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UNAMBIGUOUS SPECTRAL EVIDENCE FOR HIGH- (AND LOW-) CALCIUM PYROXENE IN ASTEROIDS AND METEORITES.

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Introduction: Spectroscopy remains a powerful tool for inferring the modal mineralogy and mafic mineral composition of asteroid surfaces [1,2]. Since similar measurements can be made on meteorite samples, spectroscopy can help link the two populations and add spatial and geologic context to detailed geochemical knowledge derived from meteorite samples.

For example, analysis of the recent *NEAR-Shoemaker* mission to Eros include detailed study of NIS spectra to assess the affinity of Eros to ordinary chondrites [3-5]. As discussed in these studies, pyroxene (PYX) and olivine (OLV) absorption are readily detectable in the spectra. Furthermore, subtleties in band parameters (position vs. area) suggest the presence of both low- and high-calcium pyroxene (LCP and HCP) [3-5], as expected from the petrology of ordinary chondrites [*e.g.* 6]. However unambiguous identification and detailed compositional inferences for both LCP and HCP (and OLV) are difficult from band parameters analysis. In this study, we examine spectra of S-asteroids and meteorites with the Modified Gaussian Model (MGM), an absorption band model [7], to explore the role of HCP in these silicate-rich spectra.

Data: *Asteroid Spectra.* High quality spectra of 17 S-asteroids have recently been measured using SpeX, a low- to medium-resolution infrared spectrograph, newly commissioned at the Infrared Telescope Facility (IRTF) on Mauna Kea, Hawaii [8-9]. In its low-resolution mode (R ~ 100), SpeX can produce spectra of faint asteroids from 0.8 to 2.5 μm with S/N comparable to data typically collected with visible wavelength CCDs. The SpeX data have been combined with visible CCD data measured during the SMASSII survey to produce high S/N spectra from 0.44 to 2.5 μm for several asteroids.

Meteorite Spectra.. Burbine *et al.* [10] have measured >70 spectra of meteorites from the well characterized Smithsonian's Analyzed Meteorite Powder collection [11]. These data and previous studies on other meteorite types, including primitive achondrites [12] and eucrites [13], are analyzed in parallel for comparison to the asteroid spectra.

Results: The 17 S-asteroids measured span a large range of the S-asteroid class. Some have very strong olivine absorptions (OLV>>PYX) and represent a continuum between S- and the olivine dominated A-asteroids [8]. Others contain strong OLV and strong PYX absorptions and may be similar to ordinary chondrites [9]. Finally, as discussed below, some asteroids are dominated by PYX absorptions.

MGM Modeling. MGM modeling of 847 Agnia (**Fig. 1**) reveals a surface composed of a mixture of two pyroxenes. The LCP results in two bands (red), while HCP results in three bands (blue). The 1.25 μm band has been interpreted by many as an indication of plagioclase. However, the spectra of PYXs (particularly HCP) contain an absorption in this region due to the presence of Fe^{2+} in the M1 crystallographic site [14]. It is noteworthy that there is no indication of OLV in the MGM fit to 847 Agnia. Two other members of the Agnia family have also been measured with SpeX and have similar spectral properties.

The MGM fit to 17 Thetis (**Fig. 2**) appears almost identical to that of 847 Agnia, indicating these two asteroids have very similar surface compositions. The only significant difference between these two spectra is in the absolute strengths of the absorption bands, with 17 Thetis having weaker bands. Interestingly, 17 Thetis plots in the S(VI) field under the Gaffey *et al.* classification [5], which is interpreted to be rich in LCP, but with an OLV component. Our analysis shows no evidence of OLV, but instead, significant HCP .

While visual and MGM analysis of 17 Thetis and 847 Agnia show them to be spectrally similar, the ratios of the 1- and 2- μm band areas (1.17 and .55) suggest these two asteroids have very different compositions (*i.e.* based on Cloutis *et al.* [15]). The presence of HCP is apparently affecting the continuum points, which in-turn affects the band ratios. MGM derived band ratios are more consistent (.92 and .74). Taken at face value these band areas suggest significant OLV components (45-70%), yet recall there is no evidence of OLV absorptions in these spectra.

Interpretation: The inferred mineralogy of these asteroids, two pyroxenes (LCP:HCP ~60:40; based on LCP to HCP band ratios [16]) and little OLV (<15%) imply that they are evolved igneous bodies. Among the meteorites, such compositions are most similar to the basaltic achondrites. For comparison, the spectra of basaltic achondrites are also examined with the MGM.

For example, the MGM fit to the Bouvante basaltic eucrite (**Fig. 3**), reveals the presence of both LCP and HCP, and no OLV. These MGM results are very consistent with the known composition of Bouvante.

MGM derived LCP:HCP range from 72:28 (from 1 μm bands ratios) to 58:42 (2 μm band ratios), while the electron microprobe modal analyses shows LCP:HCP of 68:32 [17]. In addition, the band centers for both pyroxenes in Bouvante are at long wavelengths, which is very consistent with petrologic results that show it to be iron-rich (LCP: $Wo_6En_{36}Fs_{58}$ [18]). Bouvante is also known to have no significant OLV component. Finally, it should be noted that Bouvante contains 45% plagioclase. However, as noted above, ambiguity with M1 pyroxene absorption complicates any spectral determination of plagioclase content.

This analysis gives confidence to the MGM results for asteroid spectra. Compared to Bouvante, the asteroids are less iron-rich and have more HCP suggesting, on average, a more gabbroic composition. It is likely however, that the hemispherically averaged asteroid spectra are mixtures of evolved igneous lithologies.

Conclusions: The high quality SpeX spectra include detailed absorption features which are accurately modeled with the MGM. In several S-asteroids and eucrites, we find evidence for both LCP and HCP, with little to no OLV. Similar modeling efforts with ordinary chondrite spectra, unambiguously require OLV, LCP, and HCP absorptions with inferred modes and compositions that are consistent with known petrography [10]. It is now clear that HCP is a significant contributor to the spectra of S-asteroid and silicate-rich meteorites. We therefore must approach the analysis of these spectra not simply as OLV-PYX mixtures, but as ternary mixtures of OLV, LCP, and HCP.

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References: [1] Gaffey M. J. *et al.* (1993), *Meteoritics, 28*, 161-187. [2] Pieters C. M., and McFadden, L. A. (1994), *Rev Earth and Planet Sci, 22*, 457-497. [3] McFadden L. A. *et al.* (2001) *MAPS, 36*, 1711-1726. [4] McCoy T. J. *et al.* (2001) *MAPS, 36*, 1661-1672. [5] Gaffey M. J. *et al.* (1993) *Icarus, 106*, 573-602. [6] McSween H. Y. Jr. *et al.* (1991) *Icarus, 90*, 107-116. [7] Sunshine J. M. *et al.*, *JGR, 95*, 6955-6966, 1990. [8] Binzel R. P. *et al.* (2001), *MAPS, 36*, 1167-1172. [9] Bus S. J. *et al.* (2001), *Bull AAAS/DPS 33*, #41.16. [10] Burbine *et al.* (2002) *LPSC, XXXIII* this volume. [11] Jarosewich E. (1990) *Meteoritics, 25*, 323-337. [12] Burbine T. H. *et al.* (2001) *LPSC, XXXII*, #1860. [13] Burbine T. H. *et al.* (2001) *MAPS, 36*, 761-781. [14] Burns R. G., (1993) *Mineralogical Applications of Crystal Field Theory*, 551 pp. [15] Cloutis E. A. *et al.* (1986), *JGR, 91*, 11,641-11,653. [16] Sunshine J. M. and Pieters C. M. (1993) *JGR, 98*, 9075-908. [17] Christophe Michel-Levy, M., et. al. (1987), *Bull Mineral, 119*, 449-458. [18] Delaney, J. S. *et al.* (1984), *LPSC XV*, 210-211.

Figures: MGM model fits to 847 Agnia, 17 Thetis, and the Bouvante eucrite. Plotted in each figure is the residual error (purple, offset 10%), the individual modified Gaussian distributions (solid lines), the baseline continuum (dashed), and the modeled spectrum (black line) overlying the measured spectrum (orange). All spectra include visible (gray), LCP (blue) and HCP (red) absorptions, yet show no evidence of OLV.

Fig. 1: MGM Fit to 847 Agnia

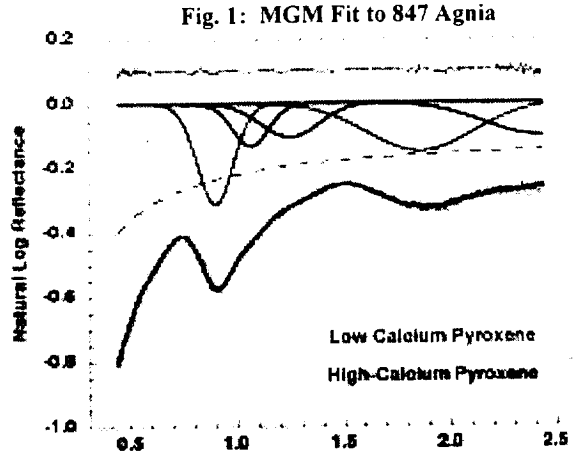


Fig. 2: MGM Fit to 17 Thetis

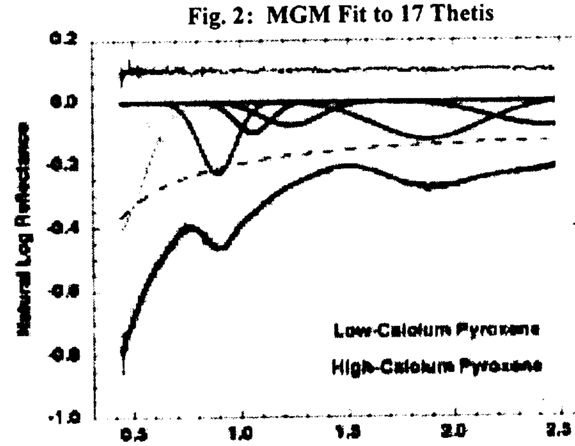
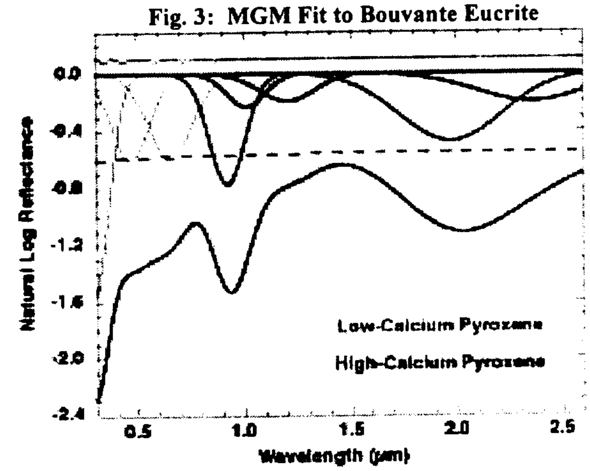


Fig. 3: MGM Fit to Bouvante Eucrite



SPECTRAL MEASUREMENTS OF METEORITE POWDERS: IMPLICATIONS FOR 433 EROS. T. H. Burbine[1], T. J. McCoy[1], E. Jarosewich[1], and J. M. Sunshine[2], [1]Department of Mineral Sciences, National Museum of Natural History, Smithsonian Institution, Washington, DC 20560-0119, USA (burbine.tom@nmnh.si.edu), [2]Advanced Technology Applications Division, Science Applications International Corporation (SAIC), 4501 Daly Drive, Chantilly, VA 20151.

Introduction: One of the goals of the NEAR-Shoemaker mission to 433 Eros was to determine if it has a meteoritic analog. The primary means of making such a link are the X-ray/gamma-ray spectrometers [1], which measure elemental compositions of the surface, and the multi-spectral imager (MSI) and near-infrared spectrometer (NIS) [2], which measure spectral reflectance.

For determining meteoritic analogs using the X-ray/gamma-ray spectrometer data, the primary data used for comparison is the set of bulk chemical analyses of meteorites done by Jarosewich [3]. These bulk chemical analyses were done on samples now found in the Smithsonian's Analyzed Meteorite Powder collection (USNM 7073). For determining meteoritic analogs using MSI/NIS spectral data, the primary data used for comparison is the set of meteoritic spectra compiled by Gaffey [4].

To expand the set of meteoritic spectra available to the scientific community, we have initiated a spectral study of over 70 samples (primarily ordinary chondrites) found in the Smithsonian's Analyzed Meteorite Powder collection and an electron microprobe study of their corresponding thin sections. This set of spectral and compositional data should allow for better constraints on the distribution of meteorites in plots of band area ratios versus Band I centers [5] and the usefulness of equations for deriving mineralogic compositions from band parameters [6]. These spectral data can also be combined with previous spectral studies of other meteorite types such as the primitive achondrites [7], eucrites [8], and angrites [9] to determine how useful the derived band parameters are for differentiating between different meteorite classes. These spectral data can also be used for testing the Modified Gaussian Model (MGM) [10,11] for determining modal abundances and mafic mineral chemistries from reflectance spectra.

Meteoritic Powders: As part of the Smithsonian's meteorite research program, approximately 300 meteorites have been analyzed in the past 36 years for bulk chemical data [3]. The primary requirement for analysis was to obtain, if possible, sufficient amount material to assure a representative sample of the whole meteorite, and to retain some material for future studies. Usually from five to forty grams of a meteorite were powdered depending on the type of meteorite and the mass available. These powders were prepared under clean conditions so that they can be used for trace element analyses and other types of chemical studies.

The meteorite samples were ground in an agate mortar in a hood with positive air pressure and then sieved through a nylon sieve to usually pass through 100 mesh (< 150 _m). A few samples were sieved to pass through 200 mesh (< 75 _m). This fine-powdered fraction (< 150 _m) consisted of silicates and sulfides and contained up to 0.4 wt.% of fine-grained metal. The meteoritic fraction larger than 100 mesh (>150 _m) was primarily metal. A detailed description of the preparation of powders and the analytical procedures is given in Jarosewich [3]. Normative mineralogies for most of the ordinary chondrites, based on the bulk chemical analyses, are found in McSween et al. [12].

Reflectance spectra at room temperature were obtained on the powders using the bidirectional spectrometer at RELAB. The incident angle was 30 degrees and the emission angle was 0 degrees. The spectral coverage was 0.32 to 2.55 μm with a sampling interval of 0.01 μm. Almost all samples were also measured out to 26 μm using a Fourier transform infrared (FTIR) spectrometer. Selection of the powders for spectral analysis was done after visually examining each sample to check for possible weathering effects.

Results: Reflectance spectra and the olivine and pyroxene mineralogies for the ~70 meteorites are currently being compiled. To determine the Band I center, a linear continuum tangent to Band I is first divided out. We have now measured the band areas and band centers of 18 meteorite powders. We are currently estimating error bars for the calculated values. Their values are plotted on a Band Area Ratio plot (Figure 1) with the olivine, ordinary chondrite, and basaltic achondrite regions defined by Gaffey et al. [5]. The average band area and band center for 433 Eros determined by NEAR-Shoemaker [6] are also plotted.

An interesting preliminary result is that the new ordinary chondrite measurements fall in the lower range of the ordinary chondrite region defined by Gaffey et al. [5]. This offset is due to the calculated Band I centers tending to be at lower wavelengths than those calculated by Gaffey et al. [5] for similar types of ordinary chondrites. Measurements of all the ordinary chondrite powders should determine if this offset is real. It is important to determine the cause of this offset since 433 Eros does not yet plot in the region defined by the first measurements of these new ordinary chondrite powders.

One possibility for this offset is the almost complete removal of metallic iron from the measured powders. Moroz and Arnold [13] have found that addition of opaques (e.g., pyrrhotite) to an olivine-orthopyroxene mixture tends to move the Band I center to longer wavelengths. We are currently planning on re-mixing the metallic iron with the fine-powdered fraction to determine if the Band I center changes with the addition of metallic iron.

Another possibility is that the wavelength calibration correction of 0.025 _m that is used [14,15] on the Gaffey [4] meteorite data is too large. This correction is done because of a later-discovered wavelength offset found between the spectra taken by the spectrometer that measured the Gaffey [4] meteorites and more recent spectra. By comparing spectra of an Apollo soil sample taken by the Gaffey [4] spectrometer and the RELAB spectrometer, Pieters and Pratt [16] found that a non-linear wavelength correction, which has an offset of +0.015 _m at a wavelength of 0.92 _m, was better. We are planning on measuring a number of ordinary chondrites also measured by Gaffey [4] to determine which wavelength calibration is better.

Of the meteorites measured, two of the most interesting mineralogically are the ungrouped chondrite Burnwell [17] and the R-chondrite Rumuruti [18]. Burnwell is more reduced than H chondrites with olivine compositions of Fa$_{15.8\pm0.2}$ and pyroxene compositions of Fs$_{13.4\pm0.7}$. Burnwell plots amongst the H chondrites in the Band Area Ratio plot (Figure 1). Rumuruti is an oxidized (~Fa$_{39}$), olivine-rich, metal-poor chondrite. As expected, Rumuruti plots within the olivine region (Figure 1).

A preliminary fit (Figure 2) using MGM was also done on LL6 chondrite Bandong. The model requires olivine and two pyroxenes (a low-calcium and a high-calcium). Inferred modal abundances derived from this model are withing 10% of those derived from normative calculations. These results are consistent with those of McFadden et al. [6] where both low- and high-Ca pyroxenes are needed to produce the Band I centers consistent with those of ordinary chondrites.

Conclusions: We are re-examing the regions defined by different meteorite classes in Band Area Ratio plots. These data will allow us to better determine the compositions of asteroids from remote sensing.

References: [1] Trombka J. I. et al. (2000) *Science, 289,* 2101-2105. [2] Veverka J. et al. (2000) *Science, 289,* 2088-2097. [3] Jarosewich E. (1990) *Meteoritics, 25,* 323-337. [4] Gaffey M. J. (1976) *JGR, 81,* 905-920. [5] Gaffey M. J. et al. (1993) *Icarus, 106,* 573-602. [6] McFadden L. A. et al. (2001) *Meteoritics & Planetary Science, 36,* 1711-1726. [7] Burbine T. H. et al. (2001) *LPSC, XXXII,* #1860. [8] Burbine T. H. et al. (2001) *Meteoritics & Planetary Science, 36,* 761-781. [9] Burbine T. H. et al. (2001) *LPSC, XXXII,* #1857. [10] Sunshine J. M. and Pieters C. M. (1993) *JGR, 98,* 9075-908 [11] Sunshine et al. (2002) *LPSC, XXXIII* this volume. [12] McSween H. Y. Jr. et al. (1991) *Icarus, 90,* 107-116. [13] Moroz L. and Arnold G. (1999) *JGR, 104,* 14109-14121. [14] Gaffey M. J. (1984) *Icarus, 60,* 83-114. [15] Gaffey M. J. and Gilbert S. L. (1998) *Meteoritics & Planetary Science, 33,* 1281-1296. [16] Pieters C. M. and Pratt S. F. (2001) personal communication. [17] Russell S. S. et al. (1998) *Meteoritics & Planetary Science, 33,* 853-856. [18] Schulze H. et al. (1994) *Meteoritics, 33,* 275-286.

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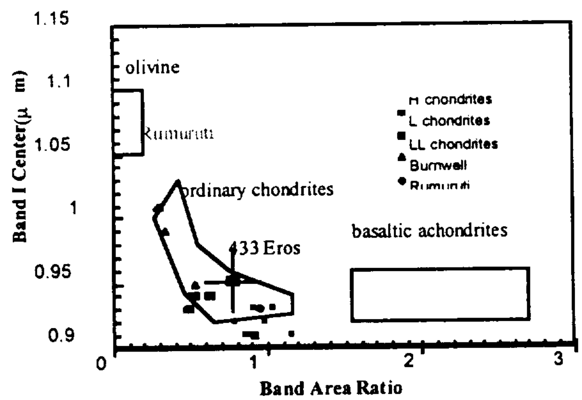

Figure 1. Plot of Band Area Ratios versus Band I Centers.

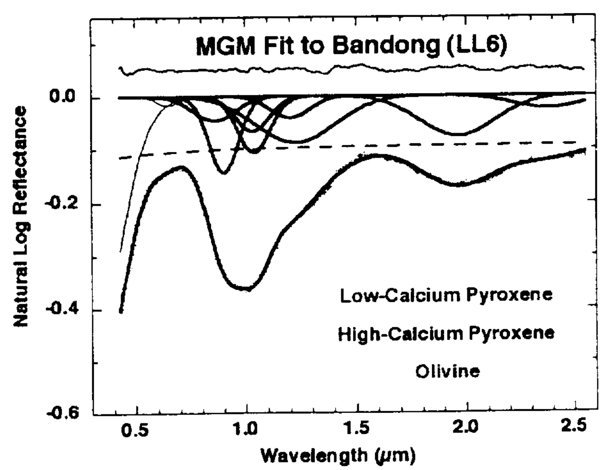

Figure 2. MGM fit to LL6 chondrite Bandong.