"CROSS-OVER" INFRARED (4-8 MICRON) SPECTROSCOPY OF OLIVINE, PYROXENE, AND PLAGIOCLASE MIXTURES: MINERAL DETECTION AND MG# DETERMINATION. C. H. Kremer[1], J. F. Mustard[1], C. M. Pieters[1], B. T. Greenhagen[2], and K. L. Donaldson Hanna[3]. [1]Department of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI, [2]Johns Hopkins University Applied Physics Laboratory, Laurel, MD, [3]Department of Physics, University of Central Florida, Orlando, FL, (christopher_kremer@brown.edu)

Introduction: Recent work has demonstrated that olivine [1] and pyroxene [2] have strong spectral bands in the 4-8 µm "cross-over" range that shift systematically in position with Mg-Fe content. Laboratory reflectance spectra of pure olivine and pyroxene, band position alone can be used to determine Mg# to within +/-10 mol% [1,2]. Positions of "cross-over" bands in pyroxene vary independently of Ca-content.

Applying 4-8 µm spectroscopy to the Moon and elsewhere requires characterization of particulate mineral mixtures in the laboratory. In natural settings, olivine and pyroxene are likely to occur alongside other minerals, such as plagioclase [3]. The mixing of these minerals' spectral bands may influence the modal abundances at which olivine or pyroxene are detectable and the apparent positions of the Mg#-diagnostic bands's minima. On the Moon, determining at what abundances olivine is detectable in troctolitic (olivine- and anorthite-bearing) rocks, in particular, would facilitate application of "cross-over" spectroscopy to remote mapping of Mg-suite rocks, which would in turn constrain models of lunar magma ocean evolution.

Although recent work in the 4-8 µm range has primarily considered reflectance measurements [1,2,4], thermal emission will dominate over reflected light in the 4-8 µm range on the Moon [5]. Therefore, applying Mg# interpretation techniques of "cross-over" spectra to the lunar surface requires comparing reflectance spectra with emissivity spectra, ideally measured under a simulated lunar environment (SLE).

In this study, we evaluate the effect of mineral mixtures on "cross-over" spectra by examining reflectance, ambient emissivity, and SLE emissivity spectra of two suites of particulate mixtures of olivine, pyroxene, and plagioclase. We determine which Mg#-diagnostic bands are present in each mixture and how the addition of other minerals affects the shape and apparent minimum position of the Mg#-diagnostic bands in olivine and pyroxene.

Background: In the 4-8 µm range, orthopyroxene has a strong, Mg#-correlated band at 5.15 µm [2], and olivine at 5.6 and 6.0 µm [1]. These bands likely arise as combinations and overtones of the fundamental vibrations at thermal infrared wavelengths.

Spectral contrast in the "cross-over" region tends to be higher in fine-grained (<45 µm) materials than in coarse-grained materials (>250 µm) [1,6], enhancing its utility in identifying minerals within the regolith. Preliminary studies indicate that the influence of space weathering may be modest in the "cross-over" region in comparison with the visible-near infrared range [4].

Methods and Materials: We examine two suites of particulate mixtures consisting of olivine, pyroxene, and plagioclase, with sample Suites 1 and 2 sieved to <32 µm and 45-75 µm, respectively (Fig. 1). Mixture Suite 1 (Figs 1a, 2-3) includes ternary and binary mixtures of San Carlos olivine (Mg90), Tanzanian orthopyroxene (~Mg90), and Miyake Jima anorthite (An98), for a total of 49 mixtures. Miyake-Jima has high Ca-content [7] and its cross-over spectral character [8] closely approximates those of lunar anorthite, making it an ideal spectral analog to lunar anorthite. Mixture Suite 2 (Fig. 1b) includes binary mixtures of San Carlos olivine (Mg91) and labradorite and Kiglapait (Mg47) olivine and labradorite (An59). Additional details about Suites 1 and 2 appear in [9] and [10], respectively.

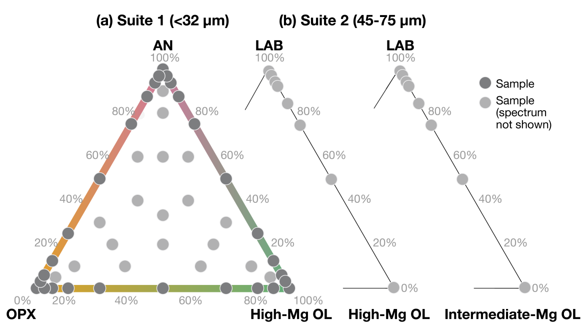

Fig. 1. Compositions of the two particulate mixture suites in this study. (a) Mixture Suite 1 consists of Tanzanian enstatite, San Carlos olivine, and Miyake Jima anorthite. (b) Mixture Suite 2 consists of labradorite (An~98) with San Carlos olivine (high-Mg) and Kiglapait olivine (intermediate-Mg). Colors and labels correspond with Figs. 2-3.

Reflectance spectra of both mixture suites were acquired at the NASA Reflectance Experiment Laboratory (RELAB) at Brown University [11]. Reflectance spectra were measured in a CO_2- and H_2O-free environment with a Pike diffuse reflectance accessory attached to a Thermo-Nicolet Nexus 870 FTIR spectrometer with an off-axis biconical viewing geometry. Emissivity spectra were measured at the Simulated Airless Body Emission Laboratory (SABEL) at JHUAPL, using a Bruker Vertex 70v spectrometer. Spectra were measured under ambient (353 K, 1 bar) and SLE conditions (343 K, 10^{-4} mbar). SLE experiments and their theoretical background are described further in [e.g., 12].

We measured the positions of the 5.15, 5.6, and 6.0 µm band minima in reflectance and emissivity spectra. Although these bands lie on a broad, negative spectral slope (Figs. 2-3), these bands consist of well-defined troughs, allowing the wavelength of the bands to be identified and directly compared between samples.

Results: For brevity, we focus on the analyses of Mixture Suite 1. We find that the Mg#-diagnostic bands of olivine and pyroxene at 5.6 and 5.15 µm exhibit minimal change in shape and position down to ~20 wt% in mixtures, while the 6.0 µm band exhibits minimal change down to ~50 wt%. Between 20-10 and 50-10 wt% olivine, the 5.6 and 6.0 µm band minima both have an apparent shift of 0.02 µm.

Hence, olivine and pyroxene are detectable in mixtures at abundances as low as ~20 wt%.We also find the minimum positions of these major bands vary little between reflectance and emissivity spectra, meaning that reflectance spectra are robust proxies in laboratory studies.

Conclusion: Collectively, our results indicate that "cross-over" spectra are a powerful tool for remotely detecting mafic minerals in lunar rocks, such as olivine in troctolite, and determining their Mg#. Moreover, reflectance spectra are a strong proxy for the character of silicates in emissivity spectra under both ambient and SLE conditions in the 4-8 µm range This study therefore represents a major initial step in bridging the gap between "cross-over" spectroscopy in the laboratory and on the lunar surface.

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References: [1] Kremer, C. H. et al. (2020) GRL, 47. [2] Kremer, C. H. et al. (2021), NESF-ELS. [3] Stöffler, D. et al. in: Papike, J.J., and Merrill, R.B. (Eds.), Proceedings of the Conference on the Lunar Highland Crust, (1980). [4] Kremer, C. H. et al. LPSC, (2022). [5] Honniball, C. I. et al. (2020) Nat. Astro. [6] Salisbury, J. W. et al. (1987) JGR:SE, 92, 702–710. [7] Brydges, T. F. V. et al. (2015) *LPS XLVI,* Abstract #1251. [8] Kremer, C. H. et al. (2021) LPS *LIII,* Abstract #2239. [9] Greenhagen, B. T. et al. (2020). [10] Cheek, L. C. and Pieters, C. M. (2014) Am. Min., 99, 1871–1892. [11] Pieters, C. M. and Hiroi, T. (2004) *LPS XXXV,* Abstract #1720. [12] Donaldson Hanna, K. L. et al. (2017) Icarus, 283, 326–342.

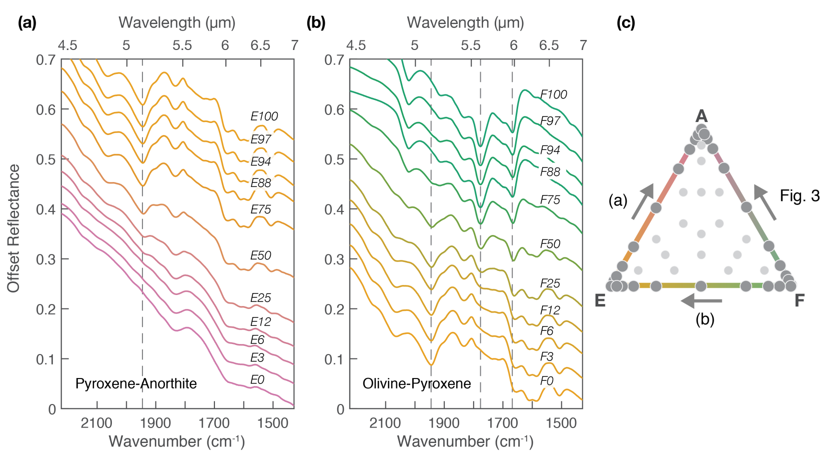

Fig. 2. Reflectance spectra from Suite 1 of binary mixtures: (a) orthopyroxene and anorthite, and (b) orthopyroxene and olivine. Dashed lines indicate the positions of the 5.15 µm band of pure orthopyroxene and the 5.6 and 6.0 µm bands of pure olivine. Compositions are given in plots (F = olivine, E = orthopyroxene) and in (c), with arrows showing arrangement of spectra in a-b from top to bottom. Spectra offset for visual clarity.

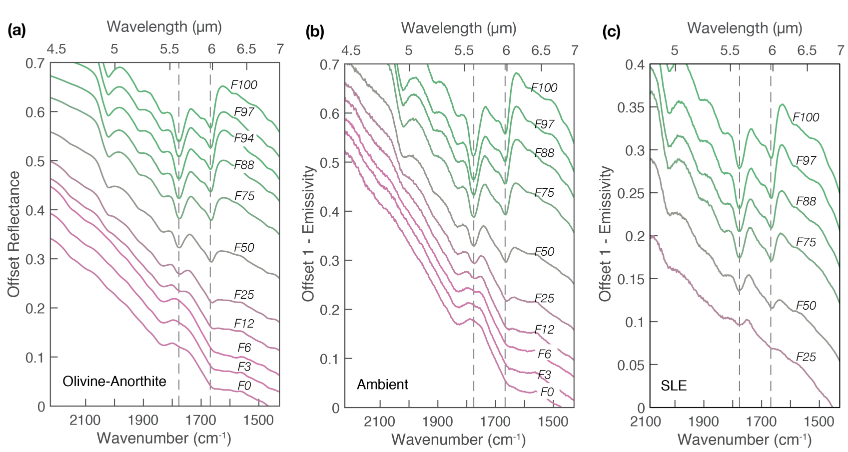

Fig. 3. (a) Reflectance, (b) ambient emissivity, and (c) SLE emissivity spectra from Suite 1 of mixtures of olivine and anorthite. Dashed lines indicate the positions of the 5.6 and 6.0 µm bands of pure olivine. Compositions are given in plots (F = olivine) and in (Fig 2c), with arrows showing arrangement of spectra in a-c from top to bottom. Spectra offset for visual clarity.