longer wavelengths are currently undetectable. Planned laser-weathering samples of anorthite that been mixed with iron-bearing materials, such as Fe metal, JSC-1AF (Fig. 2), or olivine may provide a more realistic simulation of lunar space weathering.

Conclusion: Our results show that reflectance spectra of olivine are not significantly affected by lunar-like weathering in the "cross-over" region, implying that "cross-over" spectroscopy may be used to constrain the Mg# of olivine-rich regoliths on the lunar surface. Future work will focus on laser weathering of anorthite, olivine-anorthite mixtures, and olivine- and anorthite-bearing samples with particle size distributions based on lunar regolith samples. We will focus on reflectance and emission spectra of experimentally weathered samples, some under both ambient and lunar-like conditions [6].

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