

**ESTIMATING MINERAL ABUNDANCES OF HED METEORITES FROM VIS-NIR SPECTRA AND IMPLICATIONS FOR DAWN AT VESTA.** S. Li<sup>1</sup> and R. E. Milliken<sup>1</sup>, <sup>1</sup>Dept. of Civil Engineering and Geological Sciences, Univ. of Notre Dame, IN, 46556, [sli6@nd.edu](mailto:sli6@nd.edu)

**Introduction:** Vesta is one of the largest asteroids in the asteroid belt and is believed to be the parent body of the howardite, eucrite, and diogenite (HED) meteorites, implying that it is a differentiated body. Therefore, quantitative petrologic information about Vesta's surface and interior (as exposed by impact craters) will lead to an improved understanding of geologic processes operating during the early evolution of the solar system. The Dawn spacecraft, which recently arrived at Vesta, includes a visible – near infrared (VNIR) imaging spectrometer (the VIR instrument<sup>[1]</sup>) that can be used to identify and map minerals and rock types exposed at the surface to meet this goal. However, accurate mapping of the latter requires quantitative knowledge of the former, and in this study we examine radiative transfer models (RTM) that have been primarily developed and tested for surfaces composed of particulates<sup>[2]</sup>.

Specifically, we have examined the application of Hapke modeling to VNIR laboratory spectra for a suite of eucrite and olivine diogenite meteorites. These samples provide an ideal test case for developing a RTM model tailored to analysis of Dawn data because 1) they are believed to come from Vesta, 2) they are mineralogically simple (typically dominated by  $\leq 4$  phases), 3) optical constants of the dominant phases are available in the literature, and 4) the modal mineralogy from corresponding thin sections are also available in the literature<sup>[3,4]</sup>. Here we report our initial results in quantitative estimates of modal mineralogy for these meteorites and discuss the implications for applying the Hapke RTM model to spectral data acquired by Dawn.

**Methods:** Fourteen unique eucrite<sup>[4]</sup> and seven unique diogenite<sup>[3]</sup> samples were incorporated into this study. The eucrites were particulate samples ( $< 125 \mu\text{m}$ ) whereas the diogenites were rock chips ( $\leq 5 \text{mm}$ ). The petrography and modal mineralogy for both sets of samples were described in previous studies<sup>[3,4]</sup>. VNIR spectra for the eucrite samples were also previously discussed by Mayne et al.<sup>[4]</sup>, whereas comparable spectra for the diogenites were specifically acquired for this study. All VNIR reflectance spectra were acquired from 280 - 2600 nm using the bi-directional spectrometer in the NASA RELAB facility at Brown University<sup>[5]</sup>.

The dominant minerals in the eucrites and diogenites are clinopyroxene (Cpx), orthopyroxene (Opx), plagioclase, and olivine, with lesser amounts of chromite, silica, and metal. In our application of the

Hapke model we use the optical constants ( $n$  and  $k$ ) of each mineral endmember as inputs and invert the reflectance spectra to derive both the particle size ( $D$ ) and abundance ( $F$ ) of each endmember. These outputs are determined by minimizing the residuals between each modeled spectrum (which relies on  $D$  and  $F$ ) and the corresponding observed (lab) spectrum.

The optical constants were determined one of two ways. In the first, laboratory spectra of pure mineral samples with compositions similar to those reported for the meteorites were inverted in the Hapke model to solve for  $n$  and  $k$  ( $D$  was fixed to the known mean size range of the measured sample and  $F$  was set to 1), similar to what was done by Lucey et al.<sup>[6]</sup>. In the second, the optical constants of the mineral endmembers were derived from single crystal transmission data; this is the preferred method when data are available because these measurements do not suffer from the effects of multiple scattering and they are done independent of the Hapke model (the first method is clearly somewhat circular). Indeed, there are often large differences in values determined by these methods. The value of  $k$  determined for Opx and Cpx by Lucey et al.<sup>[6]</sup>, for instance, are about 10 times weaker than the values for similar compositions derived from transmission data<sup>[7]</sup>.

For the first method, the reflectance spectra of a wide variety of pyroxenes were used, including the synthetic suite of samples studied by Klima et al.<sup>[8]</sup>. Plagioclase in eucrites and diogenites is typically An<sup>75-96</sup>, thus we chose a spectrum of bytownite from USGS spectral library. Diogenite MIL03443 contains 91% olivine and 5.7% pyroxene, thus in one iteration the spectrum of this sample was used as an endmember for olivine. Reflectance spectra of chromite, silica, and metal (iron) were from the RELAB database.

The details for the parameterization of the inverse radiative transfer model in this study were the same as that of Li and Li<sup>[2]</sup>. The particle size of each endmember was set as a free parameter, as were the mineral abundances. The trust region algorithm<sup>[9]</sup> was applied to solve mineral abundances and particle sizes simultaneously. With the algorithm, the solution regions can be constrained based on certain assumptions (e.g., mineral abundances must lie between 0 and 100%). In this model we also accounted for the fact that the optical path length is not identical to the particle diameter and that the particles are likely irregular (not spheres)<sup>[10]</sup>.

**Results and discussion:** The comparisons between modeled and measured pyroxene (Cpx+Opx) and plagioclase are plotted in Fig. 1 and 2, respectively. Nearly all modeled values are within  $\pm 5\%$  (absolute) of the measured values, with  $R^2$  values of 0.975 (pyroxene) and 0.993 (plagioclase). The eucrites used in this study contain no olivine<sup>[4]</sup>, but the results for olivine in the diogenites are presented in Fig. 3. Again, modeled values are within  $\pm 5\%$  of measured values and  $R^2 = 0.972$ . Although similar results have been obtained in previous studies for manmade particulate mixtures<sup>[11]</sup>, these results are encouraging in that they suggest the Hapke model may work well for non-particulate samples in some cases (e.g., olivine diogenites). In addition, the model clearly works well even when optical constants derived from *terrestrial* endmember minerals with similar (but not identical) compositions are used. These indicators suggest the Hapke radiative transfer model is a viable option for quantitative mineral mapping of Vesta using Dawn VIR data, possibly even for non-particulate surfaces.

The modeled particle sizes for minerals in the eucrites are all within their measured ranges. In contrast, the modeled particle sizes for minerals in the diogenites vary greatly, from 28  $\mu\text{m}$  to 17.11 mm. This large range is likely because the diogenite samples were measured as rock chips, not particulates. The physical meaning of such large modeled particle sizes is unclear, but one possibility is that the multiple scattering function is not suitable for rock chips. Future work will focus on measuring these diogenite samples as particulates for various size ranges to see if the derived mineral abundances are still accurate.

Variations in optical constants caused by chemical differences in individual phases can also be accounted for. In the pyroxene endmember library, the Cpx and Opx spectra preferentially selected by the model were the ones closest in chemistry to the actual average pyroxene compositions of the eucrites and diogenites. Also, the  $k$  values derived from VNIR spectra are the same order of magnitude as values derived from transmission data, additional evidence that this method for deriving  $k$  is appropriate.

**Conclusions:** This implementation of Hapke's model shows high accuracy in simultaneously quantifying abundances and particle sizes of individual minerals in eucrites and diogenites. Future work will expand our test set of samples to include powdered diogenites as well as the more petrographically complex howardites. Current results suggest the Hapke model has great potential for accurate quantitative mineral mapping of soils and rocks on Vesta using the Dawn VIR data if the input endmember spectral library

spans the appropriate compositional range for pyroxene, plagioclase, and olivine.

**References:** [1] Russell, C. T. et al. (2007). *Earth Moon Planets* **101**. [2] Li, S. and Li, L. (2011). *J Geophys Res-Planet* **116**. [3] Beck, A. W. and McSween, H. Y. (2010). *Meteoritics & Planetary Science* **45**. [4] Mayne, R. G. et al. (2009). *Geochim Cosmochim Acta* **73**. [5] Pieters, C. M. (1983). *J. Geophys. Res.* **88**. [6] Lucey, P. G. (1998). *J. Geophys. Res.* **103**. [7] Rossman, G. R. (2006). <http://minerals.gps.caltech.edu>. [8] Klima, R. L. et al. (2010). *Meteoritics and Planetary Science*. [9] Coleman, T. F. and Li, Y. Y. (1996). *Siam J Optimiz* **6**. [10] Shkuratov, Y. G. and Grynko, Y. S. (2005). *Icarus* **173**. [11] Mustard, J. F. and Pieters, C. M. (1987). *J Geophys Res-Solid* **92**.

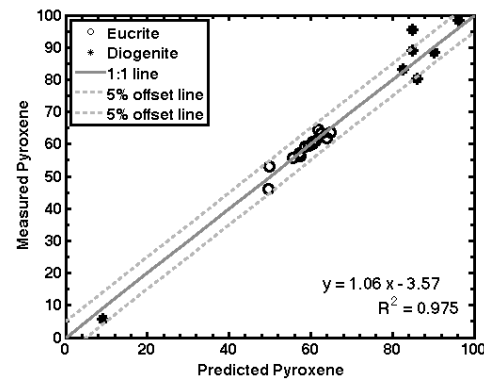


Figure 1. Comparison between modeled and measured pyroxene.

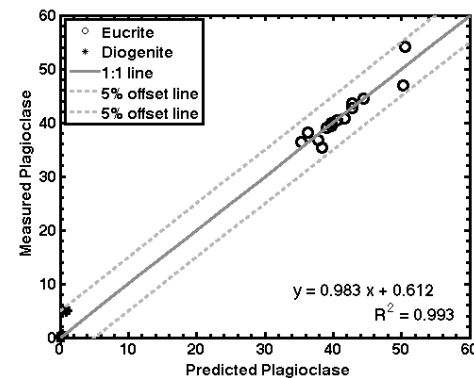


Figure 2. Comparison between modeled and measured plagioclase.

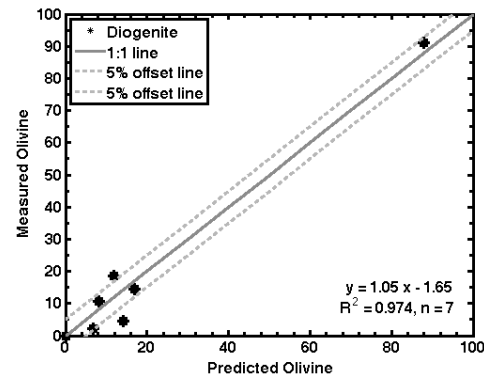


Figure 3. Comparison between modeled and measured olivine for diogenites.