MINERALOGIES OF NEAR EARTH ASTEROIDS.

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Introduction: Approximately 8,000 near-Earth asteroids (NEAs), bodies with orbits that cross or come close to Earth's orbit, have been discovered to date. One way of studying NEAs is by measuring their reflectance spectra, which allows their mineralogies to be estimated due to the characteristic olivine and pyroxene absorption bands in the visible and near-infrared (out to ~2.5 µm). However, one problem with using spectral parameters (band area ratio and band center) to determine mineralogies of NEAs is that formulas used previously for deriving pyroxene compositions [1] do not appear to work very well for ordinary chondrite assemblages [2,3]. The [1] formulas tend to calculate pyroxene mineralogies that are more Fe-rich than expected for the low-Ca pyroxenes that dominate the mineralogies of ordinary chondrites. This effect seems to be due to the fact that ordinary chondrites actually contain three pyroxenes, not two.

This problem leads to extreme caution when using [1] on NEA spectra. For example, the use of the [1] on the ground-based reflectance spectrum of 25143 Itokawa, the target of the Hayabusa sample-return mission, led to the interpretation by [4] that Itokawa experienced partial melting, due to the derived high-Fe content of the pyroxenes. In contrast, most other researchers argued that Itokawa had a composition similar to ordinary chondrites (L or LL) [e.g 5-7]. This has been confirmed by returned samples of Itokawa, which have mineralogies similar to LL chondrites [8].

To better determine the mineralogy of ordinary chondrite-like assemblages using reflectance spectra, [9] mineralogically and spectrally characterized 48 ordinary chondrites powders (prepared by [10]) and used these samples to derive new formulas for determining mineralogies from VIS/NIR spectra. The derived formulas (with the corresponding R^2, the coefficient of determination) for determining the mineralogies of ordinary chondrite assemblages are:

*ol/(ol+pyx) (±0.03) = 0.242*BAR +0.728* (R^2=0.73),

Fa (±1.3) (mol%) = -1284.9(Band I center)^2 +2656.5*(Band I center) -1342.3* (R^2=0.92), and

Fs (±1.4) (mol%) = -879.1(Band I center)^2 + 1824.9*(Band I center) – 921.7* (R^2=0.91).

Fa is fayalite content in olivine (in mol%) and Fs is ferrosilite content in low-Ca pyroxene (mol%).

Here we characterize the mineralogies of four NEAs with chondrite-like infrared spectra (433 Eros, 1626 Ivar, 1862 Apollo, and 4179 Toutatis) using [9]. This is preliminary data from a larger study of ~138 NEAs with SpeX spectra that appear visually similar to ordinary chondrites.

Methodology: Near earth asteroids were observed as part of the MIT-UH-IRTF Joint Campaign for NEO Reconnaissance (http://smass.mit.edu/minus.html) [11]. Near-infrared spectra of NEAs were obtained using SpeX, and full wavelength coverage (to ~2.5 µm) was achieved by combining SpeX data with visible spectra (0.4 – 1.1 µm) from SMASS (small-main-belt asteroid survey) [12-14] or Palomar [5]. Over 200 NEAs have been observed as part of this campaign with a considerable number of these bodies having near-infrared spectra that appear visually similar to ordinary chondrites.

The band area ratio (area of Band II/ area of Band I) of each NEA was calculated using the trapezoidal rule. Using this technique, the area of each band is determined by calculating the area under a straight line tangent to the two reflectance peaks and then subtracting the area under the curve. The band area ratio is then calculated by dividing the area of Band II by the area of Band I. The average band area ratios and the uncertainties were determined by randomly resampling each reflectance value 100 times using a Gaussian distribution for the given uncertainty. Average band area ratios and standard deviations are reported in Table 1.

Table 1. Measured band area ratios and derived ol/(ol+px)

Asteroid	sp	T (K)	BAR	Temperature correction	ol/(ol+px)
4179 Toutatis	74	263	0.486 ± 0.10	-0.026	0.62
4179 Toutatis	73	239	0.298 ± 0.14	-0.028	0.66
4179 Toutatis	30	259	0.859 ± 0.03	-0.051	0.53
1862 Apollo	47n2	265	0.300 ± 0.02	-0.015	0.66
1862 Apollo	47n1	266	0.226 ± 0.03	-0.011	0.68
1627 Ivar	88	176	0.296 ± 0.11	-0.055	0.67
1627 Ivar	76	196	0.404 ± 0.12	-0.064	0.65
1627 Ivar	74	216	0.245 ± 0.09	-0.032	0.68
1627 Ivar	73	228	0.213 ± 0.08	-0.024	0.68
433 Eros	102	230	0.637 ± 0.09	-0.069	0.59
433 Eros	101	221	0.278 ± 0.06	-0.034	0.67
433 Eros	103	238	0.553 ± 0.11	-0.053	0.61

The Band I center of each NEA was calculated using the method of [15], in which a linear slope derived from a straight line tangent to the two reflectance peaks on each side of each band is divided out, and then a second-degree polynomial is fit over the bottom third of the band. The average Band I centers and uncertainties will be determined by randomly resampling reflectance values using a Gaussian distribution for the given uncertainty; however, these calculations have not yet been completed. All Band I centers reported in Table 2 represent a single calculation. The uncertainties for the Band centers as expected to be similar to those determined by [16] for NEAs with HED-like spectra (±0.002-0.006).

Temperature Effects: Several studies have shown that band centers and band area ratios are influenced by changes in surface temperatures [e.g. 17-19]. Specifically, [19] found that band area ratios for olivine-pyroxene assemblages tend to decrease with decreasing temperature, while the direction of movement of the Band I center depends on the percentage of olivine in the sample.

Table 2. Measured band I centers and derived Fa content

Asteroid	sp	T (K)	BIC	Temperature correction	Fa
4179 Toutatis	74	263	0.975	0.000	26.3
4179 Toutatis	73	239	0.955	-0.002	22.4
4179 Toutatis	30	259	0.960	0.000	23.7
1862 Apollo	47n2	265	0.990	0.000	28.3
1862 Apollo	47n1	266	1.000	0.000	29.3
1627 Ivar	88	176	0.965	-0.007	23.5
1627 Ivar	76	196	0.965	-0.005	23.8
1627 Ivar	74	216	0.955	-0.004	22.1
1627 Ivar	73	228	0.980	-0.003	26.7
433 Eros	102	230	0.965	-0.003	24.2
433 Eros	101	221	0.985	-0.003	27.3
433 Eros	103	238	0.990	-0.002	28.1

To determine temperature corrections for each NEA, we first estimated the surface temperatures (T) (Kelvin) for all NEAs using the following equation:

$$T = [(1-A)L_o/16\eta\varepsilon\sigma\pi r^2]^{1/4}$$

where A is the asteroid albedo, L_o is the solar luminosity (3.84×10^{26} W), η is the beaming factor (assumed to be unity) [e.g. 20], ε is the asteroid's infrared emissivity (assumed to be 0.9), σ is the Stefan Boltzman constant (5.67×10^{-8} J s^{-1} m^{-2} K^{-4}), and r is the asteroid's distance from the Sun in meters. We assumed an average ordinary chondrite albedo of 0.20 [21], since most NEAs have not had their albedos measured, and r was calculated using the Minor Planet center website. We then used data from [19] to predict the shift in wavelength with decreasing temperature.

Results: We determined the band area ratios (BARs) and Band I centers of four NEAs, each of which with multiple observations. Band parameters and temperature corrections for each observation are provided in Tables 1 and 2, along with ol/(ol+px) ratios and Fa content (mol%), which were derived using the calibrations from [9]. The least root mean square of the errors on spectrally-derived values are 0.03 for ol/(ol+px) and 1.3 mol% for Fa [9]. Spectrally derived ol/(ol+px) and Fa content for each observation are plotted on Figure 1.

With the exception of 1627 Ivar, all NEAs have mineralogies consistent with ordinary chondrites. The mineralogy of 4170 Toutatis is similar to L or LL chondrites, while both 433 Eros and 1862 Apollo have LL chondrite mineralogies. Our mineralogy of 433 Eros is consistent with previous observations suggesting it has an ordinary chondrite-like composition [e.g. 22, 23], though it is not certain whether its mineralogy is best fitted by the H, L, or LL chondrites.

It is surprising that there is such a large variation in the spectral parameters for different observations, and it is unclear to what this ambiguity is attributed. This variation may suggest that that faint objects, such as many NEAs, are hard to definitively characterize mineralogically. However, it is also possible that these variations are the result of the inherent error involved in characterizing spectral parameters of asteroids. As we continue our study, will we focus on quantifying, and possibly mitigating, the error involved the methodology.

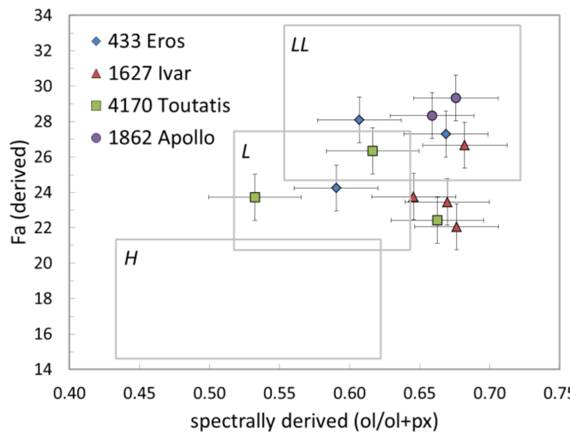

Figure 1. Spectrally derived ol/(ol+px) ratios and mol% Fa for each observation of Eros, Ivar, Toutatis, and Apollo plotted in terms of ordinary chondrite mineralogy as defined by [9].

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