QUANTIFYING LUNAR SPINEL-RICH LITHOLOGIES WITH NONLINEAR SPECTRAL UNMIXING CONSIDERING SPACE-WEATHERING EFFECTS.

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Introduction: Spectral Unmixing is a powerful tool to investigate the mineral composition of planetary surfaces. Based on hyperspectral data, in particular the Moon Mineralogy Mapper (M³) data set [1], that became available in the last decade, it is possible to obtain data of high spectral and spatial resolution. The Moon, however, is a challenging target for spectral unmixing because not only the mineral composition itself, but also space weathering has a significant influence on the measured spectra. In most approaches, this effect has been neglected (e.g., [2, 3]).

Planetary surfaces covered by regolith cannot be unmixed linearly because the mixture of different grains constitutes an intimate mixture (e.g., [4, 5]), as light traveling through the regolith undergoes several reflections. Therefore, the measured light ray contains information about the different materials encountered on its path. While the reflectance must be unmixed nonlinearly, the single scattering albedo can be unmixed linearly [4, 5]. The selection of endmembers is an essential step to determine the mineral composition. A commonly used library is the Lunar Soil Characterization Consortium (LSCC) data base [6,7] of Apollo samples. These samples have the advantage that they represent realistic mature compositions that contain a variety of different minerals. The samples, however, differ in maturity and do not cover the complete variety of lunar minerals. Minerals like spinel, which can only be found in very low percentages in the samples, cannot be characterized based on this data base. In [8] the occurrence of distinct areas with high spinel abundance was found based on spectral parameters. Spinel has a very strong 2-µm but no 1-µm absorption band and can, therefore, be easily distinguished from other minerals. Previous approaches to determine the abundance of spinel [2] used limited endmember catalogs and neglected space weathering effects.

In this work we quantify the abundance of Mg-spinel in a region at the western edge of Mare Moscoviense first identified in [8].

Methods: The method used in this work can be split into four parts. Firstly, the selection of possible endmembers, secondly, the unmixing framework itself, thirdly, the model to artificially space weather the spectra and, finally, the estimation of the degree of space weathering. We make use of the Hapke reflectance model [9] to determine the single scattering albedo and to photometrically correct the spectra. The unmixing framework described in [10] is then applied to these albedo spectra. This algorithm has been thoroughly tested on laboratory spectra of common lunar minerals [10]. We enforce the non-negativity and the sum-to-one constraint [4]. The best endmember combination is found by an exhaustive search during which the best-fit weights of each combination are determined. The goal in this work is to be able to determine mineral abundances of other minerals that are not present in pure and space-weathered form in the Apollo returned samples. Therefore, we selected endmembers from the RELAB database (http://www.planetary.brown.edu/relab/, see also Figure 1). We selected samples with a sufficiently detailed documentation, so that the elemental abundances and the mineral composition are known. For comparability we selected the main lunar minerals also found in the LSCC data base. Ilmenite is not used as an endmember due to its different phase function behavior [11] and because we expect only very little ilmenite to be present in the examined highland area.

The effects of space weathering are modeled as described in [12] based on ab-inito Mie scattering. By defining the amount of nano- and microphase iron (npFe,mpFe) we can vary the maturity and the strength of the optical effects, like reddening, darkening and subdued absorption bands (see also [13]). In this work, we estimate the degree of space weathering by finding the best-fit convex hull of all artificially space weathered endmembers with respect to the mean spectrum of the region, assuming that there are no maturity differences in the region. The resulting spectra for the best fit values are shown in Figure 2. Additionally, we assume that all endmember minerals behave similarly with respect to the space weathering model. Two representative glass endmembers were selected. In this highland setting, however, it can be assumed anyway that melted glass only plays an insignficant role in the measured spectra. For comparison, a map of the negative logarithmic band depth (NLBD) parameter (adapted from [14]), corresponding to the base-10 logarithm of the ratio between the 2-µm and the 1-µm band depth, is shown in Figure 3.

Initial Results: The results in Figure 4 show that high abundances of spinel (up to about 25%) are detected in the region near Mare Moscoviense (see also [8]). Our results confirm the finding in [8] that other mafic minerals are nearly absent (<5%) in the examined region. The remaining fraction nearly completely consists of plagioclase. In other parts of the area, where the spinel concentration is low, we detected signatures of pigeonite or Fe-clinopyroxene.

Conclusion and Ongoing Work: Our results show the applicability of the spectral unmixing approach to reflectance spectra of space-weathered lunar materials. The output strongly depends on the modeled maturity of the endmember spectra. Therefore, an automated and robust estimation of the space-weathering degree needs to be determined in future works.

References: [1] Pieters, C. M. et al. (2009). *Current Science*, 96, 4, 500-505. [2] Dhingra, D. et al. (2011). *LPSC XXXXII*, abstract #2431. [3] Keshav S. & Ramakrishnan, D. (2015). *IEEE WHISPERS*, 1-4. [4] Keshava, N. and Mustard, J. F. (2002). *IEEE SPM*, 19, 1, 44-57. [5] Heylen, R. et al., 2014, *IEEE JSTAEORS*, 7, 6, 1844-1868. [6] Taylor, L. A. et al., (2001). *J. Geophys. Res*., 106 (E11), 27,985-28,000. [7] Taylor, L. et al. (2010). *J. Geophys. Res*., 115, E02002. [8] Pieters, C.M. et al., (2011). *J. Geophys. Res*., 116, E00G08. [9] Hapke, B., (2002). *Icarus*, 157, 2, 523-534. [10] Rommel, D. et al., (2014). *Icarus*, 284, 126. [11] Yang, Y., Li et al., (2019). *J. Geophys. Res.: Planets*, 124, 31– 60. [12] Wohlfarth, K. et al. (2019). *The Astronomical Journal*, 158, 2. [13] Hapke. B. (2001). *J. Geophys. Res*., 106(E5), 10039– 10073. [14] Bhatt, M. et al. (2015). *Icarus*, 248, 72-88.

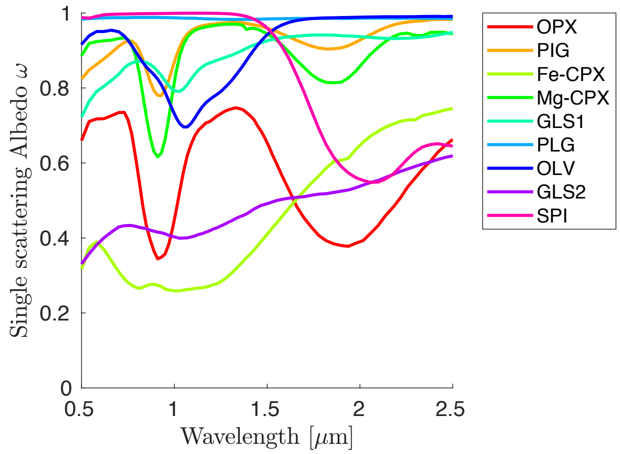

Figure 1: Selected RELAB endmember spectra. OPX = orthopyroxene (LS-CMP-021), PIG = pigeonite (PP-EAC-042), Fe-CPX = Fe-clinopyroxene (PP-EAC-086), Mg-CPX = Mg-clinpyroxene (PP-EAC-013), GLS1 = glass #1 (TP-SWP-009), PLG = plagioclase (PL-EAC-029), OLV = olivine (PO-CMP-030), GLS2 = glass #2 (JE-JEE-010), SPI = spinel (SP-EAC-017).

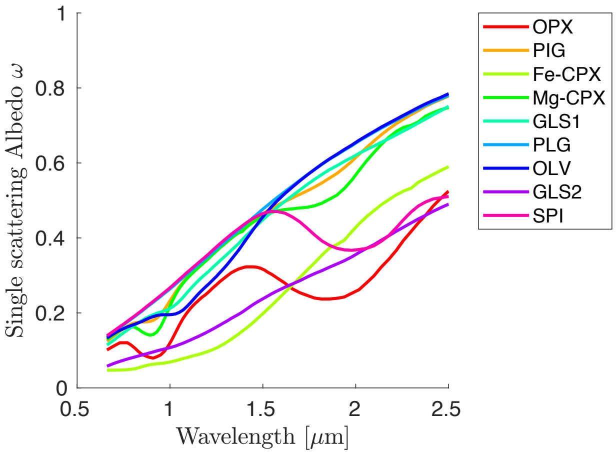

Figure 2: Space-weathered endmember spectra. Nanophase iron (npFe) was set to 1.19 wt.% and microphase iron (mpFe) was set to 2.39 wt.%.

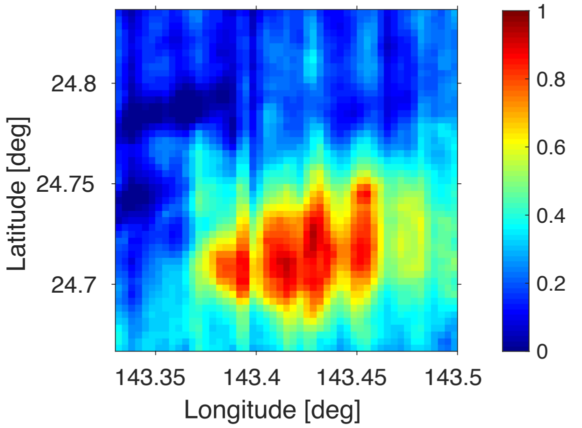

Figure 3: NLBD parameter map. A high value corresponds to a strong 2-µm and a weak 1-µm absorption, which is characteristic for Mg-spinel.

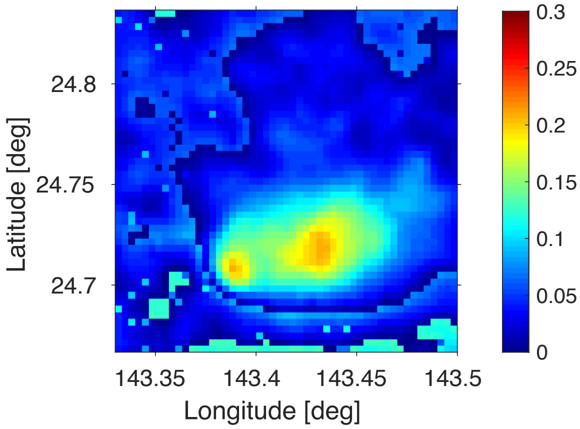

Figure 4: Fractional abundance of the endmember spinel (RELAB Sample ID: SP-EAC-017).