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Pyroxene mineralogies of near-Earth vestoids

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Abstract–We have calculated pyroxene mineralogies of seven near-Earth asteroids (NEAs) with reflectance spectra similar to HEDs (howardites, eucrites, and diogenites). Two different sets of formulas (Gaffey et al. 2002; Burbine et al. 2007) are used to calculate the pyroxene mineralogies of the NEAs from their Band I and II centers. The band centers have been adjusted to compensate for the low temperatures on the asteroid surfaces. All of the derived mineralogies from the Gaffey et al. (2002) formulas and the Burbine et al. (2007) formulas overlap. The derived wollastonite (Wo) contents are very similar with differences being only approximately 1 mol%. The derived ferrosilite (Fs) contents differ by only 3 to 8 mol%. The determined pyroxene mineralogies for all seven near-Earth vestoids are consistent with eucrites or howardites. None of the objects have pyroxene mineralogies consistent with diogenites. The absence of near-Earth vestoids with pyroxene mineralogies similar to diogenites may indicate that it is difficult to produce sizeable (km-sized or larger) bodies that are predominantly composed of diogenitic material, suggesting these objects are rubble piles of mixed ejecta.

INTRODUCTION

Since the work of Cruikshank et al. (1991), objects with V-type reflectance spectra similar to asteroid 4 Vesta and/or HEDs (howardites, eucrites, and diogenites) (Fig. 1) have been known to exist in the near-Earth asteroid (NEA) population. These near-Earth V-type asteroids were identified before Vesta-related collisional fragments (usually referred to as vestoids; Binzel and Xu 1993) were identified in the inner (~2.0–2.5 AU) main belt and direct evidence for substantial impact excavation on Vesta was revealed (Thomas et al. 1997). Cruikshank et al. (1991) identified 3551 Verenia (1983 RD), 3908 Nyx (1980 PA), and 4055 Magellan (1985 DO2) as having possible HED-like surfaces. Approximately 20 V-types (e.g., Xu et al. 1995; Abell et al. 2004; Binzel et al. 2004b; Marchi et al. 2005; de León et al. 2006; Duffard et al. 2006) have been identified in the near-Earth population. Using the Desert Fireball Network, a basaltic achondrite (Bunburra Rockhole) with a pyroxene mineralogy similar to basaltic eucrites but having an oxygen isotopic composition different from typical HEDs has recently (Bland et al. 2009) been discovered in Australia. Bunburra Rockhole was found to have been on an Aten-type (semi-major axis smaller than Earth's) orbit.

We note that in this article the term "vestoid" refers to any asteroid with visible and/or near-infrared spectra similar to laboratory-determined HED spectra. Our logic is that without petrologic information or detailed remote imaging it is impossible to definitively identify any object as a fragment of Vesta, even if the body is located in the inner main-belt. Hence, we use the term "vestoid" to indicate a spectral similarity to HEDs.

HEDs are a clan of achondritic meteorites that have continuous variations in mineralogy and chemistry (e.g., Mittlefehldt et al. 1998). Eucrites are primarily composed of anorthitic (Ca-rich) plagioclase and low-Ca pyroxene with augite exsolution lamellae, whereas diogenites are predominately magnesian orthopyroxene (Mittlefehldt et al. 1998). Howardites are polymict breccias containing fragments of both lithologic units and are the primary evidence that almost all HEDs are derived from one parent body. Within these HED breccias, there is a complete

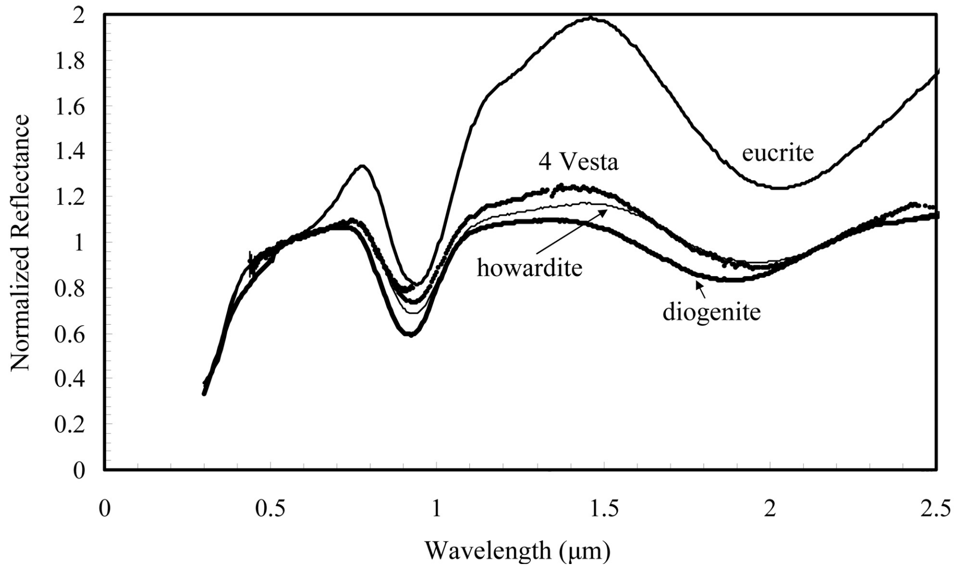

Fig. 1. Reflectance spectrum of 4 Vesta versus a eucrite, a howardite, and a diogenite. The Vesta spectrum is a combination of SMASS II (Bus and Binzel 2002) and SpeX data (Binzel personal communication). The error bars are one-sigma for the Vesta spectrum. The eucrite is Bouvante (Burbine et al. 2001), the howardite is Elephant Moraine (EET) 87503 (Hiroi et al. 1994), and the diogenite is Johnstown (Hiroi et al. 1995). All spectra are normalized to unity at 0.55 µm.

Table 1. Orbital groups, absolute magnitudes (H), albedos (p_V), and diameters of the observed near-Earth vestoids.

Asteroids	Group	H^*	Albedo (p_V)	Diameter (km)
3908 Nyx	Amor	17.4	0.16(+0.08, −0.05)[a]	1 ± 0.15[a]
4055 Magellan	Amor	14.8	0.31 ± 0.09[b]	2.49 ± 0.37[b]
(5604) 1992 FE	Aten	16.4	0.48 ± 0.14[b]	0.55 ± 0.08[b]
(6611) 1993 VW	Apollo	16.5	n.d.	(1.2)[d]
(52750) 1998 KK17	Apollo	16.5	n.d.	(1.2)[d]
(88188) 2000 XH44	Amor	16.0	n.d.	(1.5)[d]
2005 WX	Apollo	26.9	n.d.	(0.01)[d]

*Absolute magnitudes (H) are from the Minor Planet Center (http://www.cfa.harvard.edu/iau/mpc.html).

[a]The albedo and diameter of Nyx are from Benner et al. (2002).

[b]The albedo and diameter of Magellan and 1992 FE are from Delbó et al. (2003).

[c]The abbreviation n.d. (not determined) is used for objects where the albedo has not been measured.

[d]The diameters of these objects are calculated from the formula $D = (1329^{*}10^{-0.2H})/\sqrt{Pv}$ (Harris and Harris 1997) where the visual albedo (p_V) is assumed to be 0.31, which is Magellan's albedo.

spectrum of proportions of eucritic and diogentic materials: polymict eucrites are defined as containing up to 10% diogenitic material, whereas polymict diogenites contain up to 10% eucritic material (Delaney et al. 1983). Vesta has a very distinctive reflectance spectrum that can be matched very well with the spectrum of a howardite (Hiroi et al. 1995). Oxygen isotopic measurements of HEDs (e.g., Wiechert et al. 2004; Greenwood et al. 2005) are consistent with almost all HEDs originating on the same parent body. However, a few eucrites (e.g., Northwest Africa [NWA] 011, Yamaguchi et al. 2002; Ibitira, Wiechert et al. 2004; Mittlefehldt 2005) have oxygen isotopic compositions offset from the HED fractionation line, implying a different parent body or bodies for these meteorites.

Given the above evidence that nearly all HEDs are derived from a common parent body and that substantial literature points to Vesta as that probable parent (Consolmagno and Drake 1977; Binzel and Xu 1993; Thomas et al. 1997; Drake 2001), we adopt the term "vestoid" as a shorthand label of convenience for V-type near-Earth asteroids whose observations we describe here. Of course, without samples of these objects and Vesta itself, it is impossible to verify any relationship. We further note the existence in the middle (~2.5–2.8 AU) and outer (~2.8–3.3 AU) main-belt of V-type asteroids (e.g., Lazzaro et al. 2000; Roig and Gil-Hutton 2006; Binzel et al. 2007; Roig et al. 2008; Masi et al. 2008; Moskovitz et al. 2008; Duffard and Roig 2009) that are dynamically difficult to derive from Vesta.

In reflected and transmitted light, pyroxenes have distinctive absorption features (e.g., Burns 1993) that are centered near 0.9 and 1.9 µm and are due to the presence of Fe^{2+} in the pyroxenes. The band positions of these features move to longer wavelengths for increasing contents of Fe^{2+} and/or Ca^{2+}; this change can be seen in the variations found in the laboratory-determined reflectance spectra of HEDs. Even though polymict HED breccias usually contain a wide variety of pyroxenes, the resulting reflectance spectrum (e.g., Gaffey 2007) of an HED meteorite has one distinctive Band I minimum and one distinctive Band II minimum.

Table 2. Observing parameters for SpeX observations of the observed near-Earth vestoids.

Asteroids	Date (m/d/y)	Time*	Airmass#	Standard stars±
3908 Nyx	09/15/04	05:42–06:43	1.21–1.18	L110-361, 16 Cygnus B, L 93-101, Hyades 64
4055 Magellan	04/11/05	13:01–14:10	1.052–1.164	L107-684, FS 27
(5604) 1992 FE	03/29/01	11:46–12:14	1.63	L98-978, L102-1081, L104-483, L107-684
(6611) 1993 VW	05/10/05	08:13–08:40	1.19	L102-1081, L105-56, L110-361
(52750) 1998 KK17	09/15/04	12:30–13:20	1.27–1.36	L110-361, 16 Cygnus B, L 93-101, Hyades 64
(88188) 2000 XH44	01/26/04	14:00–14:32	1.11–1.15	L98-978, L102-1081
(88188) 2000 XH44	02/19/04	10:25–11:00	1.004–1.004	Hyades 64, L98-978, L102-1081, L107-684
2005 WX	11/22/05	08:56–09:57	1.04–1.10	L115-271, L93-101, Hyades 64

*The ending times for the observations are approximate. All exposure times were 120 seconds except for the (88188) 2000 XH44 (02/19/04) observations, which had exposure times of 60 seconds. There were 16 separate spectra of 3908 Nyx, 24 separate spectra of 4055 Magellan, 14 separate spectra of (5604) 1992 FE, 12 separate spectra of (6611) 1993 VW, 20 separate spectra of (52750) 1998 KK17, 14 separate spectra of (88188) 2000 XH44 (01/26/04), 28 separate spectra of (88188) 2000 XH44 (02/19/04), and 24 separate spectra of 2005 WX.

#The airmass ranges for the observations are given. When only one airmass is given, the airmass at the beginning of the observations is listed for that asteroid.

±Abbreviations used are *L* for Landolt Stars, *FS* for Faint Infrared Standard Stars, and *BS* for UKIRT Bright Standard Stars.

We have observed seven pyroxene-dominated NEAs (Table 1) with spectra resembling HEDs. This population represents approximately one-third of all known V-type NEAs. The average pyroxene mineralogies of these seven asteroids are estimated through the application of two techniques that derive pyroxene mineralogies from an object's Band I and II centers. All band centers are corrected for the effects of the low surface temperatures of asteroids. We show in detail the steps needed to calculate the pyroxene mineralogies of asteroids and the uncertainties in the calculations. Our goal is to determine how well we can identify possible meteoritic analogs for near-Earth vestoids.

DATA

All objects were observed using SpeX, a medium-resolution near-infrared spectrograph (Rayner et al. 2003) on the NASA Infrared Telescope Facility (IRTF) located on Mauna Kea. Observing procedures using SpeX are discussed in Binzel et al. (2004a) and Sunshine et al. (2004). Appropriate solar analog standard stars were used to produce the final reflectance spectra, normalized to unity at 0.55 µm. Observing parameters for the objects are listed in Table 2 and the reflectance spectra of the near-Earth asteroids are plotted in Fig. 2. The SpeX data are plotted at wavelength intervals of 0.005 µm for a wavelength range of ~0.8–2.5 µm.

Asteroid (88188) 2000 XH44 was observed on two different dates with the second set of observations having higher signal to noise. Only the 2000 XH44 spectrum with the higher signal to noise is plotted in Fig. 2. Both 2000 XH44 spectra are plotted in Fig. 3.

Visible data are available for four of the objects. Visible spectra are from Binzel et al. (2004b) and were acquired as part of the SMASS (Small Main-Belt Asteroid Spectroscopic Survey) (Bus and Binzel 2002) at the Michigan-Dartmouth-MIT Observatory (now MDM Observatory) located on Kitt Peak, Arizona.

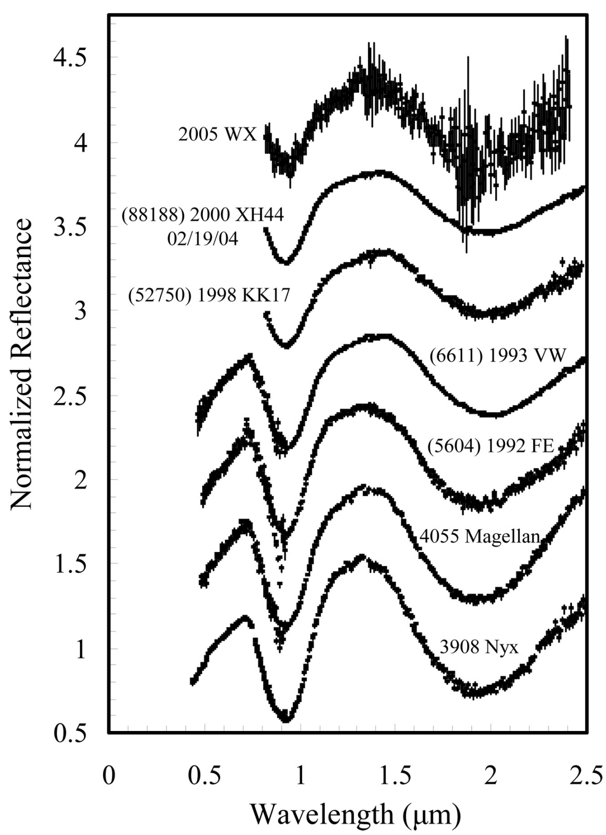

Fig. 2. Reflectance spectra of seven near-Earth vestoids. The error bars are one-sigma. Spectra are normalized to unity at 0.55 µm and offset in reflectance.

All objects (Fig. 2) have the characteristic pyroxene absorption features (Cloutis and Gaffey 1991; Burns 1993) typical of HEDs (Fig. 1), which is due to Fe^{2+} in the M2 crystallographic site in the pyroxene. All objects have a strong pyroxene band centered near ~0.94 µm and a strong pyroxene band centered near ~1.95 µm. All of the objects with visible spectra have the strong UV absorption edges found in HED spectra.

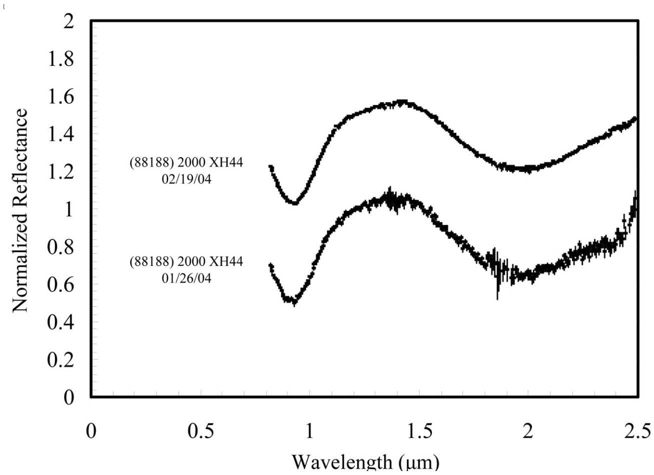

Fig. 3. Reflectance spectra of (88188) 2000 XH44 taken on 01/26/04 and 02/19/04. The error bars are one-sigma. Spectra are normalized to unity at 0.55 µm and offset in reflectance.

A subtle difference is apparent in the shape of the spectra between 1.1 and 1.4 µm. 3908 Nyx, 4055 Magellan, and (5604) 1992 FE have peaks in this region near ~1.3 µm whereas (6611) 1993 VW, (52750) 1998 KK17, and (88188) 2000 XH44 have peaks near ~1.4 µm. The spectrum of 2005 WX is relatively noisy so it is harder to determine where the peak is.

A feature at ~1.2 µm in pyroxenes has been attributed to Fe^{2+} in the M1 crystallographic site in the pyroxene (Klima et al. 2007). This ~1.2 µm feature tends to be stronger for pyroxenes that cooled relatively quickly (Klima et al. 2008), which "traps" some Fe^{2+} in the M1 crystallographic site. The ~1.2 µm band is not visually distinctive in the NEA spectra though a weak ~1.2 µm band might cause the shifting of the reflectance peak between the 1 and 2 µm bands.

PYROXENE MINERALOGIES

To calculate pyroxene mineralogies, band centers must be determined. Band centers (and the temperature corrections) are listed in Table 3. Band I centers for the asteroid spectra with visible data were calculated using the method of Storm (personal communication) that was used during the Storm et al. (2007) study. Only SpeX data were fit. A linear slope that was derived from a straight line tangent to the two reflectance peaks on each side of Band I was divided out. For asteroids without visible data, no slope was divided out and only the Band I minima were calculated for those objects. Band I centers are at slightly longer wavelengths than the Band I minima. The difference between the position of the Band I minimum and the Band I center can be as large as +0.01 µm for objects with large spectral slopes. No linear slopes were divided out to calculate Band II centers since none of the objects appeared to be significantly sloped over this wavelength region and these bands are extending past 2.5 µm. Without knowing where these bands flatten out past 2.5 µm, an accurate spectral slope determination for Band II cannot be determined. We believe our calculated Band II minima are equivalent to the Band II centers.

The method of Storm (personal communication) fits a second-degree polynomial over the bottom third of each band. The band center (or minimum) was then determined. Each reflectance value was randomly resampled using a Gaussian distribution for the observational error and then fit using another second-degree polynomial. Each spectrum was resampled ninety-nine times. The derived one-hundred band centers were then averaged to calculate an average band center (or minimum) and the sample standard deviation. If each fit gave the same band center (or minimum), no sample standard deviation is given.

All band centers and temperature corrections are listed with a precision of three significant digits since we do not want to do any further rounding until we calculate the molar contents of ferrosilite and wollastonite, which we only list at a precision of two significant digits. The formulas for calculating ferrosilite and wollastonite contents are very sensitive to the band center positions. Hence, we do not want to introduce any unnecessary error by rounding off prematurely.

Our calculated band centers for the later spectrum of (88188) 2000 XH44 are consistent, within error bars, for band centers determined for the lower signal-to-noise spectra of 2000 XH44 by Duffard et al. (2006). Our calculated Band I center for (6611) 1993 VW is consistent, within error bars, for the Band I center determined for lower signal-to-noise spectra of 1993 VW by Duffard et al. (2006) but our calculated Band II center is at a slightly longer wavelength than the one calculated by Duffard et al. (2006).

Band centers move to shorter wavelengths as the temperature of the surface decreases (Singer and Roush 1985; Roush and Singer 1987; Hinrichs et al. 1999; Moroz et al. 2000). The temperature (T) (Kelvin) of an asteroid can be estimated from the following equation:

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

where A is the asteroid albedo, L_o is the solar luminosity (3.827×10^{26} W), η is the beaming factor (assumed to be unity) (e.g., Cohen et al. 1998), 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. The theoretical temperatures do not appear to be very sensitive to the chosen parameters. Changing the emissivity by ±0.1, changing the beaming factor to 0.9, or adjusting the albedos based on the albedo uncertainty only changes the theoretical temperatures by approximately ±10 K. If the albedo has not been measured for an object, we use the albedo (0.31) of 4055 Magellan, which is intermediate between the albedos of (5604) 1992 FE (0.48) and 3908 Nyx (0.16).

To perform the temperature corrections, we use the results of Moroz et al. (2000) who measured the movement of

Table 3. Calculated surface temperatures, Band I centers with uncertainties, Band II minima with uncertainties, and temperature corrections for the near-Earth vestoids. All band centers and temperature corrections are listed with a precision of three significant digits since we do not want to do any further rounding until we calculate the molar contents of ferrosilite and wollastonite, which we list at a precision of two significant digits.

Asteroids	Surface temperature (K)	Band I center	Temperature correction	Band II minimum	Temperature correction
3908 Nyx	255	0.930	+0.001	1.954 ± 0.002	+0.007
4055 Magellan	192	0.925	+0.002	1.933 ± 0.002	+0.019
(5604) 1992 FE	216	0.929 ± 0.002	+0.001	1.955 ± 0.002	+0.014
(6611) 1993 VW	244	0.940 ± 0.001	+0.001	2.009 ± 0.003	+0.009
Asteroids	Surface temperature (K)	Band I minimum	Temperature correction	Band II minimum	Temperature correction
(52750) 1998 KK17	223	0.926 ± 0.002	+0.001	1.990 ± 0.003	+0.013
(88188) 2000 XH44[a]	226	0.920	+0.001	1.982 ± 0.005	+0.013
(88188) 2000 XH44[b]	232	0.925	+0.001	1.980 ± 0.001	+0.012
2005 WX	261	0.930 ± 0.006	+0.001	1.953 ± 0.011	+0.006

[a]Observed on 01/26/04.
[b]Observed on 02/19/04.

the band centers for two pyroxenes at temperatures of 293, 173, and 80 K. One sample ("bronzite") was an orthopyroxene (En_{83}) whereas the other sample ("enstatite") was an orthopyroxene (En_{90}) that possibly could have a small amount of high-Ca pyroxene. We fit straight lines through the data to be able to predict the shift in wavelength position with decreasing temperature. The formulas derived from the "bronzite" are

$$\text{wavelength correction for Band I center } (\mu\text{m}) = 0.0047 - 0.000015 \times T(\text{K}) \quad (2)$$

and

$$\text{wavelength correction for Band II center } (\mu\text{m}) = 0.044 - 0.00015 \times T(\text{K}) \quad (3)$$

and the formulas derived from the "enstatite" are

$$\text{wavelength correction for Band I center } (\mu\text{m}) = 0.0054 - 0.000019 \times T(\text{K}) \quad (4)$$

and

$$\text{wavelength correction for Band II center } (\mu\text{m}) = 0.0649 - 0.00022 \times T(\text{K}). \quad (5)$$

We perform the correction for the Band I center using Equations 2 and 4, average the corrections, and then add this correction to the calculated band center of each asteroid at each temperature. We do the same thing for the Band II center using Equations 3 and 5. The temperature corrections are listed in Table 3. Overall the average wavelength shift due to temperature is minimal (typically +0.001 µm) for the Band I center and larger (+0.01 µm) for the Band II center for near-Earth asteroids with surface temperatures of ~230 K relative to laboratory measurements obtained at approximately 300 K.

To calculate the pyroxene mineralogy of vestoids, formulas derived by Gaffey et al. (2002) based on analyses of a wide variety of pyroxenes, primarily terrestrial, at room temperature were used. These formulas calculate the molar contents of ferrosilite (Fs) and wollastonite (Wo), with uncertainties, from band centers determined from their reflectance spectra. The formulas are

$$\text{Fs } (\pm 5) = 268.2 \times \text{Band II center } (\mu\text{m}) - 483.7 \ (\text{Wo} < 11), \quad (6)$$

$$\text{Fs } (\pm 5) = 57.5 \times \text{Band II center } (\mu\text{m}) - 72.7 \ (\text{Wo} = 11\text{–}30;\ \text{Fs} < 25 \text{ excluded}), \quad (7)$$

$$\text{Fs } (\pm 4) = -12.9 \times \text{Band II center } (\mu\text{m}) + 45.9 \ (\text{Wo} = 30\text{–}45), \quad (8)$$

$$\text{Fs } (\pm 5) = -118.0 \times \text{Band II center } (\mu\text{m}) + 278.5 \ (\text{Wo} > 45), \quad (9)$$

$$\text{Wo } (\pm 3) = 347.9 \times \text{Band I center } (\mu\text{m}) - 313.6 \ (\text{Fs} < 10;\ \text{Wo} \approx 5\text{–}35 \text{ excluded}), \quad (10)$$

$$\text{Wo } (\pm 3) = 456.2 \times \text{Band I center } (\mu\text{m}) - 416.9 \ (\text{Fs} = 10\text{–}25;\ \text{Wo} \approx 10\text{–}25 \text{ excluded}), \quad (11)$$

and

$$\text{Wo } (\pm 4) = 418.9 \times \text{Band I center } (\mu\text{m}) - 380.9 \ (\text{Fs} = 25\text{–}50) \quad (12)$$

where Fs and Wo are given as molar contents. The values in parentheses after each formula are the compositional ranges where the equation is valid. These formulas are valid for all types of low- and high-Ca pyroxenes with 1 and 2 µm absorption features.

We also use formulas (Burbine et al. 2007) for determining Fs and Wo contents from the Band I and Band II centers and Band II minima that were derived using data from thirteen HEDs (Table 4) with high-quality reflectance spectra measured at room temperature and with calculated average pyroxene compositions. The Burbine et al. (2007) formulas are simpler to use than the Gaffey et al. (2002) formulas since the Burbine et al. (2007) formulas only work on the very restricted pyroxene mineralogies found in HEDs whereas the Gaffey et al. (2002) formulas work on a much wider range of pyroxene mineralogies. As with the

Table 4. The average enstatite (En), ferrosilite (Fs), and wollastonite (Wo) compositions and Band I and II for HEDs with known average pyroxene mineralogies* and high-resolution reflectance spectra.

Type	En	Fs	Wo	Reference	Band I minimum	Band I center	Band II minimum	RELAB ID
Eucrites monomict								
Bouvante	32.5	53.5	14.0	Buchanan (unpublished)	0.935	0.95	2.0275	MP-TXH-090-A
EET 87542	43	44	13	Burbine et al. (2001)	0.94	0.94	2.0275	MP-TXH-075-A
EET 90020	33	53	13	Burbine et al. (2001)	0.94	0.94	2.015	MP-TXH-076-A
Juvinas	36.9	51.8	11.3	BVSP[a] (1981)	0.935	0.94	2.0075	MB-TXH-070-A
PCA 82502	33	53	14	Burbine et al. (2001)	0.935	0.945	2.0225	MP-TXH-080-A
Stannern[a]	34.6	55.8	9.6	BVSP[a] (1981)	0.935	0.94	2.0125	MB-TXH-097-A
Eucrites polymict								
EETA79005	46.5	43.2	10.3	Burbine et al. (2001)	0.93	0.935	1.970	MP-TXH-072-A
LEW 87004	44	45	11	Burbine et al. (2001)	0.93	0.935	1.9625	MP-TXH-079-A
Pasamonte	42.7	43.5	13.7	BVSP[a] (2001)	0.935	0.94	2.005	MP-TXH-087-A
Petersburg	50.0	40.6	9.4	Buchanan (1995)	0.9325	0.935	1.985	MP-TXH-070-A
Howardite								
EET 87503	51.6	40.3	8.1	Buchanan (unpublished)	0.93	0.93	1.9575	MB-TXH-068-A
Diogenites								
Johnstown	73.7	23.5	2.8	Zema et al. (1997, 1999)	0.915	0.915	1.8875	MB-TXH-095-A
Tatahouine	75.5	23.0	1.5	Buchanan (unpublished)	0.92	0.92	1.895	MP-TXH-088-A

*The given pyroxene compositions represent average pyroxene mineralogies of the meteorites. We note that the sum of En, Fs, and Wo contents of EET 90020 and Pasamonte do not add up to 100% due to rounding errors and that the Burbine et al. (2001) analyses were only listed to two significant figures. Except for Tatahouine, a large number of analyses were done on thin sections of each meteorite ranging from ~30 analyses on Juvinas and ~270 analyses on EET 87503. For the equilibrated eucrites, the analyses are generally for different grains, whereas for the unequilibrated eucrites, they represent, in some cases, traverses of usually two to five analyses from core to rim. Among our meteorite samples, only Pasamonte is unequilibrated (e.g., Reid and Barnard 1979; Schwartz and McCallum 2005). For Tatahouine, six analyses were done for 30 minutes each and should represent the average pyroxene mineralogy since orthopyroxenes in diogenites have very uniform major-element chemistries (Mittlefehldt et al. 1998).

[a]BVSP is an abbreviation for the Basaltic Volcanism Study Project.

asteroids, we believe our calculated Band II minima are equivalent to the Band II centers. Uncertainties were calculated by finding the average difference between the actual molar (Fs or Wo) content and the predicted value using the formula. These formulas are

$$\text{Fs} (\pm 3) = 1023.4 \times \text{Band I center } (\mu\text{m}) - 913.82, \tag{13}$$

$$\text{Fs} (\pm 3) = 205.86 \times \text{Band II center } (\mu\text{m}) - 364.3, \tag{14}$$

$$\text{Wo} (\pm 1) = 396.13 \times \text{Band I center } (\mu\text{m}) - 360.55, \tag{15}$$

and

$$\text{Wo} (\pm 1) = 79.905 \times \text{Band II center } (\mu\text{m}) - 148.3 \tag{16}$$

where Fs and Wo are given as the molar contents. Averaging the compositions (Fs and Wo) separately from the Band I and II centers slightly reduces the uncertainty. The importance of using different sets of formulas to derive mineralogies is that we will have more confidence in the results if both sets of formulas derive similar mineralogies.

The possible ranges for the calculated mineralogies for the near-Earth asteroids are based on those given by the formulas. The possible ranges for the calculated Fs and Wo contents can be bigger than the given uncertainties for the formulas if the band position uncertainty is large enough. One question about using the Gaffey et al. (2002) formulas is that none of the formulas are given as working for Fs contents above 50 mol%, which is the Fs content of the most Fe-rich eucrites. To calculate the Wo contents where the calculated Fs content is above 50 mol%, we assume Equation 12 still works. This question may affect the calculated mineralogies and ranges in mineralogy for (52750) 1998 KK17 and the first observations (01/26/04) for (88188) 2000 XH44 using the Gaffey et al. (2002) equations.

All of the asteroids with visible data (3908 Nyx, 4055 Magellan, (5604) 1992 FE, (6611) 1993 VW), which allows the spectral slope of Band I to be divided out, fall within the band center ranges for eucrites and howardites. None of the asteroids fall within the range for diogenites. For objects without visible data ((52750) 1998 KK17, (88188) 2000 XH44, 2005 WX), it is impossible to know the exact spectral slope since the reflectance peak near 0.7 μm cannot be exactly identified and, therefore, we cannot divide out the spectral slope to determine a Band I center. We use the trend found for the distribution of band centers for HEDs (Fig. 4) to try to estimate the spectral slope correction to add to the calculated Band I minimum so a Band I center can be determined. We have added +0.01 μm to the calculated Band I minima for 1998 KK17 and both observations of 2000 XH44 to estimate these objects' Band I center positions after dividing out their respective spectral slopes. We have not added a spectral slope

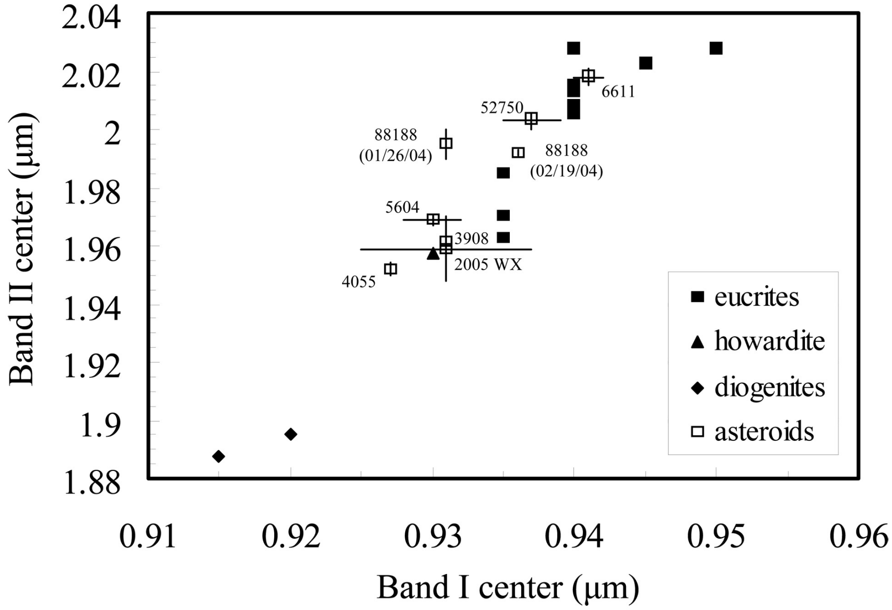

Fig. 4. Plot of temperature-corrected Band I centers versus temperature-corrected Band II centers for HEDs and near-Earth vestoids. To estimate the value of the temperature-corrected Band I center from the Band I minimum for objects without visible data, we have added +0.01 μm to the calculated Band I minima for (52750) 1998 KK17 and both observations of (88188) 2000 XH44 so that their points fall on the trend defined by the HEDs. We have not added a correction for 2005 WX since it already falls on the trend defined by the HEDs.

Table 5. Estimated pyroxene mineralogies and ranges for the near-Earth vestoids calculated from temperature-corrected band centers with uncertainties. All band centers are listed with a precision of three significant digits since we do not want to do any further rounding until we calculate the molar contents of ferrosilite and wollastonite, which we list at a precision of two significant digits.

Asteroids	Band I center (temperature-corrected)	Band II center* (temperature-corrected)	Gaffey et al. (2002) mineralogy	Burbine et al. (2007) mineralogy
3908 Nyx	0.931	1.961 ± 0.002	$Fs_{42(+6,-5)}Wo_{9 \pm 4}$	$Fs_{39 \pm 3}Wo_{8 \pm 1}$
4055 Magellan	0.927	1.952 ± 0.002	$Fs_{40(+5,-6)}Wo_{7 \pm 4}$	$Fs_{36 \pm 3}Wo_{7 \pm 1}$
(5604) 1992 FE	0.930 ± 0.002	1.969 ± 0.002	$Fs_{44(+6,-5)}Wo_{9 \pm 5}$	$Fs_{39(+5,-4)}Wo_{8(+2,-1)}$
(6611) 1993 VW	0.941 ± 0.001	2.018 ± 0.003	$Fs_{43(+6,-5)}Wo_{13(+5,-4)}$	$Fs_{50 \pm 4}Wo_{13(+1,-2)}$
(52750) 1998 KK17#	0.937 ± 0.002	2.003 ± 0.003	$Fs_{42(+16,-5)}Wo_{12(+4,-5)}$	$Fs_{47(+4,-5)}Wo_{11(+2,-1)}$
(88188) 2000 XH44[a]#	0.931	1.995 ± 0.005	$Fs_{51 \pm 6}Wo_{9 \pm 4}$	$Fs_{43(+3,-4)}Wo_{10 \pm 1}$
(88188) 2000 XH44[b]#	0.936	1.992 ± 0.001	$Fs_{42 \pm 5}Wo_{11 \pm 4}$	$Fs_{45 \pm 3}Wo_{11 \pm 1}$
2005 WX#	0.931 ± 0.006	1.959 ± 0.011	$Fs_{42(+5,-8)}Wo_{9(+7,-6)}$	$Fs_{39 \pm 7}Wo_{8(+3,-2)}$

*The temperature-corrected Band II centers are calculated using the Band II minima, which are assumed to be equivalent to the Band II centers.
#To estimate the value of the temperature-corrected Band I center from the Band I minimum for objects without visible data, we have added +0.01 μm to the calculated Band I minima for (52750) 1998 KK17 and (88188) 2000 XH44. We have not added a correction for 2005 WX.
[a]Observed on 01/26/04.
[b]Observed on 02/19/04.

correction to the Band I minimum for 2005 WX since its band minima already fall on the HED trend in Fig. 4. Therefore, we assume the Band I minimum of 2005 WX is equivalent to its Band I center.

All of the calculated pyroxene mineralogies and ranges of the near-Earth vestoids determined from the Gaffey et al. (2002) and Burbine et al. (2007) formulas are given in Table 5. We plot in Figs. 5 and 6 the calculated Fs and Wo contents for the asteroids versus the ranges found for the HEDs. All of the derived mineralogies from the Gaffey et al. (2002) formulas and the Burbine et al. (2007) formulas overlap. The derived Wo contents are almost exactly the same with differences only as big as 1 mol%. The derived Fs contents are larger with difference ranging from 3 to 8 mol%.

We subdivide the eucrites in Figs. 5 and 6 into non-cumulate and cumulate. Non-cumulate (often called basaltic) eucrites cooled relatively quickly, whereas cumulate eucrites appear to be the result of fractional crystallization of a Fe-rich eucritic melt in a magma body in the shallow subsurface. Cumulate eucrites are relatively rare with only a few known (Hsu and Crozaz 1997). The pyroxene mineralogies of cumulate eucrites overlap the

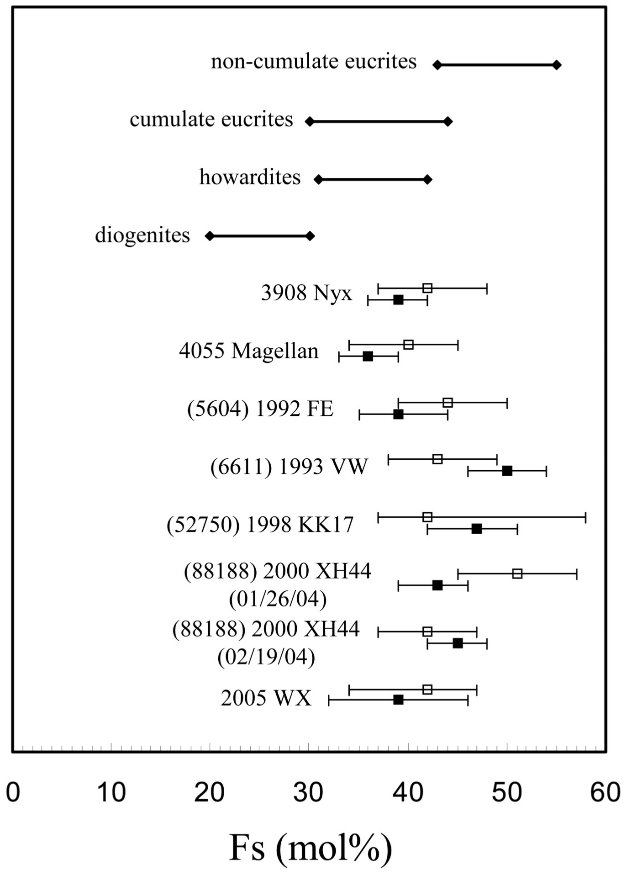

Fig. 5. Plot of ferrosilite (Fs) ranges for the non-cumulate eucrites, cumulate eucrites, howardites, and diogenites and the Fs contents and Fs ranges, derived from the error bars, for the near-Earth vestoids. All of the NEAs fall within the Fs ranges of eucrites and/or howardites. None of the objects fall within the Fs range of diogenites. The open squares are values calculated from the Gaffey et al. (20002) formulas and the filled squares are values calculated from the Burbine et al. (2007) formulas.

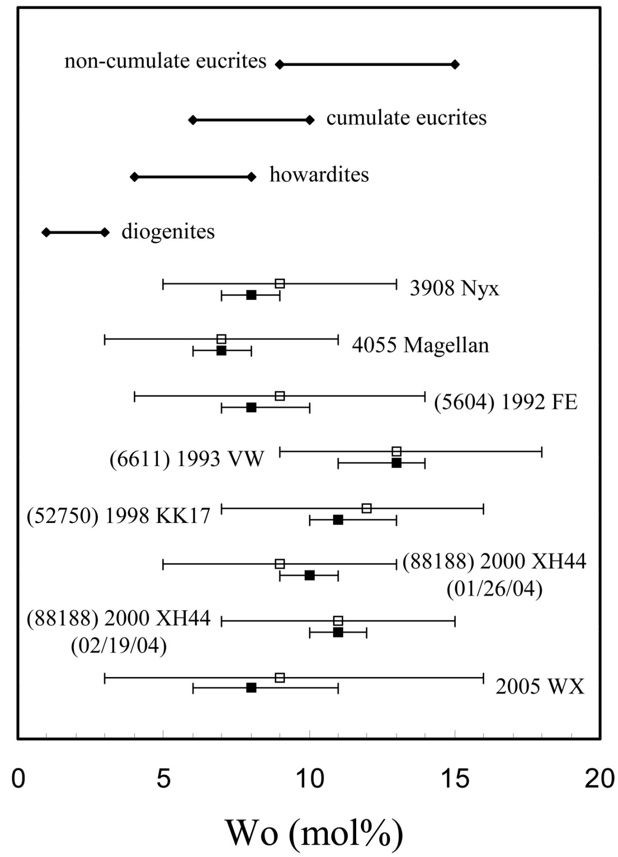

Fig. 6. Plot of wollastonite (Wo) ranges for the non-cumulate eucrites, cumulate eucrites, howardites, and diogenites and the Wo contents and Wo ranges, derived from the error bars, for the near-Earth vestoids. All of the NEAs fall within the Wo ranges of eucrites and/or howardites. Except for the lower range of the Gaffey et al. (2002) value for 2005 WX, none of the objects fall within the Wo range of diogenites. The open squares are values calculated from the Gaffey et al. (20002) formulas and the filled squares are values calculated from the Burbine et al. (2007) formulas.

average pyroxene mineralogies of howardites. The ranges of the average Fs and Wo contents of pyroxenes (e.g., Papike 1980; Basaltic Volcanism Study Project 1981; Berkley and Boynton 1992; Takeda 1997; Mittlefehldt et al. 1998) were calculated for the non-cumulate eucrites (~$Fs_{43–55}Wo_{9–15}$), cumulate eucrites (~$Fs_{30–44}Wo_{6–10}$), howardites (~$Fs_{31–42}Wo_{4–8}$), and diogenites (~$Fs_{20–30}Wo_{1–3}$).

As expected from the trends found in Fig. 4, all of the near-Earth vestoids have Fs and Wo contents consistent with eucrites and howardites. None have Fs and Wo contents consistent with diogenites. Our results are consistent with the Canas et al. (2008) study of 3908 Nyx, 4055 Magellan, and (6611) 1993 VW. Using Modified Gaussian Modeling (MGM) to analyze their reflectance spectra, Canas et al. (2008) determined that these asteroids had similar proportions of low-calcium and high-calcium pyroxenes to eucrites and underwent similar degrees of igneous processing. Duffard et al. (2006) found using MGM that both (6611) 1993 VW and (88188) 2000 XH44 were both mixtures of low- and high- Ca-pyroxene, which is consistent with our results. The pyroxene mineralogies calculated by Duffard et al. (2006) for 1993 VW ($Fs_{37 \pm 5}Wo_{9 \pm 4}$) and 2000 XH44 ($Fs_{39 \pm 5}Wo_{9 \pm 4}$) are consistent, within error bars, to the pyroxene mineralogies calculated in this study except for the Fs content of 1993 VW. The Fs content ($Fs_{50 \pm 4}$) of 1993 VW derived using Burbine et al. (2007) formulas is higher since our calculated Band II center (2.018 ± 0.003 μm) for this object is at a longer wavelength than the Band II center (1.945 ± 0.04 μm) calculated by Duffard et al. (2006).

The lack of identified vestoids with mineralogies similar to diogenites in the near-Earth population and among main-belt asteroids (Burbine et al. 2001) suggests that it may be extremely difficult to produce large (km-sized or larger) bodies that only contain diogenitic material. The diogenites form at greater depths than the eucrites; hence, the eucritic crust must always be punctured to extricate the diogenitic material. The cratering process that produces asteroid-sized fragments from large bodies (such as Vesta) may always tend to mix significant (greater than 10%) amounts of eucritic material in the ejected fragments, which would make these objects howardites. Only relatively small fragments (diameters of hundreds of meters or smaller) probably have diogenite surfaces. Most likely these pyroxene-rich NEAs are rubble piles of mixed ejecta.

All of these near-Earth vestoids have pyroxene mineralogies consistent with eucrites or howardites. If Vesta is the parent body of most HEDs then this similarity in pyroxene mineralogy between these NEAs and eucrites/howardites would support a possible relationship between these NEAs and Vesta. However, we cannot rule out that these NEAs did not originate from Vesta. Eucrites with "anomalous" oxygen isotopic compositions have average major element pyroxene mineralogies (Yamaguchi et al. 2002; Mittlefehldt 2005) indistinguishable from eucrites with "normal" oxygen isotopic values. Vestoids such as 1459 Magnya (Lazzaro et al. 2000; Hardersen et al. 2004), which are dynamically difficult to derive from Vesta, have been identified in the middle and outer main-belt and these objects appear to be evidence that other basaltic bodies besides Vesta formed in the asteroid belt. The identification of ~90 possible differentiated parent bodies (Wasson 1995) due to the large number of grouped and ungrouped iron meteorites that currently exist in our meteorite collections supports the premise that a number of asteroids with basaltic crusts formed in the asteroid belt.

It appears difficult to identify an exact meteoritic analog for these NEAs. One problem is the overlapping average Fs and Wo contents of pyroxenes in the howardites and cumulate eucrites. Cumulate eucrites are relatively rare in our meteorite collections, but it is unknown whether cumulate eucritic material is also rare on the surfaces of these objects.

Another difficulty in linking any of these objects with a specific type of HED is that the Gaffey et al. (2002) and Burbine et al. (2007) formulas almost always give slightly different values and the ranges for the calculated mineralogies tend to encompass both the eucrite and howardite ranges. Without knowing which set of formulas work "better," it is difficult to determine a specific meteoritic analog. Sample return from these objects would give considerable insight into this conundrum.

CONCLUSIONS

We have calculated pyroxene mineralogies of seven near-Earth vestoids from their Band I and II centers using two different sets of formulas (Gaffey et al. 2002; Burbine et al. 2007). The observed near-Earth vestoids all have pyroxene mineralogies consistent with eucrites or howardites. None of the objects have pyroxene mineralogies consistent with diogenites. The absence of near-Earth vestoids with pyroxene mineralogies similar to diogenites may indicate the extreme difficulty in producing large (km-sized or larger) bodies that only contain diogenitic material. It is difficult to determine more precise meteoritic analogs without knowing which set of formulas work better.

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