29.05

S-Type Asteroid Spectral Continua: Redness and Fe,Ni Metal

Beth E. Clark[1] and Takahiro Hiroi[2]. [1]McDonald Observatory, University of Texas at Austin, 78712. [2]NASA Johnson Space Center, Houston Texas, 77058.

Combining evidence from recent spectral surveys and compositional modeling, we show that our previous notions of inner asteroid belt geology may have to be reconsidered. Spectroscopic interpretations have long associated S-type asteroids, the most abundant class of asteroids in the inner main belt, with various combinations of olivine, orthopyroxene, and Fe,Ni metal (Pieters *et al.* 1976; Gaffey and McCord, 1978). It is currently supposed that S-types are thus best represented by the achondrite and anomalous stony-iron meteorites (McCord and Gaffey, 1974; Gaffey, 1984; Bell *et al.* 1985). With the following reasoning however, we suggest that metallic components may not be responsible for the redness of most S-type asteroid spectra, and that their meteoritic spectral analogs are therefore yet open to question.

1) First, S-type asteroids have red spectral continua that increase from 0.7 to 1.5 μm across the mafic mineral absorption band at 1 μm. This slope has long been attributed to a Fe,Ni metal component among the surface materials. **2)** There is a distinct break in continuum slope at ~1.5 μm at which point the continuum levels off from 1.5 to 2.5 microns. The cause of this break has been assumed to be due to silicate components. **3)** 90% of the S-type asteroids measured for the 52-color (Bell *et al.* 1988) *and* SCAS infrared surveys (Clark *et al.* 1994) show this break in continuum. Broadband JHK colors of S-types (Veeder *et al.* 1978) also show this characteristic. **4)** Metallic Fe,Ni has a red spectral continuum that increases uniformly and almost linearly with wavelength from 0.5 to 2.5 μm (Gaffey, 1976, 1986; Britt and Pieters, 1988). **5)** S-type asteroids have been compositionally modeled with achondrite meteorites and the Mundrabilla Fe,Ni meteorite, but with only 40% success (Hiroi, *et al.* 1993). **6)** S-types have also been modeled with pure mineral endmembers. However, the success rate is equally ambiguous (Clark, 1993). **7)** The break in IR continuum slope from 1.5 to 2.5 μm is the main cause of distress in modeling S-asteroids with mixtures of silicate and Fe,Ni metal endmembers (Clark, 1994; Hiroi *et al.* 1993). ***i.e. The silicate component spectral turnover at 1.5 μm is insufficient to mask the spectral redness from 1.5 to 2.5 μm of metal components included to account for the redness from 0.7 to 1.5 μm.*** It may be that S-types have other important phases that could account for the continuum turnover. For example, spinel and cpx have been suggested, but not yet investigated (Hiroi, 1994).

It becomes increasingly clear that mineralogic interpretations of S-type spectral continua are not so trivial as supposed. The bad news is that we still don't know why S-types are red. The good news is that spectral continua may be compositional information afterall. Among the implications of this suggestion is the radical idea that we do not necessarily know what kind of rock comprises most of the geology of the inner asteroid belt.

29.06

Space Weathering on S-Class Asteroids: Myth vs. Reality

Jeffrey F. Bell (Hawai'i Institute of Geophysics and Planetology)

MYTH: In the 1960s meteoriticists expected on the basis of meteorite fall statistics, cooling rates, and collisional evolution models that the asteroid belt would be dominated by ordinary chondrite material at all sizes. When the first spectroscopic surveys in the early 1970s did not find any OC-like objects among the larger asteroids, the failure of the original prediction was rationalized by invoking a "space weathering" process that camouflaged the hypothetical OC asteroids with spectrally altered regoliths that exhibit S- or C-type spectra. None of the original reasons for expecting large OC asteroids are still valid. Modern meteorite cooling models suggest that the OC parent bodies were never more than ~50km in diameter. The steep crater abundance curve on Gaspra shows that the uniform power law of index -3.5 predicted by classical collisional evolution models for asteroids does not exist. The true asteroid size distribution is now believed to follow the complex post-mare lunar cratering function. It now appears possible that chondrites and irons have very different size distributions, breaking the assumed link between meteorite fall statistics and asteroids. Furthermore, a genuine OC (Class Q) asteroid has been found in the asteroid belt at the solar distance and size predicted by a model assuming no space weathering (Bell *et al., Asteroids II*, p. 942). The Galileo images of Ida show an extremely uniform surface, with no fresh crater bottoms showing OC-like spectra. Meteoriticists now recognize a much larger number of differentiated meteorite classes which are good alternate analogs for S asteroids. All these discoveries are strong arguments against the "classical" space weathering model.
REALITY: However, there is now strong evidence for a very different sort of space weathering on S-type asteroids, one which mostly affects silicate band depth rather than continuum slope and curvature. It has long been observed that small Earth-crossing asteroids tend to have deep bands relative to large main-belt objects, but it was not clear if this was related to size or orbital history. Recently it was shown that main-belt S asteroids below ~100km diameter show a smooth function of decreasing band depth with increasing size (Gaffey *et al.*, ICARUS **106**, 592). This effect is found in all S-types, independent of Ol/Pyx ratio or other mineralogical parameters, and it appears to "saturate" near 100km diameter with all S asteroids above this size having roughly similar band depths. These features suggest the existence of a change in regolith properties on all S-type asteroids with surface gravity and/or age. The differences between Gaspra and Ida in crater density, spectral uniformity, and thermal inertia are consistent with such a change. This effect, rather than intrinsic mineralogical differences, probably accounts for most of the spectral differences between Ida and its satellite seen by Galileo.

29.07

Visible Spectroscopy of dark, primitive asteroids.

M. Lazzarin (Dip. Astron., Univ. Padova, Italy), C. Barbieri (Dip. Astron., Univ. Padova, Italy), M. Di Martino (Oss. Astron. Torino, Italy), M.A. Barucci (Obs. Paris, France), M. Fulchignoni (Univ. Paris VII, France)

Asteroids and comets have a close relationship with the planetesimals which formed from the solar nebula 4.57 billion years ago. Since then, comets have been submitted to very low levels of evolutionary pressure and the differentiation of some asteroids has been spread over at most the first few million years. As such, small bodies have preserved material which witnessed the condensation and the early phases of the formation of the solar system. In particular, speaking about asteroids, it is now evident that the darkest objects are also the most primitive. Laboratory spectra suggest that the sources of the low–albedo matter may be a mixture of organic compounds together with acqueous alteration products of igneous minerals. Therefore, these asteroids may be the most closely related to comets.
In this context we started in 1993 an observational program of dark asteroids, precisely those of taxonomic class C, D and P to investigate spectroscopically these objects in order to study their surface composition and make a comparison among the different taxonomical classes, to reveal possible weak features of cometary origin to learn about the possible link between comets and asteroids. The data, 20 low resolution spectra in the visible range, have been obtained during different observational runs carried out at the Observatories of La Silla–Chile and of Asiago–Italy. The results of the survey will be presented and discussed.

29.08

Spectral Observations of Near-Earth Asteroids

E. S. Howell, A. S. Rivkin (U. Arizona), R. L. Marcialis (Pima College), M. C. Nolan, J. A. Grier (U. Arizona), S. J. Bus, and S. M. Slivan (MIT)

Over the past year, we have studied the composition of near-Earth asteroids. Using both visible and near-infrared photometry and spectroscopy, we have obtained physical data for 15 near-Earth asteroids to assign taxonomic classifications and determine surface mineralogy. If the apparent discrepancies between asteroid spectra and meteorite spectra are due to regolith processes that affect the spectral slope, albedo, and band depth, these effects may be less prevalent on smaller near-Earth asteroids than on main-belt objects. Near-Earth asteroids are the more immediate parents of meteorites, at least in a statistical sense, and may be more similar to meteorites in spectral appearance.

Two near-Earth asteroids 4953 1990 MU and 4954 Eric, both determined to be S class, had particularly favorable apparitions in 1994. We coordinated simultaneous visible and near-infrared observations for 4954 Eric. Spectra in both wavelength regions were also obtained for 4953 1990 MU, although separated by several days. These objects both show a pyroxene absorption band centered near 2 μm. The near-infrared spectra were obtained using the F. L. Whipple Observatory Mulitiple Mirror Telescope (MMT) and the FSPEC near-infrared spectrometer. Most of the

CCD spectra were taken with the 1.54-m Catalina Station telescope. However, the simultaneous visible observations of 4954 Eric were obtained at the 2.4-m Michagan-Dartmouth-MIT telescope. We combined visible and near-infrared photometry taken over a time period of less than 2 hours from the McGraw-Hill telescope and MMT, respectively, to scale the CCD and near-infrared spectroscopy into a composite reflectance spectrum of 4954 Eric. Analysis of these spectra and the compositional implications will be presented.

29.09

Unusual Colors for Small Earth Approachers

D. Rabinowitz (DTM, Carnegie Inst. Washington), E. Howell, and M. Hicks (LPL, U. Arizona)

In March and April of 1994, seven new Earth approachers with sizes ranging from 5 to 75m were discovered at the Spacewatch Telescope of the University of Arizona during a search optimized to detect small Earth approachers (SEAs). Two of these objects (1994 ES1 and 1994 GV) were observed spectroscopically (0.5 - 0.9 μm), and one (1994 EU) was observed through Harris B and V, and Cousins R filters (0.44, 0.55, and 0.67 μm). These new observations, and previous color measurements for five other SEAs (1991 VA, 1991 VG, 1992 DU, 1992 JD, and 1993 KA), show that the reflectance spectra of SEAs differ markedly from the reflectance spectra of main-belt asteroids and larger Earth approachers. Some of the SEA spectra are unusually reddened at wavelengths longward of 0.55 um, and a few show sharp absorptions shortward of 0.55 um. Unfortunately, most of these spectra are not sampled over a wide enough wavelength range to compare conclusively with meteorite samples. However, it is clear that SEAs originate from diverse sources, and that some of these sources have not been observed spectroscopically among the main-belt asteroids or larger Earth approachers. Possible sources, consistent with the sources determined by analysis of the SEA orbits [1] are cometary debris, and impact ejecta from the Moon, Mars, Earth, or an undiscovered population of Earth Trojans.

[1] Rabinowitz, D.L., 1994, Icarus, in press.

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29.10-T

System Analysis of Telescope and Laboratory Polarimetric Data for Rough Surfaces

Sergej V. Vasilyev (Astron. Obs., Kharkiv State University, Ukraine)

The attempt to describe the polarization phase curves of atmosphereless bodies and laboratory data is made by principal component method. The data include the polarization phase curves of more than 50 asteroids, some comets and various laboratory data including the meteorites, lunar and artificial samples. Linear independent parameters completely describing all the differences among the initial curves have been found. Two and three-dimensional plots of these parameters (eigenvalues) show the asteroid and comet grouping in accordance with their belonging to composition types. Such diagrams can be used for independent determination of asteroid types. On the other hand the laboratory samples revealed the sensitivity of the method to physical changes in examined surface. It was found that some parameters have a significant correlation with physical parameters. The small number of obtained parameters and their linear independence has allowed to provide more correct comparison of telescope and laboratory data. The results of comparative analysis are discussed.

29.11-P

Light Scattering by Stochastically Rough Particles

K. Muinonen (Observatory, U. Helsinki)

The geometric optics approximation for light scattering by stochastically rough particles has been studied by Peltoniemi *et al.* (*Appl. Opt.* **28**, 4088, 1989); the present report is a natural continuation of their work. I describe three-dimensional stochastic particle shapes by multivariate lognormal statistics and compute full 4×4 scattering phase matrices, thus improving significantly on the earlier approach. The stochastic geometry can be generated by using spherical harmonics expansions having random variable coefficients that satisfy certain statistical conditions. A new autocorrelation function has been devised for the particle radius, allowing an analytical derivation of the spherical harmonics coefficients. Once the particle geometry has been generated, scattering in the geometric optics approximation can be computed via rather general ray tracing algorithms for an arbitrary particle shape $r = r(\theta, \phi)$ (θ and ϕ being spherical coordinates). I present scattering phase matrices for a large selection of particle refractive indices and statistical shape parameters; in particular, I compute asymmetry parameters both including and excluding the forward diffraction component. The results help us understand light scattering by solar system dust particles, and thereby constrain the physical properties of, for example, asteroid regoliths and cometary comae.

29.12-P

Asteroid 4769 Castalia: Interpretation of Optical Lightcurves Using a Radar-Derived Shape Model

R. S. Hudson (Washington State U.), S. J. Ostro, A. W. Harris (JPL/Caltech)

A 167-parameter, 3-D shape model of Castalia[1], obtained from inversion of delay-Doppler images, constrained the object's subradar latitude on the date (Aug. 22, 1989) of the observations by defining an annular sky region that contains Castalia's pole. We have used the shape model and nominal Hapke parameters for S asteroids[2] to model Castalia lightcurves obtained at Table Mountain Observatory on Aug. 23-25, 1989, at solar phase angles ranging from 58° to 90°. This investigation defines the projected pole's azimuthal orientation around the radar line of sight and yields a least-squares estimate of the orientation of Castalia's north or south pole (within 10° of $\lambda = 250°$, $\beta = -40°$). There is insufficient geometric leverage to distinguish the rotation sense or to estimate values of Hapke parameters. The model lightcurves match the TMO data surprisingly well, given the modest number of shape parameters in the model and the fact that part of the asteroid was not seen by the radar.

Visual comparison of the lightcurves with the frame-by-frame geocentric appearance of the sun-illuminated shape model reveals the detailed relationship between the asteroid's visible, illuminated, projected surface area and its disc-integrated brightness. For example, one can see why one lightcurve minimum is deeper and sharper than the other and why one maximum is weaker and flatter than the other -- small asymmetries in Castalia's overall shape and in the character of concavities at various scales play roles in determining the form of a lightcurve under any given viewing/illumination geometry. The availability of a detailed shape model clearly enhances the interpretability of lightcurves, especially for very small (and hence potentially very irregular) objects observed at large phase angles.

In their inversion of the radar images, Hudson and Ostro presented models corresponding to lower and upper bounds on Castalia's bifurcation. The lightcurve data clearly favor the more bifurcated model. Our experience suggests that optical lightcurves may enhance the accuracy of future radar reconstructions of small asteroid shapes, to a degree that would depend on the geometrical circumstances encountered in the radar and optical observations as well as on the asteroid's shape and spin state. For example, optical determination of a target's the spin vector would shrink the parameter space for the radar inversion. In some cases, lightcurves might provide extra leverage in splitting the N/S ambiguity in single delay-Doppler images.

[1] R. S. Hudson and S. J. Ostro 1994, *Science* **263**, 940-943.

[2] P. Helfenstein and J. Veverka 1984. In *Asteroids II* (R. P. Binzel, T. Gehrels, and M. S. Matthews, eds.), pp. 557-593, Univ. of Arizona, Tucson.