PARTICLE PHASE FUNCTIONS OF TYPICAL LUNAR MINERALS DERIVED FROM PHOTOMETRIC SPECTRAL MEASUREMENTS.
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Introduction: The Hapke model [1] is widely used in estimating the mineralogical and chemical information from reflectance spectra in the visible to near infrared wavelength region [2]. This physics-based model expresses reflectance as a function of single scattering albedo, viewing geometry, the opposition effect, single particle scattering phase function (phase function, PF), and multiple scattering [1, 2]. Among these parameters, the PF is perhaps the least well-characterized for minerals relevant to many planetary surfaces, including the Moon. Both laboratory measurements and radiative transfer modeling have been carried out to understand the wavelength dependence of the PF and how it changes for select materials [2-6]. While most work focused on the 0.4 to 1.0 μm wavelength range [7], a more recent study showed that the PF is wavelength dependent up to 2.5 μm [6].

Mustard et al. [2] have assessed different PF of typical lunar-type minerals (e.g., pyroxene, olivine, and plagioclase) using lab mixtures and found that the uncertainty of unmixing results was significantly reduced by using a single (non-wavelength dependent) PF derived from spectro-photometric measurements. That study suggested a two-term Legendre (LG) polynomial was sufficient to describe the PF of those minerals:

$$P(g) = 1 + b \cdot \cos(g) + c \cdot (\frac{3}{2} \cdot \cos(g) - \frac{1}{2}) \qquad (1)$$

Although $P(g)$ is wavelength dependent, it was found that the average values of coefficients b and c (b=-0.4, c=0.25) for pyroxene, plagioclase, and olivine obtained in [2] could be reasonably adopted in studies utilizing Hapke's model [e.g., 8, 9]. However, the measurements in [2] only covered a wavelength range of 0.6-1.6 μm and ilmenite was not included. Imenite is a very important opaque mineral on the lunar surface and may exhibit very different PF behavior compared with transparent or semi-transparent silicate minerals (i.e., pyroxene, plagioclase, and olivine). For example, [10] found that the spectral unmixing results of ilmenite mixtures had large uncertainties when assuming the same PF for ilmenite as for silicate endmembers.

Here we report the results of our spectro-photometric measurements on typical lunar minerals, including ilmenite, over a wavelength range of 0.4 to 2.6 μm. We also examine the Henyey-Greenstein PF [7] to compare model results with the LG-based data. As a first test to examine whether spectral unmixing of lunar materials can be significantly improved by use of a wavelength dependent PF we apply our results to spectra of samples from the Lunar Rock and Mineral Characterization Consortium (LRMCC) database [11].

Methods: Pure terrestrial olivine (OLV), orthorhombic pyroxene (OPX), labradorite (LAB), and ilmenite (ILM) were ground and sieved into a size distribution of 45-75 μm. Bidirectional reflectance measurements were carried out in the RELAB at Brown University with a fixed incidence angle (45°) and varied emission angles (+60° to -60°) in the principle plane. A Labsphere Spectralon plaque with a 99% nominal reflectance in the visible region is used as the reference standard. The reflectance spectra were obtained by ratioing the radiance from samples to the radiance from the Spectralon measured under identical viewing geometry. However, the Spectralon is more forward scattering than a perfect Lambertian body [12] and its reflectance decreases to ~95% beyond 1.8 μm. Moreover, the Spectralon has an absorption near ~2.14 μm that may cause a spurious peak if not properly calibrated [13]; corrections are thus needed prior to any quantitative photometric analysis. Due to the lack of absolute photometric reflectance data of Spectralon from 0.4 to 2.6 μm, we use the following formula to obtain reflectance [13]:

$$REFF_{sample}(45°, e, \lambda) = \qquad (2)$$

$$\frac{I_{sample}(45°, e, \lambda)}{I_{spectralon}(45°, e, \lambda)} \cdot REFF_{spectralon}(45°, e, 627nm) \cdot REFF_{spectralon}(45°, 0°, \lambda)$$

We applied the same version of the Hapke model as described in [2] to derive the single scattering albedo (SSA) and b, c of the PF from the corrected spectra.

Results: Fig. 1 shows the spectra of OLV measured at four different viewing angles before and after photometric correction of Spectralon. The forward scattering nature of the Spectralon has resulted in higher reflectance values of samples measured in a backscattering direction compared with those measured in the forward scattering direction. Once corrected, the spectra show higher reflectance in the forward scattering direction that is consistent with the forward scattering nature of olivine grains [2].

Phase curves of Hapke's reflectance factor (REFF) confirm that OLV, OPX, and LAB are forward scattering over the full wavelength range, with the highest

reflectance values at (i, e) of (45°, -60°). In contrast, as shown in Fig. 2, the highest reflectance for ILM is at (45°, 60°) and indicates more backward scattering.

The LG and HG PF were derived for all samples, and the associated parameters for the LG case are shown in Fig. 3. Negative b values indicate forward scattering (OLV, OPX, LAB), whereas positive values mean backward scattering (ILM), which is also suggested by the coefficient c in the HG PF [7]. The parameter c of the LG PF is an indicator for the side scattering and is very similar for all samples, with an average of ~0.15. The derived wavelength-dependent LG and HG b, c parameters were applied to a Hapke spectral unmixing model for a low-titanium lunar basalt. The results were compared with those based on single (average) PF values, and no significant differences were observed.
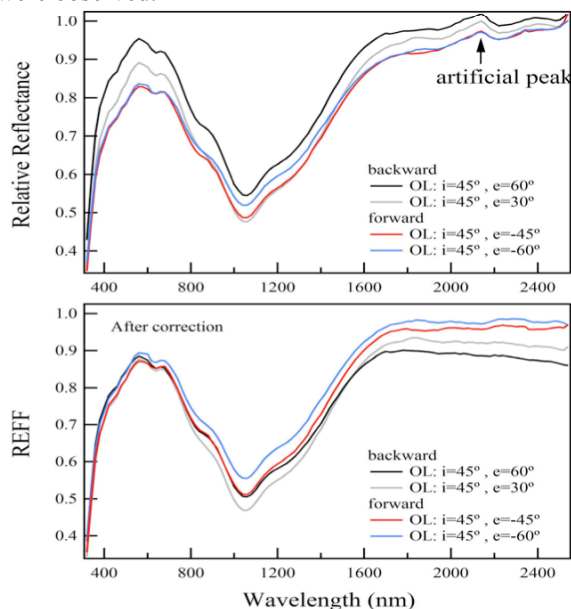

Fig. 1 Olivine spectra before and after Spectralon correction. Top: Reflectance spectra relative to Spectralon measured in forward (i=45°, e=60°, 30°) and backward (i=45°, e=-45°, -60°) directions; bottom: REFF spectra after correction for the non-Lambertian behavior and wavelength dependence.

Conclusion and Future Work: The non-Lambertian behavior of the Spectralon may cause significant brightening/darkening effects on the VNIR reflectance spectra measured at different scattering configurations, and therefore appropriate corrections for the photometric properties of Spectralon are needed in order to obtain accurate reflectance spectra and PF values of geologic materials. Scattering properties of ILM are quite distinct from those of common silicates, and using constant b and c values derived from measurements of forward scattering materials (e.g., silicates) may result in large uncertainties in estimates of opaque phases. Ongoing work is focused on carrying out pho-

tometric measurements on laboratory mixtures composed of ILM and other endmembers with different scattering properties to examine these issues and to estimate the PF of bulk mixtures.
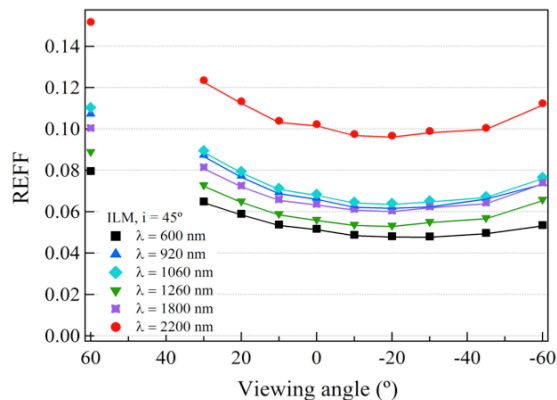

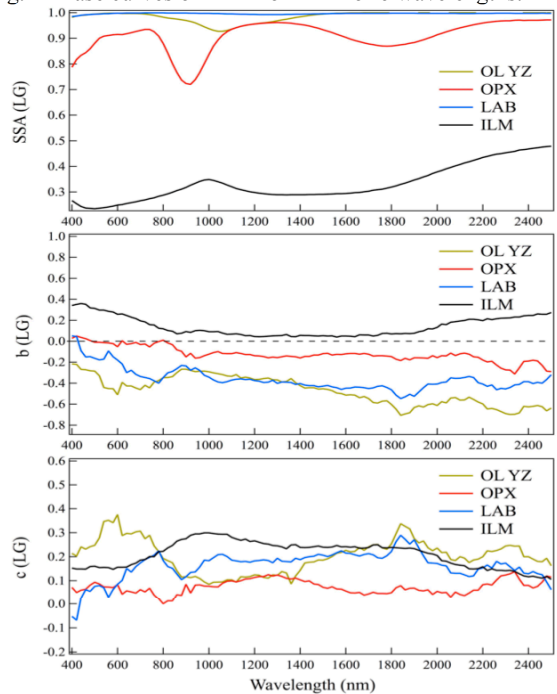Fig. 2 Phase curves of REFF of ILM for 6 wavelengths.

Fig. 3 Derived values of SSA (top), b (middle), and c (bottom) of the four minerals, using the LG PF, plotted as a function of wavelength.

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