ASTEROID MODAL MINERALOGY USING HAPKE MIXING MODELS: VALIDATION WITH HED METEORITES.

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Introduction: The mineralogical characterization of asteroid surfaces is accomplished through the interpretation of terrestrial or space-based visible/near-infrared reflectance (VNIR) spectroscopy. This is the most sensitive technique for asteroid remote sensing and has been widely used to estimate the surface mineralogy for many asteroids. The spectral properties of asteroid surfaces are governed by the properties of the asteroid regolith, including the mineralogy, physical properties, the amount of impact-produced glass, and the degree of space weathering. Hapke’s formulations [1,2] and the recent work of [3] has permitted the creation and utilization of a model designed to produce a simulated spectrum of a given asteroid surface given a modal mineralogy, within simplifying assumptions. In [4], Clark and coworkers employed this model to make determinations about the composition and degree of space weathering on the bright and dark regions in and adjacent to Psyche crater on asteroid 433 Eros. Here, we share results of our efforts to validate the model using published mineral modes and spectra from eucrites and diogenites.

Model Description: Theory. As outlined in [4], the model is based extensively on the work of Hapke [1], who showed how VNIR spectra of mineral mixtures could be computed from their optical constants at arbitrary grain sizes and relative abundances. In [2], Hapke presented the methods necessary for the computation of the optical effects of submicroscopic iron (SMFe), which has an important role in the optical effects of lunar (and presumably asteroid) space weathering processes. The spectrum of any meteorite assemblage of intimately mixed components can be simulated for any grain size.

Olivine, orthopyroxene, clinopyroxene, plagioclase feldspar, troilite, Fe-Ni metal, Fe-bearing glass (as volume percent) and SMFe are input into the model and subsequently used to calculate the reflectance spectrum. The model requires optical constants for all input components. The method of [3] is used to calculate optical constants for olivine and pyroxene. The chemistries of olivine and orthopyroxene are linked to conform to the relationship between olivine and pyroxene Mg-number in ordinary chondrites from [5]. The optical constants for Fe-bearing glass were calculated in [3]. The method of [3] is also used to compute the iron-dependent optical constants of plagioclase, utilizing reflectance spectra of plagioclase from the U.S.G.S. Denver library. The methods of Hapke [1,2] are used to compute the single scattering albedos of all transparent components using the input SMFe abundance, the calculated optical constants, and the input grain size. The SMFe is assumed to be pure iron, coating the transparent minerals and distributed uniformly. This may or may not be an accurate representation of actual asteroid space weathering processes, owing to the unknown influence upon space weathering effects of the larger quantities of nickel present on asteroid surfaces. The single scattering albedo of troilite is computed from a fit to the derived single scattering albedos of three different sizes of troilite. The single-scattering albedo of FeNi metal for the input grain size is computed from Mie theory. The particle size of all components is assumed to equal the input particle size. The calculated single-scattering albedos are subsequently combined using Eq. 17 of Hapke [6]. The methods of [7,8] are used to calculate the single particle phase functions. Finally, the mixture single scattering albedo is converted to reflectance using Eq. 37 of [6].

Operation. The operator inputs and iterates on an initial guess to produce a model spectrum grossly consistent with the unknown spectrum, then a gradient descent algorithm is applied to refine the fit parameters and report a final modal composition.

Methodology: To validate the ability of this model to accurately reproduce a given meteorite spectrum, we input the modal abundances of the polymict eucrites Y74450 and ALHA76005 [9], the eucrites Stannern and Juvinas [10], and the diogenites Johns-town and EETA79002 [11]. The input target spectra were RELAB spectra of these meteorites from previous studies or spectra downloaded from the RELAB public database [12,13]. The RELAB standard viewing geometry is incidence = 30°, emission = 0°, and phase = 30°. The input grain size was 25 µm.

Results: Qualitatively, the model is capable of producing simulated spectra that greatly resemble laboratory spectra of the same meteorite. Figure 1 shows an example of the program’s output, showing both the laboratory spectrum and the simulated spectrum of the Y74450 polymict eucrite. Except for a slight divergence at long wavelengths and slight differences in the depth of the 1 µm absorption feature, the simulated reflectance spectrum is a very good approximation of the laboratory spectrum.
Quantitatively, the model proved capable of reproducing the modal mineralogy of the modeled meteorites to an accuracy of \(\pm 12\) vol \%. As shown in Figure 2, there is a high degree of correlation between the measured and modeled modal abundance of the meteorite constituents.

As a further test of the ability of the model to determine the composition of asteroid surfaces, we modeled the surface composition of asteroid 4 Vesta using the same modal abundances of the eucrites and diogenites and the 4 Vesta spectrum from the 52-color survey as the target spectrum [14]. This produced the following results: 1) The meteorite composition in our study that generated the closest match to the spectrum of 4 Vesta was that of the polymict eucrite ALHA76005, which is provided in Figure 3. This is generally consistent with our understanding of eucrite origin and the presumably brecciated nature of the surface of 4 Vesta [15]. 2) The model always minimized the degree of space weathering. No abundance of submicroscopic iron above 0.26 wt. \% Fe was allowed. This is consistent with the assertions (e.g., [12]) that the surface of Vesta has experienced a minimal degree of space weathering.

The ability of the model to closely reproduce both the spectral shape and the modal mineralogy of meteorite compositions increases confidence in the capability of intimate mixture models based on radiative transfer formulations to accurately determine the surface composition of asteroids.