ASTEROID SURFACE MINERALOGY USING HAPKE MIXING MODELS: THE SPECTRAL EFFECTS OF COARSE-GRAINED METAL. S. J. Lawrence[1], P. G. Lucey[1], and G. J. Taylor[1]. [1]Hawai'i Institute of Geophysics and Planetology, SOEST, 1680 East-West Rd., Honolulu, HI, 96822 (slawrenc@hawaii.edu)

Introduction: The spectral properties of asteroid surfaces are governed by the mineralogy, the physical state, the amount of impact-produced glass, and the degree of space weathering of the asteroid regolith. Hapke's theories [1,2] and the work of [3] were used to create a model that calculates the spectrum of an airless planetary surface for a given modal mineralogy and mineral chemistry, within simplifying assumptions.

This model, called the S-Class Asteroid Spectral Interpreter, (SASI), was first introduced in [4]. The ability of this model to accurately reproduce eucrite and diogenite spectra was shown in [5], and preliminary efforts to use the model to determine the modal mineralogies of S-class asteroids were discussed in [6]. Our efforts continue to evolve the SASI algorithm into a robust tool for the accurate interpretation of asteroid spectra. Here, we present a new theoretical treatment for the spectral effects of coarse-grained iron-nickel metal, which is an important component of asteroid surfaces, and discuss some implications regarding its spectral effects.

Model Description: As outlined in [4] and discussed again in [5] and [6], 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 method for the computation of the optical effects of submicroscopic iron (SMFe), which plays an important role in the optical effects of space weathering processes.

Olivine, orthopyroxene, clinopyroxene, plagioclase feldspar, troilite, Fe-Ni metal, Fe-bearing glass (all as volume percent) and the abundance of SMFe (in parts per thousand) are input into the model and 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, pyroxene, plagioclase, and Fe-bearing glass. The chemistries of olivine and pyroxene are linked to conform to the relationship between olivine and pyroxene Mg-number in ordinary chondrites from [7]. The methods of Hapke [1,2] are used to compute the single scattering albedoes 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 representation for the spectral effects of SMFe is the most satisfactory approach given our current knowledge of space weathering processes. However, this may or may not be an accurate representation of actual asteroid space weathering processes, due to the unknown effects of the larger quantities of nickel present on asteroid surfaces.

The opaque components are treated differently because Hapke's treatment that relates optical constants to single scattering albedo only holds for transparent material where $k \ll 1$; his treatment of nanophase iron is a special case for coatings and inclusions within or on a host and is not extensible to the general case of opaques. For troilite, the single scattering albedo is computed from a fit to the derived single scattering albedoes of three different sizes of troilite. The single-scattering albedo of Fe,Ni-metal is derived using the new methods described in the following section.

All components are assumed to be spherical particles and the size of all components is assumed to equal the input particle size. The calculated single-scattering albedoes are subsequently combined using Eq. 17 of [8]. The single-particle phase function of [9] is used. Finally, the mixture single scattering albedo is converted to reflectance using Eq. 37 of [8].

Coarse-grained Fe,Ni-Metal: Previous spectral mixing model treatments of asteroid reflectance spectra involving coarse-grained metal have used iron spectra obtained from either terrestrial sources or meteorites as components. Prior work that calculated mixtures used linear mixing, and the intimate mixture case has not been treated. Intimate mixtures can be computed using single scattering albedoes inverted from reflectance spectra, but the difficulty of producing unaltered metal powders has stymied this approach. We have taken a more theoretical approach to compute single scattering albedo (the probability that a photon will survive an encounter with a grain) for coarse metal particulates.

For metals which are completely opaque and highly reflective, the reflectivity of a surface for an arbitrary geometry can be computed exactly using Fresnel's equations and the optical constants of the metal. The version of the Fresnel equations we used for this calculation are numeric approximations for the Fresnel reflectance of metals in *s* and *p* polarizations at any incidence angle, which are equations 4(36) and 4(37) from [10], and were used with the optical constants for metallic iron from [11]. Our approach is to numerically integrate the reflectivity of an arbitrary particle illuminated by collimated light over the entire illuminated portion of the surface. This integration is necessary because reflectivity varies with incidence and emergence angle for the surface.

However, we found that the single scattering albedo computed from this integration is very close to the reflectance of the same metal illuminated normally, even for rather extreme particle shapes, because of the relatively small cross-sectional area of the extreme angles. Given the errors inherent in the optical constants of the various components of this model, we elected to use the Fresnel reflectance at normal incidence as a reasonable approximation for the single scattering albedo of a metal particle.

Coarse-Grained Metal Spectral Effects: One of the major questions in asteroid studies has been the effect of space weathering processes on asteroid surfaces. It is reasonable to assume that asteroidal space weathering resembles the lunar example. However, the effect of the larger quantities of metal present on asteroid surfaces on the space weathering process is largely unknown [4], although some promising work has recently been done in this area [12]. In [13], it was shown that mixtures of primitive achondrites and Fe,Ni-metal could account for a significant fraction of the S-Class asteroids studied without invoking lunar-style space weathering processes. Other workers have also discussed the effects of coarse-grained metal on asteroid spectra [14,15].

To help address this question, we used the updated SASI model described above to compare the spectral effects of coarse-grained Fe,Ni-metal and SMFe. Figure 1 shows the simulated effects of increasing the amounts of coarse-grained metal in a chondritic assemblage of silicates and metals. As more metal was added, the abundance of the non-metallic components was renormalized. Increasing the abundance of coarse-grained Fe,Ni-metal gradually suppresses spectral features. For comparison, Figure 2 shows the simulated effects of increasing the abundance of SMFe in a chondritic assemblage. This modeling shows that in some situations the spectral effects of coarse-grained metal are similar to those of SMFe. For example, Figure 3 compares an arbitrary H-class ordinary chondrite assemblage with 21 volume percent Fe,Ni-metal but a minimal abundance of SMFe to an arbitrary L-class ordinary chondrite assemblage with less Fe,Ni-metal but a larger abundance of SMFe. Using current techniques, it would be very difficult to distinguish between these two spectra.

Conclusions: Additional work within this parameter space is required to determine methods for distinguishing the relative effects of SMFe and coarse-grained Fe,Ni-metal. Our future work will also involve using the methods outlined in [6] in conjunction with the technique presented here in order to extract compositional information from existing asteroid spectral datasets, which will provide useful information that will help to address this question. These results also serve to highlight the need for both the in-situ analysis of asteroid surfaces and asteroid surface sample return missions in order to shed more light on asteroid space weathering processes as well as the relationship between meteorites and their parent asteroids.

References: [1] Hapke B., *Theory of Reflectance and Emittance Spectroscopy*, Cambridge Univ. Press, Cambridge, 1993. [2] Hapke B., *JGR 106*, E5, pp. 10,039-10074, 2001. [3] Lucey P. G., *JGR 103¸*E1, pp. 1703-1714, 1998. [4] Clark B. E. et al. *MAPS* 31, pp. 1617-1637, 2001. [5] Lawrence S. J. and Lucey P. G. *LPSC 35*, Abstract #2128, 2004. [6] Lawrence S. J. et al. LPSC 36 Abstract # 2362, 2005. [7] Keil K. and Fredrickson K., *JGR 69*, pp. 3487-3515, 1964. [8] Hapke, B., *JGR 86*, pp. 3039-3054, 1981. [9] Mustard J. F. and Pieters C. M. *JGR 94* pp. 13619-13634, 1989. [10] Heavens O. S. *Optical Properties of Thin Solid Film,* Dover Publications, 1991. [11] Ordal M. A. et al. *Applied Optics 24*, 24, pp. 4493-4499. [12] Horz et al. *MAPS 40,* 9/10, pp. 1329-1346, 2005. [13] Hiroi, T., et al. *MAPS 29*¸ pp. 394-396, 1994. [14] Gaffey M. J. *Icarus 66,* pp. 468-486, 1986. [15] Gaffey M. J. and Gilbert S. L. *MAPS 33,* pp. 1281-1295, 1998.

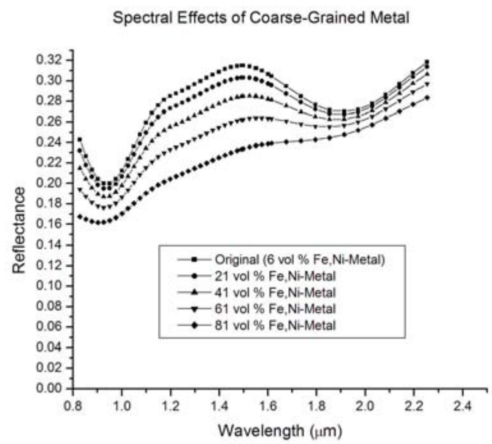

Figure 1: The predicted spectral effects of increasing the abundance of coarse-grained Fe,Ni-metal in a chondritic composition. The modeled particle size is 25 μm.

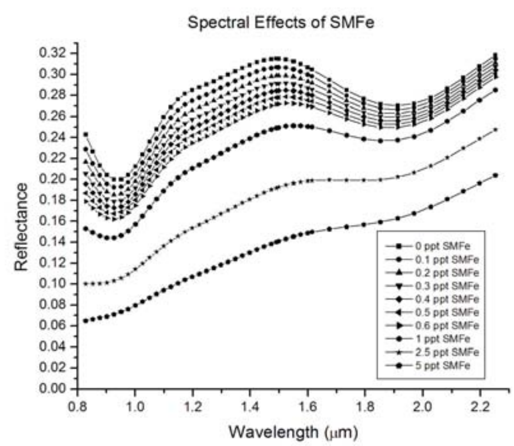

Figure 2: The predicted spectral effects of adding SMFe to an ordinary chondritic omposition. Modeled particle size is 25 μm.

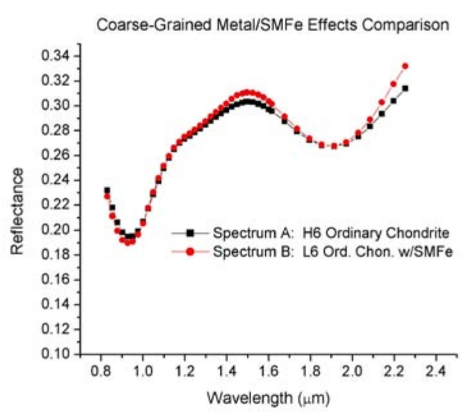

Figure 3: A comparison between an arbitrary H-class ordinary chondritic composition with 21 volume percent metal and minimal SMFe to an arbitrary L-class ordinary chondrite composition with 6 volume percent metal and 0.4 ppt SMFe.