-~ ~ ~ ~ , ~, /N / ~~

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

J. M. Sunshine[1], S. J. Bus[2], T. H. Burbine[3], T. J. McCoy[3], and R. P. Binzel[4]. [1]Science Applications International Corporation, Suite 400, 4051 Daly Dr., Chantilly, VA 20151 (sunshinej@saic.com), [2]University of Hawaii, Institute for Astronomy, Hilo, HI 96720, [3]Department of Mineral Sciences, National Museum of Natural History, Smithsonian Institution, Washington, DC 20560, [4]Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139.

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.

Acknowledgements: Support for this research from NASA's PGG program (NASW-00012 to J.M.S.) is greatly appreciated. All meteorite spectra were collected at Brown University's Keck/NASA Reflectance Experiment Laboratory (RELAB), a multi-user facility supported by NASA (NAG5-3871).

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

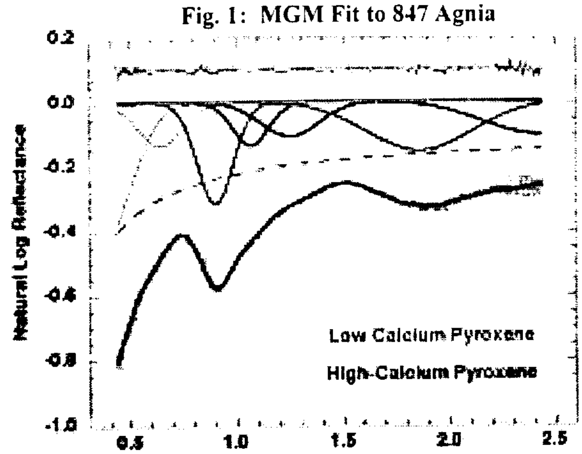

Fig. 2: MGM Fit to 17 Thetis

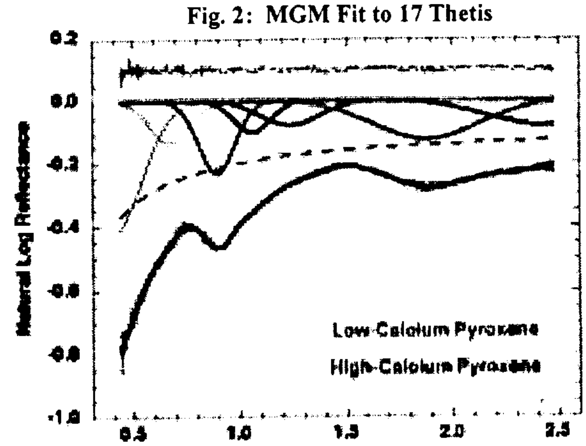

Fig. 3: MGM Fit to Bouvante Eucrite