

**AN IMPROVED RADIATIVE TRANSFER MODEL FOR ESTIMATING MINERAL ABUNDANCE OF IMMATURE AND MATURE LUNAR SOILS.** D. Liu<sup>1</sup> and L. Li<sup>1</sup>, <sup>1</sup>Department of Earth Sciences, 723 W. Michigan Street, Indiana University-Purdue University, Indianapolis, IN, 46202, email: liudawe@imail.iu.edu and ll3@iupui.edu

**Introduction:** Remote determination of lunar surface mineral abundance and distribution at global scale is critical for getting insight into the origin and formation of the Moon [1-3]. Hapke's radiative transfer model has been widely applied for this mapping purpose because of its capacity of accommodating the spectral effects of viewing geometry, space weathering and particle size [4-11]. However, the derived mineral abundance with this approach has been shown accurate only for immature lunar soils [5, 11]. Assuming that the poor performance of the model for mature lunar soils may originate from inaccurate description for the effect of submicroscopic-iron (SMFe), we adopt the equation introduced in [11] to model the SMFe effect and propose an improved Hapke's radiative transfer model by incorporating this equation to the framework in [12]. Here we report the progress of using this improved Hapke's radiative transfer model to estimate the mineral abundance of both immature and mature lunar soils.

**Model Description:** In his previous work [13-15], Hapke proposed a method to convert bidirectional reflectance to the average single scatter albedo (SSA) of a mineral mixture, which is the linear combination of SSA of mineral endmembers weighted by their mass fraction. SSA of each mineral endmember can be evaluated by equation (5.44) in [15]. The most important parameter for calculation of each endmember SSA for space weathered soils is the absorption coefficient ( $\alpha$ ) shown as equation (24a) in [14], which was derived by Hapke using the Maxwell-Garnet model. However, *Lucey and Riner* [11] pointed out that Hapke's absorption coefficient for space weathered soils is only appropriate for SMFe with particle size smaller than 50 nm and reddening and darkening the host mineral, not for the larger SMFe that only darkens the host material and is mainly included in host mineral grains. This is especially the case for mature lunar soils which contain more-larger SMFe due to the presence of agglutinate. *Lucey and Riner* [11] developed a new model considering the effects of both larger and smaller SMFe:

$$\alpha = \frac{4\pi n_h k_h}{\lambda} + \frac{36\pi z M_c \rho_h}{\lambda \rho_{Fe}} + \frac{3q_a M_i \rho_h}{d_{Fe} \rho_{Fe}}, \quad (1)$$

where  $M_c$  is the mass fraction of smaller SMFe coating on the surface of a host particle,  $M_i$  is the mass fraction of larger SMFe in the particle,  $q_a$  is the absorption

efficiency of an SMFe particle which can be evaluated by Mie theory,  $n_h$  and  $k_h$  are real part and imagery part of optical constant of the host mineral,  $\rho_h$  is the density of host mineral,  $\rho_{Fe}$  is the density of SMFe,  $d_{Fe}$  is particle size of SMFe,  $z$  is defined by equation (12) in [14] and  $\lambda$  is wavelength. The third term is added to account for the contribution from larger SMFe in the mineral. Equation (1) is only used to calculate  $\alpha$  of agglutinate glass and for other endmember components, equation (24a) in [14] is still valid because these remaining components only contain extremely fine grained SMFe coating on the their surfaces [16-17]. Combining this new expression for the absorption coefficient of agglutinate glass with equations (1-7) in [12] makes an improved Hapke radiative transfer model.

Nine mare and ten highland samples from the Lunar Soil Characteristic Consortium (LSCC) dataset were used to test this improved Hapke's radiative transfer model. Reflectance and mineral abundance of each LSCC soil sample from the particle size groups < 10, 10-20 and 20-45 $\mu$ m was used. Seven endmembers used were: agglutinate glass, orthopyroxene, clinopyroxene, olivine, ilmenite, plagioclase and volcanic glass and their optical constants and reflectance spectra were adopted from [12].

In order to apply this improved model, particle size (PS) and mass fraction of both larger ( $M_i$ ) and smaller ( $M_c$ ) SMFe should be known first. According to the work by [12], these parameters were first estimated using the LSCC reflectance spectra and mineral abundance data as input into the improved model through a non-linear fitting procedure. After this step, the similar fitting procedure was repeated for estimating the mineral abundance with the measured spectra by LSCC and the derived PS,  $M_i$  and  $M_c$  values as input into the improved model.

**Results and Discussion:** Shown in Figure 1 are comparisons between modeled and measured LSCC mineral abundance. It can be seen that the estimated abundances for agglutinate glass, plagioclase and pyroxene are highly correlated to the measured and the correlation has been significantly improved when compared with the results shown in [12]. In addition, this high performance for estimating agglutinate glass, pyroxene and plagioclase is based on the use of all the 57 lunar samples including both immature and mature lunar soil samples. This contrasts to the results in [12]

where high correlation was obtained only for immature soil samples.

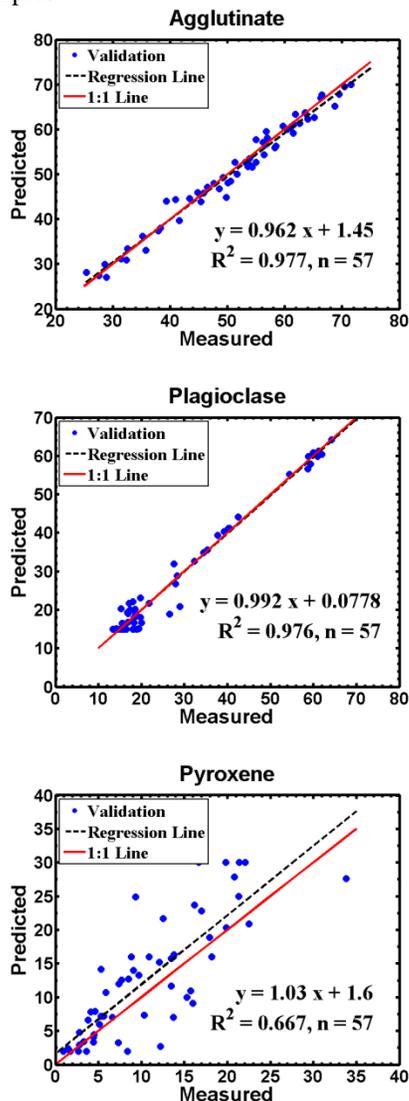


Fig. 1. Comparison between measured and modeled mineral abundance

For olivine, ilmenite and volcanic glass, the correlations are not as good as agglutinate glass, pyroxene and plagioclase with their corresponding  $R^2$  being 0.424, 0.764 and 0.566, respectively. Although ilmenite also shows a relative higher  $R^2$ , it is overestimated. The relatively poor correlations for these three components of the lunar soils could be attributed to three reasons. First, the optical constants of endmember components used here are not accurate. In this test, the optical constants ( $n$  and  $k$ ) for each mineral endmember component were fixed for all the 57 lunar soil samples, but in reality they vary because of the variation in chemical composition and this could introduce errors in estimated mineral abundances. This is especially the case for olivine whose chemical

composition varies widely. Second, the method for calculating ilmenite SSA may not be appropriate because equation (5.44) in [15] for calculating endmember SSA is only applicable for transparent material with  $k^2 \ll 1$ . Yet, ilmenite is an opaque mineral and may violate this assumption. Third, the three endmember components only account for a small portion of the total mineral abundance and thus their contribution to the detected reflectance is much smaller than those by agglutinate glass, pyroxene and plagioclase.

**Conclusions and Future work:** Based on the work of [11-12], an improved Hapke's radiative transfer model has been developed. Using this improved Hapke's radiative transfer model, the abundance of plagioclase, pyroxene and agglutinate glass in both immature and mature lunar soils can be effectively estimated. The estimated abundance for olivine, ilmenite and volcanic glass show poor correlation to measured values because of the inaccurate optical constants applied and inappropriate equation used to calculate ilmenite SSA.

Our future work will be focused on selecting suitable spectrum for each endmember component for deriving the optical constants of an endmember component. In addition, an alternative method [6] should be applied to calculate ilmenite SSA. After making these two modifications, we will test whether the correlation between measured and derived abundance for olivine, ilmenite and volcanic glass could be improved and if so, this improved model could ultimately be used to quantify the mineral abundance on the lunar surface.

**References:** [1] Hörz, F. (1978) *LPS III*, 3311-3331. [2] Tompkins, S. and C. M. Pieters (1999) *Meteoritics & Planet. Sci.*, 34, 25-41. [3] Hiesinger, H. and J. W. Head (2006) *Rev Mineralogy & Geochemistry*, 60, 1-81. [4] Clark, B. E., et al. (2001) *Meteoritics & Planet. Sci.*, 36, 1617-1637. [5] Lucey, P. G. (2004) *Geophys Res Lett*, 31, L08701. [6] Lawrence, S. J., and P. G. Lucey (2007) *JGR*, 112, E07005. [7] Wilcox, B. B., et al. (2006) *JGR*, 111, E09001. [8] Cahill, J. T. S., and P. G. Lucey (2007) *JGR*, 112, E10007. [9] Cahill, J. T. S., et al. (2010) *JGR*, 115, E12013. [10] Denevi, B. W., et al. (2008) *JGR*, 112, E02003. [11] Lucey, P. G., and M. A. Riner (2011) *Icarus*, 212, 451-462. [12] Li, S., and L. Li (2011) *JGR*, 116, E09001. [13] Hapke, B. (1981) *JGR*, 86, 3039-3054. [14] Hapke, B. (2001) *JGR*, 106, 10039-10073. [15] Hapke, B. (2005) *CAMBRIDGE UNIVERSITY PRESS*. [16] Keller, L. P., and D. S. McKay (1993) *Science*, 261, 1305-1307. [17] Keller, L. P., and D. S. McKay (1997) *Geochimica et Cosmochimica Acta*, 61, 2331-2341.