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Compositions of Near-Earth Asteroids

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This year we have continued observational studies of near-Earth asteroids and development of techniques for determining their compositions. The analysis techniques have been applied to the spectra of several bodies in preparation for their application to near-Earth asteroids.

In mid-November 1989, we made near-IR observations of three near-Earth asteroids: 1865 Cerberus, 1989 VA, and 1989 VB. We were able to observe these asteroids in 6 broad-band visual and near-IR filters (0.4 to 2.5 μm). We were also able to obtain a few narrow-band measurements in the IR, but the asteroids were too faint to measure beyond 2.5 μm . Simultaneous, high-resolution visual CCD spectra were measured for these objects, but the data have not yet been reduced to determine their quality.

In collaboration with Jeff Bell at the University of Hawaii, we have obtained narrow-band spectra of the Martian satellite Deimos in the 1- to 3- μm spectral region. Both satellites of Mars have spectra similar to C-class asteroids; therefore, this was an opportunity to test the models developed for main-belt asteroids on an object closer to the Sun. Our preliminary analysis indicates that there is little or no water present in the surface silicates. We hope to obtain spectra of Phobos from the infrared spectrometer on the Soviet Phobos mission to analyze next year.

Simultaneous with the observing project, we are also continuing our laboratory studies (funded by NASA) of meteorites and meteorite analogs which are used in spectral analysis of our telescopic data. These spectra will also be used in compositional modeling of some of the asteroid spectra, using Hapke reflectance theory.

Extensive work has been done developing applications of Hapke reflectance theory to compositional analysis. Hapke theory is an adaptation of radiative transfer theory to particulate surfaces. The surface is assumed to be composed of irregularly shaped, randomly oriented particles that are large compared with the wavelength of the light. The particles are in contact, but coherent effects are assumed to average out due to the random orientation and irregularity of the particles. Diffraction is also not included in the derivation because the light diffracted by one particle in the surface encounters another particle before it has dispersed sufficiently to be distinguished from the incident light. By definition, all of the light striking a particle is either scattered or absorbed; therefore, the maximum extinction efficiency of a particle in a surface is one.

In the derivation, the light reflected from the surface is separated into singly and multiply scattered components. The term for the singly scattered component includes all the geometric information, and the multiply scattered component is approximated by the isotropic solution.

The principal equation is an expression for the bidirectional reflectance:

$$r = \frac{w}{4\pi} \frac{\mu_0}{\mu_0 + \mu} \left\{ \left[1 + B(g) \right] P(g) + H(\mu_0)H(\mu) - 1 \right\},$$

where

- w = the single scattering albedo,
- μ_0 = the cosine of the incidence angle,
- μ = the cosine of the emission angle,
- g = the phase angle,
- $B(g)$ = the backscatter function,
- $P(g)$ = the phase function, and
- $H(\cdot)$ = the Chandrasekhar H-function for isotropic multiple scattering.

The single scattering albedo is the percentage of total light encountering a grain that is scattered out of the grain. The backscatter function describes the magnitude and extent of the opposition effect observed at low phase angles. The phase function describes the average angular scattering behavior of the grains in the surface. This basic equation can be manipulated to calculate other quantities, such as the radiance coefficient, the directional hemispherical reflectance, and the normal albedo.

The reflectance of an intimate mineral mixture can be calculated from this equation by substituting average quantities for the single scattering albedo and phase function. The average single scattering albedo is an average of the single scattering albedos of the components, weighted by their relative cross-sectional areas. The average phase function is weighted both by cross-sectional area and single scattering albedo because bright grains contribute a higher portion of the light that strikes them to the total surface reflectance. These equations can be used to determine the relative abundances of minerals in a mixture if the end members are known or can be inferred.

Two applications of relevance to near-Earth asteroids were initiated by Marcia Nelson in her graduate work at the University of Hawaii. The composition of Vesta was determined by fitting a mixture equation to telescopic spectra of Vesta and, in collaboration with Paul Lucey at the University of Hawaii, the theory was used to calculate many lunar analogue spectra to aid in the interpretation of lunar telescopic spectra.

High-resolution, visible, and near-infrared spectra of Vesta have been available for many years. The spectra have been interpreted repeatedly, and a consensus has emerged that the majority of Vesta's surface is very similar, if not identical, to the eucrite meteorites. The eucrites are basalts, which are composed of plagioclase and pyroxene, with little to no olivine or metal. Hapke's equations can be fit to a spectrum to determine the relative abundances of the components, given spectra of the end members. The theory has matched laboratory spectra well, so Vesta was chosen for the first unconstrained test because its spectrum is already so well analyzed.

Spectra of actual eucrite mineral separates are not available, so spectra of the most chemically similar pyroxene, plagioclase, and olivine available were chosen as end members. The single scattering albedos of the end members were determined by fitting the directional hemispherical reflectance equation to the end-member spectra. Then, the abundances of the end members were determined by fitting the normal albedo of a mixture equation to the spectrum of Vesta using the single scattering albedos of the end members as input. The abundances determined were 65% plagioclase/35% pyroxene, which is essentially eucritic. This is an extremely good result, considering the large uncertainties and known approximations in the inputs. Efforts will be made to improve the inputs and the fitting techniques this year so they can be used to analyze other asteroids.

A different approach was used in applying Hapke theory to the analysis of lunar spectra. Instead of analyzing individual telescopic spectra, the theory was used to calculate synthetic mixture spectra from which spectral trends were determined. The eventual goal of the project is to construct actual calibration plots using parameters derived from the synthetic spectra. It was sidetracked this year when it was discovered what a powerful tool this is for investigating the systematics of spectra of intimate mineral mixtures. It is possible to calculate any mixture that can be defined, containing as many components as desired, providing spectra of the end members are available. It is also possible to quickly calculate mixture series, holding components fixed, or varying them as desired. The mixture series calculated to date have explored orthopyroxene, clinopyroxene, olivine, and plagioclase mixtures, and have begun to explore the spectral effects of ilmenite and agglutinates. The effect of shocked plagioclase has yet to be included.

This has proven to be an important, general-purpose tool for quickly investigating the spectra of mineral mixtures. It will be particularly useful in testing the validity of the end members chosen before more time-consuming fits are run to determine absolute abundance. It is also an excellent tool for directing laboratory investigations,

aiding in testing end members, and determining the relevant mixtures to actually create. It will undoubtedly be used regularly in work on near-Earth asteroids next year.

Presentations

The following papers were presented at the American Astronomical Society Division of Planetary Sciences meeting, October 31-November 3, 1989:

J. F. Bell, P. G. Lucey, J. C. Gradie, J. C. Granahan, D. J. Tholen, J. R. Piscitelli, and L. A. Lebofsky, "Reflection Spectroscopy of Phobos and Deimos."

L. A. Lebofsky and T. D. Jones, "The Nature of Low Albedo Asteroids From 3- μ m Multi-Color Photometry and Spectrophotometry."

M. L. Nelson and J. F. Bell, "Modal Mineralogy of Vesta From Hapke Theory."