Antarct. Meteorite Res., **16**, 185–195, 2003

Deriving asteroid mineralogies from reflectance spectra: Implications for the MUSES-C target asteroid

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Abstract: In an effort to both bolster the spectral database on ordinary chondrites and constrain our ability to deconvolve modal, mineral chemistry and bulk chemical composition information from ordinary chondrites, we have initiated a spectral study of samples with known bulk compositions from the Smithsonian Institution's Analyzed Meteorite Powder collection. In this paper, we focus on deriving a better formula for determining asteroid mineralogies from reflectance spectra. The MUSES-C mission to asteroid 25143 1998 SF36 will allow any derived mineralogies to be tested with a returned sample.

key words: Asteroids, space missions, ordinary chondrites, asteroid mineralogies, reflectance spectra

1. Introduction

One of the goals of asteroid spectroscopy is to determine asteroid compositions from reflectance spectra. Determining asteroid mineralogies is important for a variety of reasons. Scientifically, it allows for an understanding of compositional and thermal gradients in the solar nebula by knowing the orbital locations of objects with different chemical and isotopic compositions. Financially, many iron-rich asteroids could be very important resources for elements relatively rare on the Earth's surface such as precious metals (Kargel, 1994). For the preservation of the human race, an asteroid on a collision course with Earth may have to be diverted or destroyed and it is vital to know the object's composition when formulating scenarios for keeping the approaching body from hitting the Earth.

A number of minerals widely found in meteorites can be identified by their diagnostic spectral properties. Among these, olivine and pyroxene are major components of most meteorites and, thus, a variety of spectral parameters have been developed to determine the relative abundances of these two minerals and their respective compositions. Olivine has three absorption bands that make up its feature centered near 1 μm. Pyroxenes tend to have features centered near 0.9 (Band I) and 1.9 μm (Band II), although some high-Ca (or calcic) pyroxenes (Adams, 1975; Cloutis and Gaffey, 1991) lack a distinctive ~2 μm feature (Band II). The ~1 and ~2 μm features in pyroxenes tend to move to longer wavelengths with increasing Fe and/or Ca-contents. For example, pigeonite tends to have similar spectral properties to orthopyroxene except that the pigeonite band centers tend to be at longer wavelengths (*e.g.,* Burns, 1993).

All of these features can be readily observed in the spectra of various meteorites (Fig. 1). The highly oxidized R-chondrite Rumuruti is dominated by FeO-rich olivine and, not surprisingly, its overall spectrum is dominated by an olivine feature. In contrast, Acapulco (the first recognized acapulcoite) is relatively reduced and orthopyroxene dominates its modal mineralogy. This is reflected in the strong ~1 and ~2 μm bands that dominate its spectrum. Ordinary chondrites (H, L, and LL) are mixtures of olivine and pyroxene and can be seen to have spectral features due to both minerals. The angrite D'Orbigny contains both olivine and a Ti-rich calcic pyroxene unofficially termed fassaite. Despite containing significant amounts of pyroxene, its spectrum lacks a distinctive ~2 μm feature (Burbine *et al.,* 2001).

During the past 20 years, considerably effort has been devoted to determining quantitatively the mafic mineral abundances of asteroids from analyses of the relative strengths of the ~1 and ~2 μm bands. While this information is often depicted graphically (*e.g.,* band area ratio (Band II area/Band I area) *vs.* Band I center) (Gaffey *et al.,* 1993), linear regressions have been developed that relate band area ratio to the relative abundances of olivine and pyroxene. The area of a band is the area between the absorption band and a tangent line drawn between two peaks on either side of the

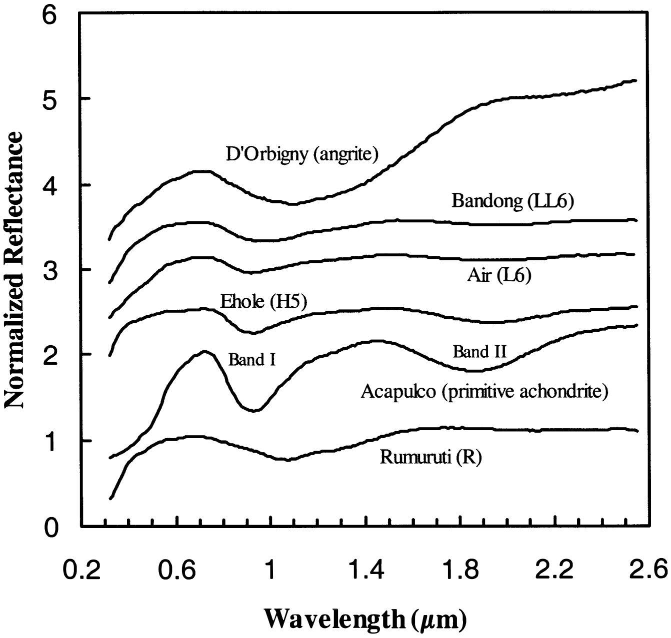

Fig. 1. Reflectance spectra of a number of meteorite types. Meteorites are normalized to unity at 0.55 μm and offset in reflectance. From top to bottom, the meteorites are Rumuruti (R), Acapulco (acapulcoite) (offset by 0.5 from spectrum beneath it), Ehole (H5) (offset by 1.0), Air (L6) (offset by 0.5), Bandong (LL6) (offset by 0.5), and D'Orbigny (angrite) (offset by 0.5). Grain sizes for Rumuruti, Ehole Air, and Bandong are less than 150 μm. Grain sizes for Acapulco and D'Orbigny are less than 125 μm.

band (*e.g.,* Cloutis *et al.,* 1986). Dividing the area of Band II by the area of Band I produces the band area ratio (BAR). The calculated band area ratio is not a function of the albedo of the sample since any albedo information is lost during the division of the areas.

Cloutis *et al.* (1986) were the first to find that the ratio of pyroxene to olivine plus pyroxene (pyx/(ol+pyx)) was a linear function of the band area ratio for mixtures of olivine to orthopyroxene (opx). The spectrum of a sample of olivine would have a band area ratio of ~0 while a spectrum of orthopyroxene would have a band area ratio of ~2. The formula that Cloutis *et al.* (1986) derived is

$$\mathrm{BAR} = 0.024 \times (\mathrm{pyx}/(\mathrm{ol}+\mathrm{pyx})) - 0.125,$$

where pyx/(ol+pyx) is expressed as a percentage. Gastineau-Lyons *et al.* (2002) expressed this formulation as

$$\mathrm{pyx}/(\mathrm{ol}+\mathrm{pyx}) = 0.417 \times \mathrm{BAR} + 0.052,$$

where pyx/(ol+pyx) is expressed as a decimal. This equation can also be expressed as $\mathrm{ol}/(\mathrm{ol}+\mathrm{pyx}) = -0.417 \times \mathrm{BAR} + 0.948$. The expression of Gastineau-Lyons *et al.* (2002) differs only in that it utilizes the band area ratio of a meteorite or asteroid of unknown modal mineralogy to derive that mineralogy, while Cloutis *et al.* (1986) was primarily interested in determining theoretical band area ratios from mineral mixtures of known proportions. The Gastineau-Lyons *et al.* (2002) formula was used by McFadden *et al.* (2001) to derive the ratio of pyroxene to olivine on 433 Eros.

Our work was motivated by two factors. First, it became clear that the number of ordinary chondrite falls measured spectrally was far below the number available for analyses. Secondly, we wanted to see if information other than relative mafic mineralogy could be derived from spectra. Specifically, can we derive mineral compositions and/or bulk chemical compositional information from the spectra. In this paper, we address only the first of these topics—deriving improved relationships between spectra and mafic mineralogy from an expanded spectral database of, primarily, ordinary chondrites. We discuss the implications of this work for asteroid spectroscopy in general and the MUSES-C mission specifically.

2. Data

We have initiated a spectral study of meteorites with known bulk compositions, almost all sampled from the Smithsonian Institution's Analyzed Meteorite Powder Collection (USNM 7073). These powders were prepared and analyzed, primarily by one of us (EJ), over the course of ~30 years as part of a systematic effort to collect the highest-quality data on the bulk composition of meteorites (Jarosewich, 1990). These samples were analyzed for oxides of major and minor elements (*e.g.,* Si, Mg, Ca, Na), elements bound in metal and sulfides (*e.g.,* Ni, Co, S), water, and carbon using wet chemistry.

Meteorite samples (except Acapulco, Allegan, and D'Orbigny) are from the Smithsonian Institution's Analyzed Meteorite Powder Collection. When originally prepared for chemical analyses, these samples were ground in an agate mortar in a hood with positive air pressure to prevent contamination. The samples were then typically sieved to pass through a 100 mesh ($<150\,\mu$m) nylon sieve. A few samples were sieved to pass through a 200 mesh ($<75\,\mu$m) sieve. The fine-powdered fraction ($<150\,\mu$m) consisted of silicates and sulfides and contained up to 0.4 wt% of fine-grained metal. The fraction larger than 100 mesh ($>150\,\mu$m) was primarily metal. In this work, we analyzed only the fine-grained fraction dominated by silicates. The effect of the exclusion of metal on the spectra is not completely understood, but we see no reason to believe it would effect the derived olivine:pyroxene ratio.

Acapulco and D'Orbigny were ground in an agate mortar and sieved to grain sizes less than $125\,\mu$m. The Acapulco sample is also depleted in metal due to the problems of grinding metallic iron. One sample (Allegan) was not sieved, but was shaken until it was disaggregated into a fine powder. No metallic iron was removed from this sample. Measurement of metal-free and metal-bearing Allegan samples should provide additional insights into the effect of excluding metal from the majority of our spectral samples.

Reflectance spectra were obtained using the bidirectional spectrometer at Brown University's Keck/NASA Reflectance Experiment Laboratory (RELAB). Representative spectra are shown in Fig. 1. The spectral coverage was 0.32 to $2.55\,\mu$m with a sampling interval of $0.01\,\mu$m. The incident angle was 30° and the emission angle was 0°. A few meteorite powders sent to RELAB had very noisy spectra and/or anomalous spectral properties. These meteorites were not included in this analysis and will have their spectra remeasured.

Band area ratios and band centers were determined from the spectra. We used the trapezoidal rule to determine the band areas. By looking at how the band area ratios changed as the far wavelength peak (at ~$2.55\,\mu$m) was chosen, the average uncertainty in the calculated band area ratios were estimated to be ± 0.03. The band center is the band minimum determined after a linear continuum has been divided out of the spectrum. The linear continuum was divided out over a range that encompassed the peak at ~$0.7\,\mu$m (between the ultraviolet or UV feature and Band I) and the peak at ~$1.5\,\mu$m (between Band I and Band II). After the continuum had been divided out, we then chose the lowest point as the band center. We estimate the uncertainty in the calculated band center as $\pm 0.01\,\mu$m, the resolution of the spectra.

CIPW norms (*e.g.,* Raymond, 1995) were used to calculate olivine, hypersthene (orthopyroxene), and diopside (a high-Ca pyroxene) abundances from bulk compositions. We recognize that Gastineau-Lyons *et al.* (2002) found a systematic offset between modal and normative ol/(ol+pyx) ratios, probably reflecting the inability of the CIPW norm to account for a Si-rich mesostasis glass phase. All bulk compositional data are from Jarosewich (1990) except for Acapulco (Yanai and Kojima, 1991), Burnwell (Russell *et al.,* 1998), D'Orbigny (Mittlefehldt *et al.,* 2002), Forest Vale (Noonan *et al.,* 1972), Magombedze (Jarosewich, personal communication), and Rumuruti (Jarosewich, personal communication). Acapulco is an acapulcoite (a type of primitive achondrite), Burnwell is an anomalous chondrite (Russell *et al.,* 1998) with fayalite and ferrosilite compositions slightly lower than H chondrites, D'Orbigny is an angrite (*e.g.,* Mittlefehldt *et al.,* 2002), Forest Vale is an H4 chondrite, Magombedze is an H5 chondrite, and Rumuruti is an R chondrite.

Table 1. Meteorites measured in this study.

Meteorite	Type	RELAB ID	Grain size	ol/(ol+pyx)# (norm)	ol/(ol+opx)# (norm)	BAR±	Band Center
Acapulco*	acapulcoite	TB-TJM-043	<125μm	0.52	0.55	0.99	0.93
Aïr	L6	TB-TJM-063	<150μm	0.63	0.67	0.49	0.93
Allegan*	H5	TB-TJM-104	none measured	0.49	0.52	1.08	0.91
Andura	H6	TB-TJM-088	<75μm	0.61	0.67	0.98	0.93
Apt	L6	TB-TJM-064	<150μm	0.67	0.72	0.51	0.94
Aumale	L6	TB-TJM-101	<150μm	0.60	0.64	0.67	0.94
Avanhandava	H4	TB-TJM-066	<150μm	0.52	0.55	0.97	0.92
Bandong	LL6	TB-TJM-067	<150μm	0.73	0.78	0.29	1.01
Burnwell	anom. chondrite	TB-TJM-068	<150μm	0.54	0.57	0.95	0.93
Butsura	H6	TB-TJM-069	<150μm	0.54	0.59	0.78	0.92
Chantonnay	L6	TB-TJM-070	<150μm	0.70	0.74	0.53	0.94
Chela	H5	TB-TJM-071	<150μm	0.53	0.56	1.15	0.91
Denver	L6	TB-TJM-072	<150μm	0.61	0.65	0.63	0.94
D'Orbigny*	angrite	TB-TJM-062	<125μm	0.65	1.00	0.03	1.22
Dwaleni	H6	TB-TJM-072	<150μm	0.54	0.58	0.91	0.93
Ehole	H5	TB-TJM-074	<150μm	0.56	0.60	1.03	0.93
Forest Vale	H4	TB-TJM-093	<75μm	0.45	0.48	0.92	0.94
Girgenti	L6	TB-TJM-103	<150μm	0.63	0.67	0.59	0.94
Greenwell Springs	LL4	TB-TJM-075	<150μm	0.66	0.71	0.53	0.95
Guareña	H6	TB-TJM-094	<150μm	0.55	0.59	0.78	0.93
Hallingeberg	L3	TB-TJM-076	<150μm	0.60	0.66	0.62	0.94
Honolulu	L5	TB-TJM-096	<150μm	0.66	0.71	0.60	0.93
Itapicuru-Mirim	H5	TB-TJM-097	<150μm	0.51	0.54	0.97	0.93
Karatu	LL6	TB-TJM-077	<75μm	0.72	0.77	0.34	0.99
Kuttippuram	L6	TB-TJM-098	<75μm	0.65	0.72	0.64	0.93
La Criolla	L6	TB-TJM-100	<150μm	0.66	0.72	0.56	0.91
Mabwe-Khoywa	L5	TB-TJM-107	<150μm	0.61	0.65	0.78	0.92
Magombedze	H5	TB-TJM-108	<150μm	0.56	0.60	0.91	0.93
Malakal	L5	TB-TJM-109	<150μm	0.61	0.65	0.83	0.93
Marilia	H4	TB-TJM-078	<150μm	0.50	0.54	0.87	0.91
Messina	L5	TB-TJM-099	<150μm	0.61	0.65	0.68	0.93
Mezö-Madaras	L3.7	TB-TJM-079	<75μm	0.61	0.67	0.91	0.91
Mirzapur	L5	TB-TJM-111	<150μm	0.61	0.65	1.00	0.92
Nejo	L6	TB-TJM-112	<150μm	0.59	0.63	0.61	0.94
Patrimonio	L6	TB-TJM-113	<150μm	0.62	0.66	0.71	0.94
Rio Negro	L4	TB-TJM-081	<150μm	0.60	0.63	1.00	0.92
Rumuruti	R	MT-TJM-013	<150μm	0.94	1.00	0.07	1.10
São Jose do Rio Preto	H4	TB-TJM-082	<150μm	0.55	0.58	1.09	0.91
Schenectady	H4	TB-TJM-083	<150μm	0.60	0.63	0.84	0.92
Tuan Tuc	L6	TB-TJM-084	<150μm	0.59	0.63	0.72	0.94
Uberaba	H5	TB-TJM-085	<150μm	0.57	0.60	0.93	0.93
Valdinizza	L6	TB-TJM-087	<150μm	0.62	0.66	0.61	0.94
Vouillé	L6	TB-TJM-086	<150μm	0.56	0.60	0.61	0.93

* Samples not from the Smithsonian Analyzed Meteorite Powder Collection. The Allegan sample has not been sieved.

#All ol/(ol+pyx) (norm) and ol/(ol+opx) (norm) ratios are calculated from bulk compositional data using mineral abundances (weight percents) determined from a CIPW norm (http://www.union.edu/PUBLIC/GEODEPT/COURSES/petrology/norms.htm). The calculated mineral abundances are very similar to abundances previously determined for ordinary chondrites (McSween *et al.,* 1991) and D'Orbigny (Mittlefehldt *et al.,* 2002) using CIPW norms.

±BAR is the band area ratio.

The published bulk FeO value (Jarosewich, 1990) for Forest Vale appears too low (5.84 wt%) compared to bulk FeO values for other relatively unweathered H chondrites (8.76–14.53 wt%) and FeO values determined from electron microprobe analyses of Forest Vale's olivine and pyroxene. Jarosewich (personal communication) believes there may have been a sampling problem with this meteorite. We use the FeO value (8.61 wt%) calculated by Noonan *et al.* (1972) using microprobe analyses of the olivine and pyroxene and modal abundances of these minerals.

All bulk compositions were determined from wet chemistry except for D'Orbigny, whose bulk composition was determined by fused-bead, electron microprobe analysis (Mittlefehldt *et al.,* 2002). Except for Acapulco, Allegan, and D'Orbigny, the sample used for determining the bulk composition and the sample measured for reflectance spectra were taken from the same material.

For each meteorite, we calculated (Table 1) the ratio of olivine (ol) to olivine plus pyroxene (pyx). Using the uncertainties of the oxide values (*e.g.,* 0.20% for SiO_2; 0.05% for Al_2O_3; 0.25% for FeO; 0.10% for MgO) (Jarosewich, 1990), we estimate the average statistical uncertainty of the ol/(ol+pyx) ratio as 0.01. The pyroxene component contains orthopyroxene, pigeonite, and diopside since these minerals would be expected to contribute to the 1 and 2 μm features. We also give the ratio of olivine to olivine plus orthopyroxene to show that each meteorite (except for D'Orbigny) contains roughly similar percentages of orthopyroxene.

3. Results

As expected (Cloutis *et al.,* 1986), the band area ratios (BAR) for the ordinary chondrites (plus the unusual chondrite Burnwell and the primitive achondrite Acapulco) correlate very well with the normative weight ratio of olivine to pyroxene. These meteorites have ol/(ol+pyx) ratios between ~0.50 and ~0.70. D'Orbigny (angrite) and Rumuruti (R chondrite) do not fall along this trend. Both D'Orbigny and Rumuruti have band area ratios approaching zero; however, they have very different mineralogies. D'Orbigny has an ol/(ol+pyx) of 0.65 and contains negligible orthopyroxene while Rumuruti is dominated by olivine (ol/(ol+pyx)=0.94) and contains negligible orthopyroxene.

A least-squares fit to the data (excluding D'Orbigny and Rumuruti) (Fig. 2) gives

$$\mathrm{ol}/(\mathrm{ol}+\mathrm{pyx}) = -0.228 \times \mathrm{BAR} + 0.768,$$

with an r^2 of 0.932. We note that excluding two LL chondrites with band area ratios of ~0.3, which are slightly offset from the H and L chondrites, yields a very similar best fit with slope of 0.207 and y-intercept of 0.750. Average uncertainties for the calculated ol/(ol+pyx) ratios are ±0.03. This uncertainty was derived by comparing the normative ol/(ol+pyx) ratio for each meteorite sample with the ol/(ol+pyx) ratio derived from its band area ratio for the 41 meteorites samples used in deriving the equation. This equation is dramatically different in slope than the equation derived by Cloutis *et al.* (1986). Their equation is

$$\mathrm{ol}/(\mathrm{ol}+\mathrm{pyx}) = -0.417 \times \mathrm{BAR} + 0.948.$$

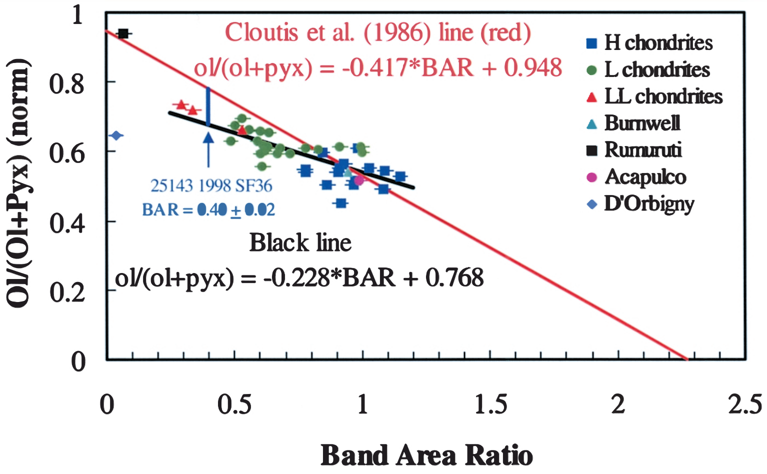

Fig. 2. Plot of band area ratio versus normative ol/(ol+pyx) ratio for the measured meteorites. The black line is the fit to the data for the meteorites measured in this study (excluding the angrite D'Orbigny and the R-chondrite Rumuruti). The red line is derived from an equation in Cloutis et al. (1986). Estimated errors bars (±0.03) for the band area ratios are plotted for each of the meteorites. The estimated error bar (±0.01) for the ol/(ol+pyx) ratio is smaller than the data points. The blue line shows the difference in the estimated ol/(ol+pyx) ratio for the Muses-C target asteroid 25143 1998 SF36, which has a BAR of 0.40±0.02 (Binzel et al., 2001), when using the equation derived in this paper and the Cloutis et al. (1986) equation.

This equation has a much steeper slope than our derived equation.

The deviation between our equation and that of Cloutis *et al.* (1986) is significant. Gastineau-Lyons *et al.* (2002) previously noted a similar deviation between predicted and modal mineralogies. There are a number of possible explanations for this discrepancy. Gastineau-Lyons *et al.* (2002) believed that the discrepancy results from the fact that the ordinary chondrites contain a high-Ca pyroxene component such as diopside, which has different spectral properties than the orthopyroxene used by Cloutis *et al.* (1986). The mixtures used by Cloutis *et al.* (1986) were all sieved to particular size ranges and did not contain any grains smaller than 38 μm. The samples used in this study did contain very fine-grained material since they were sieved to just be smaller than a particular size range. Ueda *et al.* (2002) has shown that olivine-dominated mixtures with very-fine grain sizes (<45 μm) have smaller band area ratios than those of coarser mixtures (45–70 μm).

Also, the regression line of Cloutis *et al.* (1986) was calculated for olivine-orthopyroxene mixtures ranging from 10% olivine and 90% orthopyroxene to 90% olivine and 10% orthopyroxene, while our formulation is for a much more restricted range of compositions. With this in mind, it is worth considering when our formulation might be better applied. Our equation appears valid for silicate mineralogies similar to ordinary chondrites. The silicate mineralogies of ordinary chondrites are composed of olivine, pyroxene, and feldspar. Ordinary chondrites contain ~30–60 wt% olivine. The pyroxene component is dominated by orthopyroxene (~15–30 wt%), but ordinary chondrites do contain a small amount (~3–6 wt%) of pyroxenes (diopside and pigeonite) with higher calcium contents. Plagioclase feldspar would not be expected to contribute significantly to the spectral properties of ordinary chondrites. The spectra effects of feldspar are only seen in mixtures dominated by plagioclase (Crown and Pieters, 1987). The amount of plagioclase feldspar in ordinary chondrites is only ~8 wt%.

This equation also appears valid for other meteorites mineralogically similar to ordinary chondrites, specifically those with ol/(ol+pyx) ratios between ~0.5 and ~0.7. Both the primitive achondrite Acapulco and the anomalous chondrite Burnwell fall very near the derived line in Fig. 2. Both these meteorites contain silicate mineralogies of olivine and pyroxene (mainly orthopyroxene but with some high-Ca pyroxene), and plagioclase feldspar.

Our equation does not appear valid for meteorites dominated by olivine (such as the R chondrite Rumuruti). The y-intercept (BAR=0) for our equation is 0.768. An assemblage that is composed almost entirely of olivine would have a BAR of approximately 0 and would have an ol/(ol+pyx) ratio of approximately 1. The Cloutis *et al.* (1986) (y-intercept of 0.948) appears to be a better predictor of the ol/(ol+pyx) ratio for assemblages dominated by olivine. Likewise, our equation appears invalid for angrites. The D'Orbigny angrite falls far from the defined line, owing to its unusual pyroxene composition and the lack of a spectral 2 μm feature. Further work must be done to see how our equation holds for HEDs (howardites, eucrites, diogenites) and ureilites.

McFadden *et al.* (2001) used the Cloutis *et al.* (1986) formula for predicting the mineralogy of 433 Eros. Eros has a Band Area Ratio of 0.77 ± 0.18, which is near the intersection point of our equation and the Cloutis *et al.* (1986) equation. Since the value for Eros is near the intersection point, there is little difference in the ol/(ol+pyx) ratio determined by the two equations. Our ol/(ol+pyx) ratio for Eros is 0.59 ± 0.04. Interestingly, Eros has a band area ratio intermediate between the H and L chondrites.

4. Caveats

There are a number of caveats that need to be noted when deriving compositional information from an asteroid. Meteorite reflectance spectra are measured at room temperature; however, main-belt asteroids tend to have much lower surface temperatures (~150–200 K) (Hinrichs *et al.,* 1999). Moroz *et al.* (2000) has shown that there are slight changes in the band area ratio for ordinary chondrite samples with decreasing temperature.

It is unclear how alteration of the surface (usually called "space weathering") affects the band area ratio. Irradiation experiments by Yamada *et al.* (1999) using a pulse laser to simulate the effects of micrometeorite impacts suggest that olivine is more readily spectrally altered than pyroxene. However, the production of nanophase iron (*e.g.,* Sasaki *et al.,* 2001; Kurahashi and Sasaki, 2002), which darkens the surface and reddens the bands, through micrometeorite impacts may coat both olivine and pyroxene grains in olivine-pyroxene mixtures and could affect both types of material somewhat equally. Hiroi and Sasaki (2001) have shown that the band area ratios of monomineralogic assemblages do not noticeably change during laser alteration.

Some asteroids with band area ratios consistent with olivine-pyroxene assemblages may have vastly different mineralogies. Sunshine *et al.* (2002) have identified a number of objects with band area ratios that fall within the range of ordinary chondrites, but have spectral features due to orthopyroxene and high-Ca pyroxene and appear to contain little olivine.

5. MUSES-C target asteroid

The target asteroid for the MUSES-C mission is S-class asteroid 25143 1998 SF36. MUSES-C will briefly touch down on the surface of 1998 SF36 2-3 times and fire a projectile into the surface each time (Fujiwara, 1999; Zolensky, 2000). It will collect the sample in horn-shaped receptacle.

The ground-based spectrum of 1998 SF36 (Binzel *et al.,* 2001) has a band area ratio of 0.40±0.02. It is within this range of band area ratios (~0.2–0.5) that our derived equation differs significantly from that of Cloutis *et al.* (1986). We would infer an ol/(ol+pyx) ratio of 0.68±0.01, while Cloutis *et al.* (1986) would favor a ratio of 0.78 ±0.01. Our favored mafic mineralogy is found in both L and LL chondrites; however, the Band I center (0.99±0.01 μm) for this object is consistent (Binzel *et al.,* 2001) with LL chondrites. Visually, 1998 SF36 looks like an LL chondrite that has been reddened (Fig. 3). (Reddening refers to the reflectance increasing with increasing wavelength.)

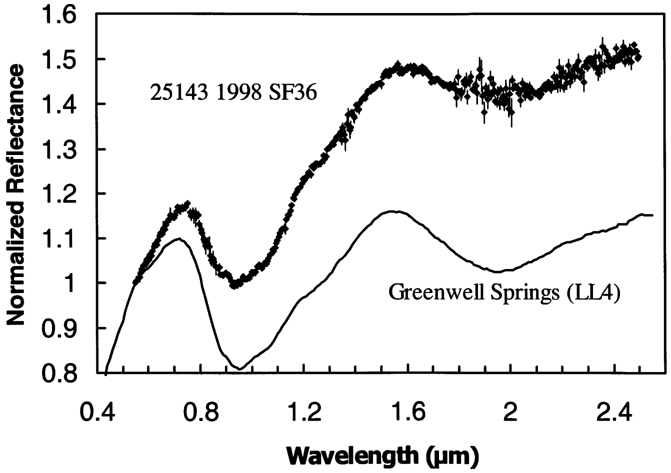

Fig. 3. Reflectance spectra of 25143 1998 SF36 (Binzel et al., 2001) versus Greenwell Springs (LL4). Asteroid 1998 SF36 looks like a reddened LL chondrite.

6. Conclusions

In the near-future, only a few asteroids will have samples returned to Earth. So to determine the surface compositions of asteroids, methods for determining asteroid mineralogies must be derived from ground-based observations. Reflectance spectroscopy appears to be the best way of determining the abundances of olivine and pyroxene on the surfaces of asteroids.

The derived equation ($ol/(ol+pyx) = -0.228 \times BAR + 0.768$) for determining the $ol/(ol+pyx)$ ratio from the band area ratio appears valid for mafic mineralogies roughly similar to those found in ordinary chondrites and should be useful for estimating the mineralogies of chondritic and primitive achondritic assemblages. This equation appears to better estimate the mineralogy of meteorites than the equation derived by Cloutis *et al.* (1986) and should, therefore, work better on asteroids. The sample return mission to MUSES-C will allow us to test how well we can determine asteroid mineralogies from reflectance spectra. From our derived equation, we predict that the returned sample will have an $ol/(ol+pyx)$ ratio of approximately 0.68.

Our future work includes measuring more meteorite spectra (particularly LL chondrites and primitive achondrites) to refine our equation for determining $ol/(ol+pyx)$ ratios. We plan on probing thin sections of each of the meteorites that had their spectra measured to see how well spectral parameters (*e.g.,* band minima) are functions of mineral chemistry.

Acknowledgments

This work was supported in part by NASA grants NAG5-9777 (TJM) and NASW-00012 (JMS). A Smithsonian Postdoctoral Fellowship was awarded to the first author (THB) to work on possible compositional and spectral analogs to the Muses-C target asteroid. Brown University's Keck/NASA Reflectance Experiment Laboratory (RELAB) is a multi-user facility supported by NASA grant NAG5-3871. The authors thank Takahiro Hiroi and Sho Sasaki for very thoughtful reviews that greatly improved the manuscript. We would also like to thank Takahiro Hiroi for running the samples at RELAB. We would like to thank Gero Kurat for the D'Orbigny sample.

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(Received July 31, 2002; Revised manuscript accepted January 27, 2003)