The mystery of 506.5 nm feature of reflectance spectra of Vesta and Vestoids: Evidence for space weathering?

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Although asteroid 4 Vesta and Vestoids have been believed to be the source of a group of basaltic meteorites called HEDs, there have been detailed spectral analyses on the spectral redness and the 506.5 nm absorption band, suggesting controversy on their space weathering processes and origins. In order to evaluate a possibility that such an apparent inconsistency may be explained by the space weathering, the 506.5 nm spectral feature and reddening trend are examined for Vesta and Vestoids, HED meteorites, lunar soils, and laser irradiated pyroxene samples in this paper. Our results indicate that all fresh HED meteorites have the 506.5 nm band at different wavelengths according to their classes, lunar soils seem to lose the 506.5 nm band as they mature, and pulse laser irradiation on the pyroxene sample seems to reduce the 506.5 nm band. Therefore, absence of the 506.5 nm band on some Vestoids can be due to space weathering although the relationship between the visible redness and presence/absence of the 506.5 nm band of Vesta and Vestoids is inconsistent with the assumed HED-lunar space weathering trend based on the above laboratory results. Other possible explanations are that some Vestoids experienced shock heavy enough to erase the 506.5 nm band and that pyroxenes on some Vestoids are not similar to those in HED meteorites. Even if the latter case is true and some Vestoids are not made of HED materials, HED meteorites could still come from Vesta unless we assume all Vestoids have to be fragments of Vesta.

1. Introduction

Asteroid 4 Vesta has been believed to be the source of a group of basaltic meteorites called HED meteorites (e.g., McCord *et al.*, 1970; Gaffey, 1983, 1997; Hiroi *et al.*, 1994). There have been about twenty small asteroids discovered that have somewhat similar reflectance spectra to Vesta inside and outside the Vesta group (Binzel and Xu, 1993), which led some to believe those small asteroids (“Vestoids”) came from Vesta together with HED meteorites. However, more detailed spectral analyses (Hiroi *et al.*, 1995; Hiroi and Pieters, 1998) suggested that Vestoids may have gone through heavier space weathering (e.g., Pieters *et al.*, 2000) than Vesta to an intermediate extent between HED meteorites and lunar soils or some Vestoids could come from a different source other than Vesta. Recent observations indicate that Vesta and the Vestoids do not always have the 506.5 nm absorption feature (Cochran and Vilas, 1998; Vilas *et al.*, 2000). The question is what causes its occurrence and/or disappearance. In order to investigate a possibility that such an apparent inconsistency is due to different degrees of space weathering on Vestoids, the 506.5 nm spectral feature and reddening trend are examined for Vesta and Vestoids, HED meteorites, lunar soils, and laser irradiated pyroxene samples in this paper.

2. Experimental

In addition to the HED meteorite samples used in previous studies (Hiroi *et al.*, 1995; Hiroi and Pieters, 1998), samples of eucrites (A-87272, A-881819, ALH85001, Bereba, Bouvante, EETA79005, GRO95533, Ibitira, Jonzac, LEW85303, LEW87004, Pasamonte, PCA82502, Serra de Mage, Y-792510, Y-792769, Y-793591, and Y-82082), howardites (Binda, Bununu, EET83376, EET87513, Frankfort, GRO95535, Le Teilleul, QUE94200, Y-7308, Y-790727, and Y-791573), and diogenites (A-881526, Aioun el Astrouss, GRO95555, LAP91900, and Tatahouine) have been ground and dry-sieved to make powders of <25 μm in grain size. Reflectance spectra of these samples were measured at every 5 nm from 300 to 2600 nm in wavelength in order to calculate the visible redness and the 1-μm band strength (Hiroi and Pieters, 1998) using the RELAB spectrometer (Pieters, 1983). The grain size of 25 μm was chosen based on a previous match between reflectance spectra of Vesta and HED meteorite samples (Hiroi *et al.*, 1994).

The visible redness and the 1-μm band strength were calculated by Hiroi and Pieters (1998) based on laboratory reflectance spectra of eight lunar soil samples and laser irradiated Johnstown diogenite samples (Wasson *et al.*, 1998) measured at RELAB, and telescopic observations of Vesta and twenty Vestoids (Binzel and Xu, 1993).

Seventeen non-Antarctic HED meteorite samples among the above, together with four lunar soil samples (12030, 12001, 10084, and 15041) sorted into powders of 20–45 μm in grain size, were chosen for reflectance spectra measurement at every 1 nm from 500 to 512 nm for characterizing their 506.5 nm absorption band using the same RELAB facility. Similar measurements of pulse laser irradiated orthopyroxene power samples of <75 μm in grain size (Yamada *et al.*, 1999) were made at Future Space Systems Laboratory at Tsukuba Space Center of National Space Development Agency (NASDA) for characterizing their 506.5 nm absorption band. This pulse-laser experiment is the best known simulation of the lunar and S-asteroid type space weathering (Sasaki *et al.*, 2001). Detection results (presence/absence) of the 506.5 nm band of Vesta and thirteen Vestoids were taken from Vilas *et al.* (2000).

3. Nature of the 506.5 nm Band of Pyroxenes and Space Weathering Effect

Shown in Fig. 1 are reflectance spectra of powder samples of nine eucrites, five howardites, and three diogenites measured at every 1 nm for characterizing the 506.5 nm band. Every HED meteorite measured in this study has the 506.5 nm band. Diogenites which consist almost entirely of orthopyroxene show the band centered at a shorter wavelength (around 505.8 nm) than eucrites which consist mainly of clinopyroxenes which show the 506.5 nm band at around 507.6 nm. Two vertical lines in Fig. 1 indicate these two wavelength positions to show the approximate range of the 506.5 nm band center for HED meteorites.

One eucrite (Serra de Mage) shows the band center at a much shorter wavelength than the other eucrites. Only Serra de Mage is a cumulate eucrite (Harlow *et al.*, 1979). Except Moore County, all known cumulate eucrites have completely inverted pigeonite (thus, orthopyroxene). The bulk composition of pyroxene is more Mg rich than those in ordinary eucrites. This may be why the 506.5 nm band of Serra de Mage is centered at a wavelength closer to that of diogenites which also consist mainly of orthopyroxene.

Shown in Fig. 2 are reflectance spectra of four lunar soil samples (sorted to 20–45 μm) measured at every 1 nm. The spectra are arranged in order of maturity measure (Is/FeO) shown in parenthesis next to each sample name in the figure. Two vertical lines show the HED band center range defined in Fig. 1. Only the immature soil (12030) shows a clear 506.5 nm absorption band extending from the shortward to

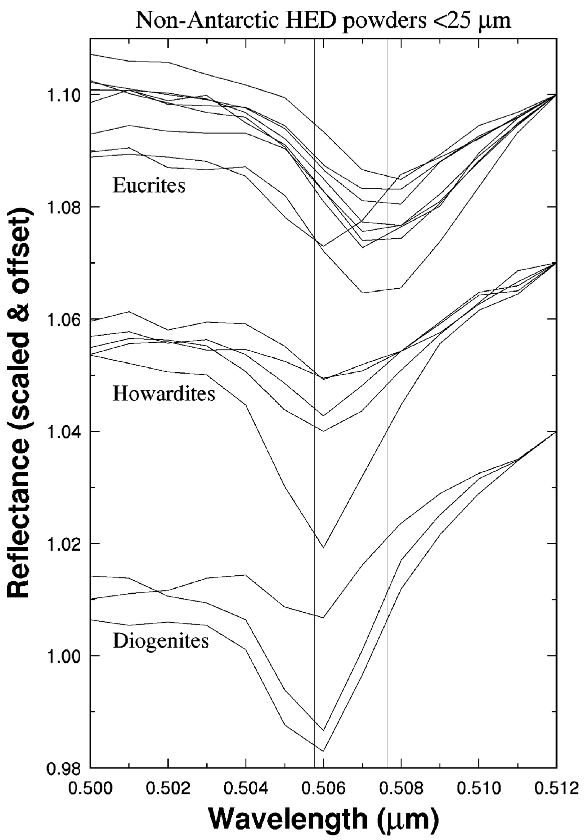

Fig. 1. Reflectance spectra of power samples (<25 μm) of nine eucrites (Bereba, Bouvante, Ibitira, Jonzac, Millbillillie, Padvarninkai, Pasamonte, Serra de Mage, and Stannern), five howardites (Binda, Bununu, Frankfort, Kapoeta, and Le Teilleul), and three diogenites (Aioun el Astrouss, Johnstown, and Tatahouine) measured at every 1 nm for characterizing their 506.5 nm absorption band. Each spectrum is scaled to 1.0 at 512 nm, and the three classes are offset from one another for clarity. Two vertical lines indicate an approximate range of the 506.5 nm band centers from the shortest at 505.8 nm for diogenites to the longest at 507.6 nm for eucrites. One eucrite (Serra de Mage) shows the band center at much shorter wavelength than the other eucrites. The 506.5 nm bands are much deeper than the error level of the measurements.

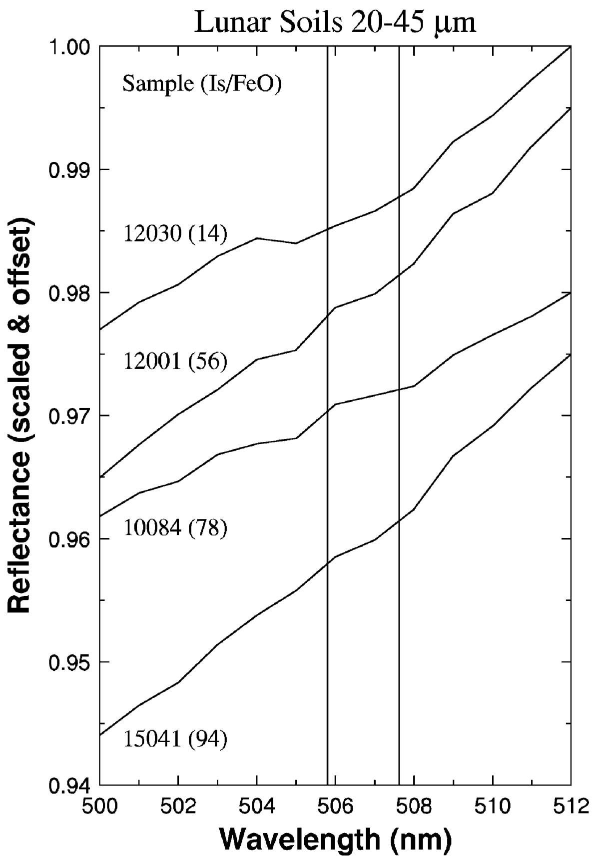

Fig. 2. Reflectance spectra of four lunar soil samples (sorted to 20–45 μm) measured at every 1 nm. The spectra are shown scaled to 1.0 at 512 nm and offset from one another for clarity. Is/FeO value of each soil is shown in parenthesis next to its sample name as a measure of its maturity. Two vertical lines show the HED band center range defined in Fig. 1. Only the immature soil (12030) shows a clear 506.5 nm absorption band. The approximate error level of these spectra is 0.2% in scaled reflectance.

the longward extremes of the HED band center range. Soil 15041 may possibly show a weak band at the longest extreme of the HED band center range, and other soil samples do not show any clear band.

A similar plot is shown in Fig. 3 for orthopyroxene samples treated by pulse laser irradiation (Yamada *et al.*, 1999). In this case, the untreated orthopyroxene sample shows the 506.5 nm band at the diogenite position, consistent with the orthopyroxene dominated composition of diogenites. As the orthopyroxene sample is irradiated with pulse laser, the band position remains unchanged while the spectrum continuously becomes redder. The pulse laser irradiation used for this sample was shown to convert the overall spectral shape of olivine and orthopyroxene samples to match with the A and R asteroids (Hiroi and Sasaki, 2001). It is naturally expected that this treatment would cause a similar effect on the 506.5 nm band, too.

Based on the observations in Figs. 1, 2, and 3, we can derive the following nature of the 506.5 nm band of pyroxene. In spite of the claim by an earlier study (Vilas *et al.*, 2000) that only augite would show the 506.5 nm feature, all HED meteorites including diogenites consisting almost solely of orthopyroxene show the 506 nm band at different wavelengths according to their varying pyroxene chemical compositions. Lunar samples also show the 506.5 nm band at different wavelengths according to their varying pyroxene compositions, and space weathering on those samples is likely to reduce and possibly erase the 506.5 nm absorption band as was also demonstrated by pulse-laser irradiation experiment on a orthopyroxene sample.

4. Space Weathering Trend of HED Meteorites, Vesta and Vestoids, and Lunar Soils

Shown in Fig. 4 is a plot of the 1-μm band strength vs. the visible redness (Hiroi and Pieters, 1998) of HED meteorite samples (indicated as H, E, and D), Johnstown diogenite (J) and its laser irradiated (L) samples from Wasson *et al.* (1998), Padvarninkai (P) and its impact melt (S) samples, Kapoeta (K) sample, Vesta and Vestoids (filled circles) from Binzel and Xu (1993), and lunar soil samples (open triangles). The large filled circles indicate Vesta and Vestoids with the 506.5 nm band, medium filled circles indicate Vestoids where the 506.5 nm band may exist, and the small filled circles indicate Vestoids without the 506.5 nm band according to Vilas *et al.* (2000).

Because of the diversity of visible redness of HED meteorites demonstrated in Fig. 4, the visible redness contains both the space weathering effect and compositional effect of HED-like materials. However, there is some trend that the high visible redness region (upper portion) is dominated by eucrites while the lower visible redness region is filled with mixtures of eucrites, howardites, and diogenites. Although

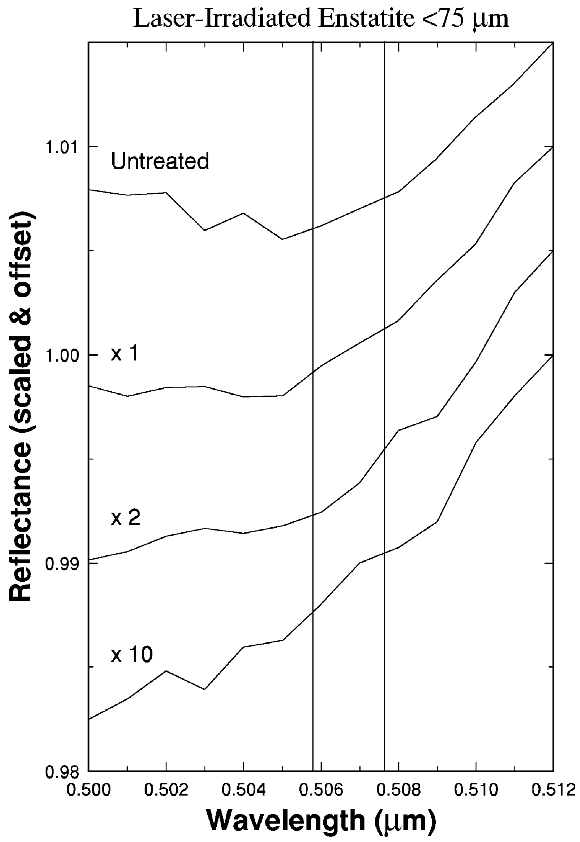

Fig. 3. Reflectance spectra of orthopyroxene powder samples treated with pulse laser irradiation to different degrees (Yamada *et al.*, 1999) measured at every 1 nm. The spectra are scaled to 1.0 at 512 nm and offset from one another for clarity. Each number after "x" indicates the number of pulse laser treatments. Two vertical lines show the HED band center range defined in Fig. 1. The 506.5 nm band is located near the left vertical line indicating the diogenite-like pyroxene composition, and the band becomes weaker and the spectrum becomes redder as the degree of pulse laser irradiation increases. An approximate error level of the measurements is 0.2% in scaled reflectance.

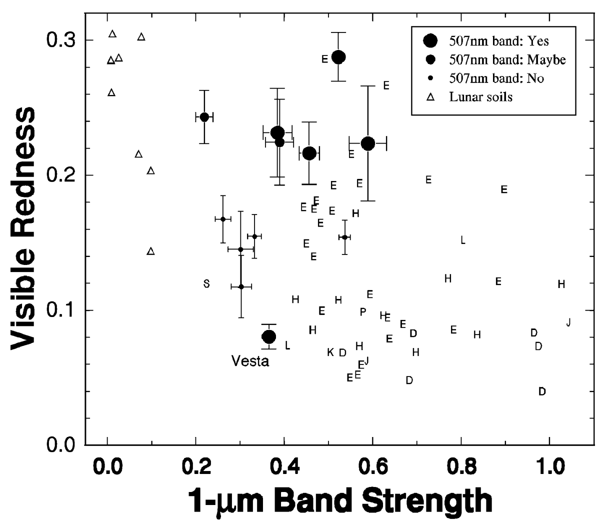

Fig. 4. A plot of the 1-μm band strength vs. the visible redness (Hiroi and Pieters, 1998) of HED meteorite samples (indicated as H, E, and D) including Johnstown diogenite (J) and its laser irradiated (L) samples from Wasson *et al.* (1998), Padvarninkai (P) and its impact melt (S) samples, and Kapoeta (K) sample, Vesta and Vestoids (filled circles) from Binzel and Xu (1993), and lunar soil samples (open triangles). The largest filled circles indicate Vesta and Vestoids that have the 506.5 nm band detected, medium size filled circles indicate Vestoids where the 506.5 nm band may or may not exist, and the smallest filled circles indicate Vestoids without the 506.5 nm band according to Vilas *et al.* (2000).

lunar samples also have a diversity of visible redness, they have much higher visible redness and weaker 1-μm band strength than HED meteorites because they were subject to heavy space weathering.

On the other hand, Vesta and Vestoids plot in the intermediate region between HED meteorites and lunar soils as pointed out by Hiroi and Pieters (1998). Although the diversity of Vesta and Vestoids in visible redness is consistent with the similar diversity of HED meteorites, the shape of the visible spectrum (Hiroi *et al.*, 1995) and weaker 1-μm band of many Vestoids compared with those of HED meteorites clearly indicate effects of space weathering on the asteroids, which is possibly similar to but less extensive than lunar space weathering.

5. Mystery of the 506.5 nm Band of Vesta and Vestoids

The most puzzling thing in Fig. 4 is the relationship of the presence/absence of the 506.5 nm band (Vilas *et al.*, 2000) and the space weathering trend of Vesta and Vestoids described in the previous section. Vesta's spectrum looks very similar to howardite's (Hiroi *et al.*, 1994) and both show the 506.5 nm band. This is reasonable if we assume Vesta has a fresh howardite-like surface. However, there is a trend that Vestoids with redder visible spectra show the 506.5 nm band and that Vestoids with bluer visible spectra do not show the 506.5 nm band as shown in Fig. 4. This observation is not expected based on a simple space weathering process, and we can only suggest the following explanations however complex or unlikely they may seem.

The first possible explanation is that Vestoids with the 506.5 nm band had relatively red visible spectra as some fresh eucrites do and did not experience any extensive space weathering that could have erased the 506.5 nm band. Vestoids without the 506.5 nm band may have had relatively blue visible spectra as diogenites, many howardites, and some eucrites do, and experienced heavy space weathering that erased the 506.5 nm band.

The second possible explanation is that Vestoids without the 506.5 nm band could have received heavy impacts that erased the 506.5 nm band. As demonstrated by the impact melt of Padvarninkai eucrite (S in Fig. 4), the 1-μm band can become weaker without significantly increasing the visible redness (conversion from point P to S in Fig. 4). Because even some lunar soils which are space weathered more heavily than any Vestoids show the 506.5 nm band, it is conceivable that the cause of absence of the 506.5 nm band among some Vestoids is due to shock or effects other than space weathering. In that case, the majority of Vestoids must be space weathered, and only those that experienced heavy shock have lost the 506.5 nm band.

The third possible explanation is that Vestoids without the 506.5 nm band are not made of HED materials but some kind of material rich in pyroxene that does not have a 506.5 nm band. This explanation would be supported by the existence of a pyroxene-rich rock, especially among meteorites, whose reflectance spectrum does not show the 506.5 nm band. Even if those Vestoids are not made of HED materials, it would not contradict with the highly-believed hypothesis that HED meteorites came from Vesta unless we proclaim too simplistically that all Vestoids must come from Vesta.

6. Conclusions

All HED meteorites have been shown to have the 506.5 nm band centered at different wavelengths according to pyroxene composition. Evidence has been presented that space weathering can reduce the 506.5 nm band of pyroxene. However, Vesta and some Vestoids did not apparently suffer enough space weathering that could have erased the 506.5 nm band. On the other hand, the five Vestoids without the 506.5 nm band must have gone through either heavy space weathering or shock that could erase the 506.5 nm band if they are made of HED materials. It is also possible that they are made of non-HED materials rich in pyroxene without the 506.5 nm band even as fresh. This possibility that some Vestoids did not come from Vesta would not necessarily deny the hypothesis that HED meteorites came from Vesta unless we believe all Vestoids must also come from Vesta.

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