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ORIGIN OF VESTOIDS SUGGESTED FROM THE SPACE WEATHERING TREND IN THE VISIBLE REFLECTANCE SPECTRA OF HED METEORITES AND LUNAR SOILS

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Abstract: The extended visible reflectance spectra of asteroid 4 Vesta and Vestoids (R. BINZEL and S. XU, Science, **260**, 186, 1993) have been compared with the space weathering trend of HED meteorites and lunar soils. In accordance to our previous study (T. HIROI *et al.*, Icarus, **115**, 374, 1995), many Vestoids show more weathered visible reflectance spectra than those of Vesta and HED meteorites. The Vestoids outside the HED-lunar space weathering trend tend to have orbits which require large ejection velocities if they came from Vesta. This result suggests that the Vestoids off the HED-lunar space weathering trend are quite distinct from the other Vestoids and may come from other asteroid(s), such as the projectile which collided with Vesta and excavated the majority of Vestoids inside the Vesta family.

1. Introduction

Asteroid 4 Vesta has been long known to have a basaltic surface composition similar to HED meteorites (MCCORD *et al.*, 1970). Vesta's surface heterogeneity was detected from its reflectance spectra at various rotational phases (GAFFEY, 1983, 1997), suggesting the possibility of eucrite or howardite covered surface with large craters excavating diogenite and dunite layers (GAFFEY, 1997). The existence of such craters was supported by a recent 4-color observation of Vesta by Hubble Space Telescope (BINZEL *et al.*, 1997), which also suggests existence of old basaltic crust.

On the other hand, 20 small (5–10 km) Vesta-like asteroids (Vestoids) were found inside the Vesta family and in between the Vesta-family orbits and the 3:1 Kirkwood Gap (BINZEL and XU, 1993). The "Vesta family" here is defined as a group of asteroids with similar orbital elements (semimajor axis, inclination, and eccentricity) which could result directly from a break-up of one parent body. Although it seems obvious that these Vestoids in Vesta-family were created in a collisional event with Vesta, the origin of Vestoids, especially those outside the Vesta family, is not clear (WASSON, 1995). Analyses of reflectance spectra of Vesta and Vestoids suggested the possibility of significant compositional differences or space weathering of Vestoids in comparison with HED meteorites (HIROI *et al.*, 1995). Also, recent NIR (1–1.6 μm) spectral measurements of some Vestoids (BURBINE and BINZEL, 1997) show much redder 1-μm band continuum than Vesta or HEDs, confirming the suggestion by HIROI *et al.* (1995).

In this paper, the study of reflectance spectra of Vestoids (HIROI *et al.*, 1995) is revisited to evaluate any space weathering trends among Vestoids suggesting their origin. Vestoids are compared with HED meteorites and lunar soils, including two HED samples altered by a natural shock brecciation process and an artificial irradiation by laser beam.

2. Experimental

Telescopic reflectance spectra of Vesta and 20 Vestoids used here are from Binzel and Xu (1993), and laboratory reflectance spectra of HED meteorites powders (<25 μm) are from Hiroi *et al.* (1995) except for Kapoeta howardite which is newly measured in this study. These samples were ground into powders of <25 μm. Reflectance spectra of Johnstown diogenite sample (<75 μm) before and after laser-irradiation are from Wasson *et al.* (1997).

In addition, a relatively dark portion from Padvarninkai eucrite was ground into powder of <25 μm and its reflectance spectrum was measured. The portion of Padvarninkai eucrite has dispersed troilites and possibly oxides set in a finely crystallized matrix, and other mineral fragments, suggesting its shock origin (Yamaguchi, pers. commun. 1997). This sample is tentatively called "shock breccia" in this paper.

Reflectance spectra of eight lunar bulk soils (12024, 12030, 12037, 12070, 14141, 14240, 15301, and 15601) whose bulk FeO contents are similar to those of HED meteorites were taken from the RELAB database as analogs of HED materials that have experienced various degrees of space weathering.

3. Effects of Laser Irradiation and Shock

Reflectance spectra (0.3–2.6 μm) of Johnstown diogenite (untreated and laser-irradiated) and Padvarninkai eucrite (bulk and shock breccia) are shown in Fig. 1. As shown in Fig. 1a, both the laser-irradiated diogenite and the shock breccia of eucrite are much darker and their absorption bands around 1 and 2 μm seem to be much weaker than their untreated or bulk samples. Similar effects were reported for shocked enstatite and labradorite (Adams *et al.*, 1979).

When these spectra are scaled to 1.0 at 0.56 μm in Fig. 1b, it becomes clear that the altered samples show weaker 1 and 2 μm bands, redder (increasing reflectance toward longer wavelength) around the 2 μm band, and slightly altered (smoothed) visible spectral profile in the 0.3–0.75 μm range. Although these two alteration processes (natural and synthetic) are very different, apparent spectral alteration effects shown here are not too different.

4. HED-Lunar Space Weathering Trend

In order to illustrate the trend of space weathering, shown in Fig. 2 are normalized reflectance spectra of a fresh diogenite, the laser-irradiated diogenite, Vesta, a Vestoid, and a lunar soil. The visible spectrum become redder and the 1-μm band becomes shallower in the order above. In order to quantify the degree of space weathering, the following spectral parameters are defined:

$$1\text{-}\mu\text{m band depth} = \ln R_{\mathrm{M}} - \ln R_{\mathrm{C}}, \tag{1}$$

$$\text{Visible redness} = \ln R_{\mathrm{M}} - \ln R_{55}, \tag{2}$$

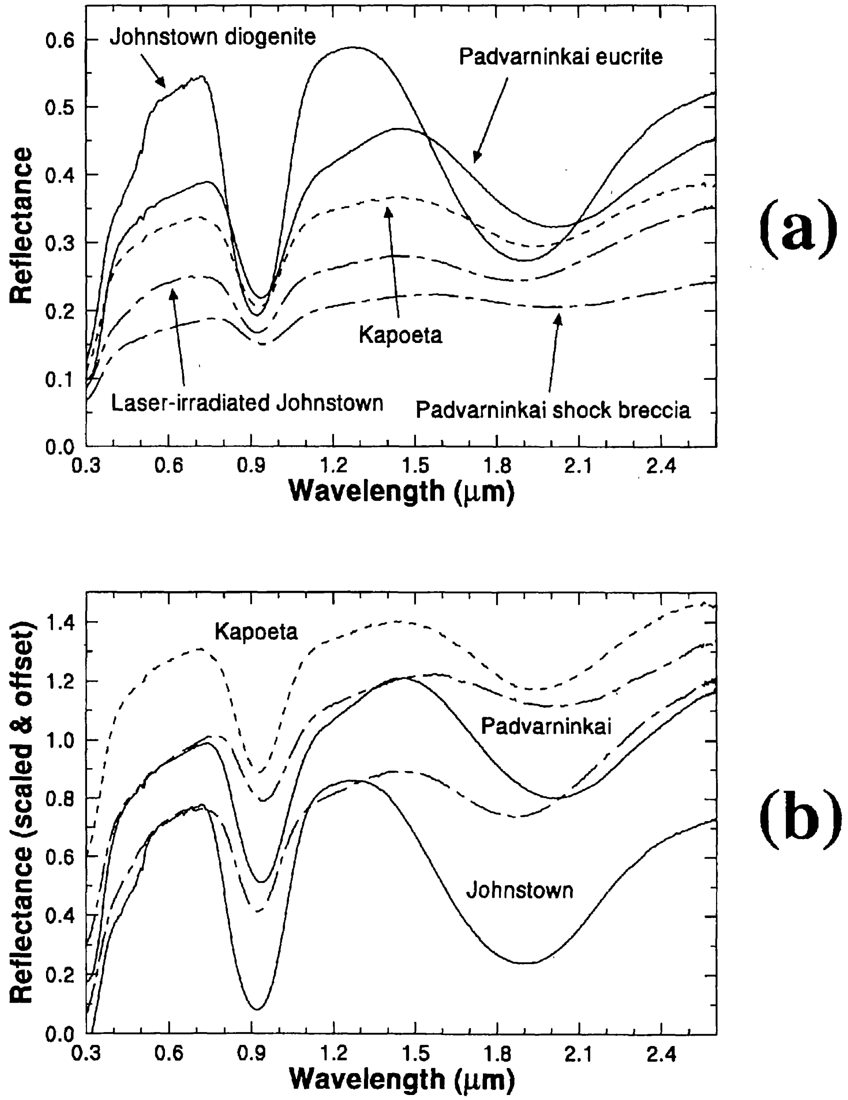

Fig. 1. Visible-NIR reflectance spectra of Kapoeta howardite sample (<25 μm), Johnstown diogenite samples (<75 μm) before and after laser-irradiation experiment (Wasson et al., 1997), and the bulk (Hiroi et al., 1995) and shock breccia samples (<25 μm) of Padvarninkai eucrite. Reflectances are plotted in actual value in (a), and scaled to 1.0 at 0.56 μm and offset in (b).

where R_M indicates the reflectance maximum around 0.74 μm, R_C at the 1-μm band center, and R_{55} at 0.55 μm as defined in Hiroi *et al.* (1995). Although the albedo of Vestoids are not known and their reflectances are normalized at one wavelength, the 1-μm band depth and the visible redness are independent of such a constant factor because it will cancel out in eqs. (1) and (2). These two parameters for HED meteorites, lunar soils, and Vesta-like asteroids are listed in Table 1. Plots of the 1-μm band depth *vs.* the visible redness are shown in Fig. 3.

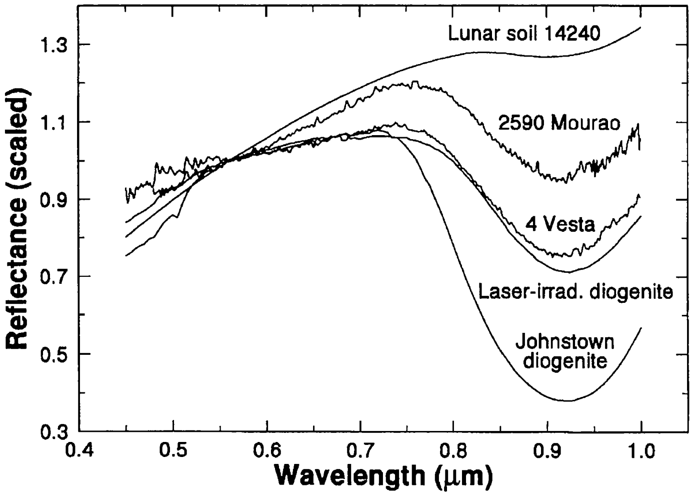

Fig. 2. Normalized reflectance spectra of Johnstown diogenite, the laser-irradiated one, Vesta, Vestoid 2590 Mourao, and lunar soil 14240. They are normalized to 1.0 at wavelength 0.56 µm.

Table 1. The 1-mm band depth and visible redness of HED meteorites, lunar soils with similar bulk FeO contents to HEDs, Vesta, and Vestoids (standard deviation values are given as last digits in parentheses).

	1-µm band depth	Visible redness		1-µm band depth	visible redness
HED meteorites			*Vesta & Vestoids*		
ALH-76005 (Euc)	0.4462	0.1741	4	0.365 (9)	0.081(9)
ALH-78132 (Euc)	0.5120	0.1753	1273	0.415 (28)	0.214 (28)
Juvinas (Euc)	0.6039	0.1129	1906	0.236 (14)	0.247 (14)
Millbillillie (Euc)	0.5804	0.0563	1929	0.463 (14)	0.158 (14)
Padvarninkai (Euc)	0.5835	0.0947	1933	0.333 (16)	0.155 (16)
Stannern (Euc)	0.4701	0.1360	2011	0.385 (33)	0.232 (33)
Y-74450 (Euc)	0.4521	0.1493	2113	0.389 (32)	0.225 (32)
Kapoeta (How)	0.5038	0.0692	2442	0.589 (43)	0.224 (43)
EET 87503 (How)	0.4665	0.0859	2590	0.222 (8)	0.191 (8)
EET 79002 (Dio)	0.6854	0.0474	3153	0.377 (22)	0.139 (22)
Johnstown (Dio)	0.5886	0.0644	3155	0.522 (18)	0.288(18)
Y-74013 (Dio)	0.5337	0.0704	3268	0.257 (28)	0.176 (28)
Y-75032 (Dio)	0.6949	0.0820	3657	0.537 (13)	0.154 (13)
Padvarninkai shock breccia	0.2241	0.1199	3869	0.457 (23)	0.216 (23)
Untreated Johnstown <75 µm	1.0426	0.0912	3944	0.315 (24)	0.192 (24)
Partly laser-irradiated Johnstown	0.8038	0.1522	3968	0.301 (28)	0.145 (28)
Fully laser-irradiated Johnstown	0.4020	0.0689	4005	0.507 (25)	0.241 (25)
Lunar soils			4038	0.219 (20)	0.243 (20)
12024	0.0255	0.2873	4147	0.303 (23)	0.118 (23)
12030	0.0979	0.2037	4215	0.435 (38)	0.261 (38)
12037	0.0703	0.2161	4546	0.261 (18)	0.168 (18)
12070	0.0109	0.3051			
14141	0.0978	0.1441			
14240	0.0090	0.2616			
15301	0.0079	0.2856			
15601	0.0762	0.3029			

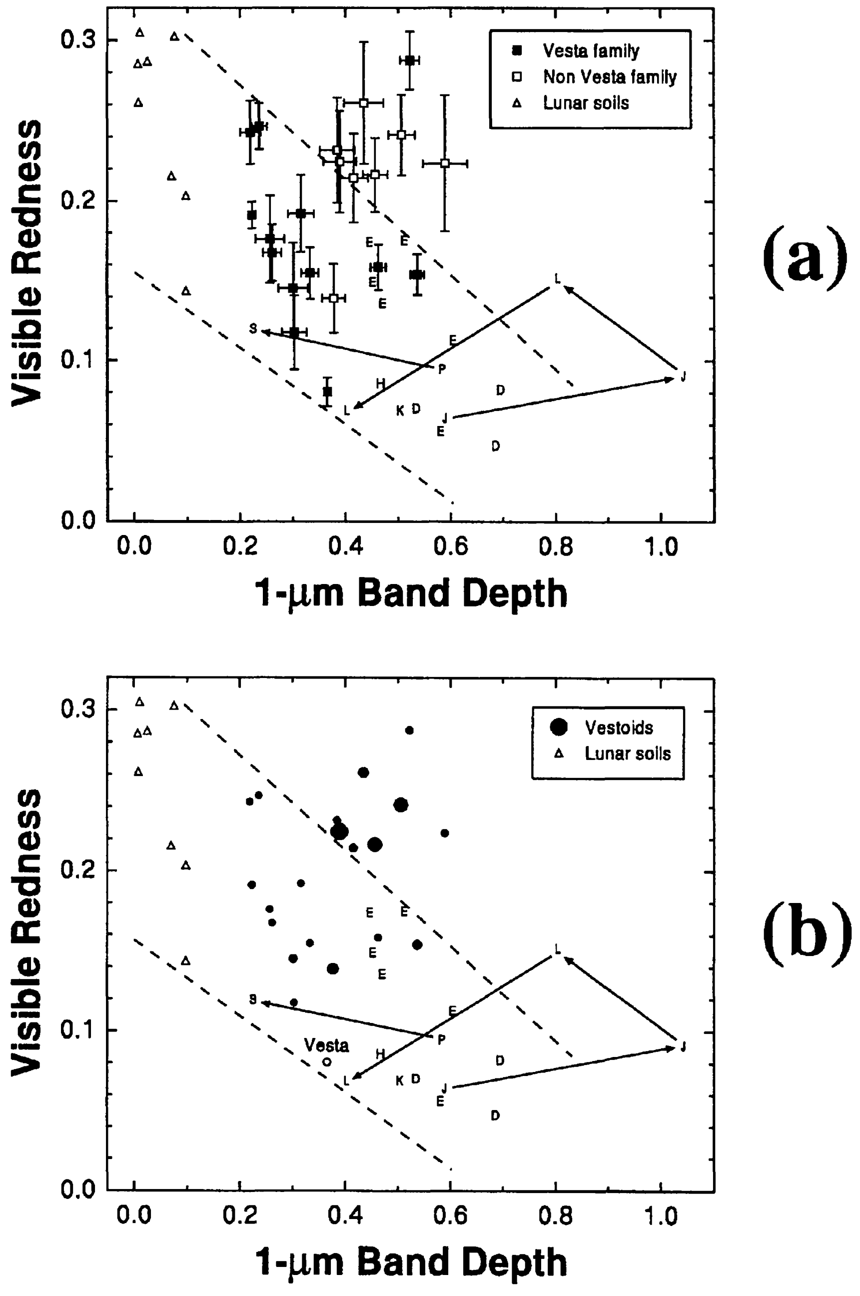

Fig. 3. Plots of the 1-μm band depth vs. the visible redness of reflectance spectra of Vesta, Vestoids, fresh and altered HED meteorites, and lunar soils. H, E, and D indicate howardite, eucrite, and diogenite, respectively. Padvarninkai eucrite sample and its shock breccia portion (Hiroi, 1997) are indicated as P and S, respectively. These two points are connected by an arrow. Two different grain-size fractions (<25 μm and <75 μm) of Johnstown diogenite are indicated as J, and partly and fully laser-irradiated samples (Wasson et al., 1997) of the Johnstown sample (<75 μm) are indicated as L. These points are connected by arrows in the above order. Open triangles indicate lunar soils. (a) Filled squares indicate Vestoids in the Vesta family, open squares Vestoids outside the Vesta family. (b) Each Vestoid is indicated as a filled circle whose size is proportional to the ejection velocity from Vesta (Binzel and Xu, 1993) if it came from Vesta.

As seen in Fig. 3a, there is a trend of spectral alteration (broken lines) defined by fresh HEDs (H, E, D, P: Padvarninkai, K: Kapoeta, and J: Johnstown), altered HEDs (S: Padvarninkai shock breccia and L: laser-irradiated Johnstown diogenite), majority of Vestoids in the Vesta family (filled squares), and lunar soils. The shock on Padvarninkai caused its position (P) to move in the upper left direction to the shock breccia (S). Also, as seen from two different grain-size fractions (<25 and <75 μm) of Johnstown diogenite (J), grain-size change caused the point to move in the upper right direction. In addition, laser irradiation caused the point to move in the upper left direction (partly irradiated sample) and then in the lower left direction (fully irradiated sample).

The majority of Vestoids inside this trend show more weathered reflectance spectra than those of Vesta and HEDs. On the other hand, the majority of Vestoids outside the Vesta family (open squares) do not follow the above HED-lunar space weathering trend but have redder visible spectral profiles and similar 1-μm depths to the fresh HEDs. The probability that seven out of eight Vestoids off the HED-lunar space weathering are located outside the Vesta family by chance is

$$ {}_{12}C_1 \cdot {}_{8}C_7 \,/\, {}_{20}C_8 = 0.00076, \tag{3} $$

which is negligibly small.

Shown in Fig. 3b is a similar plot to Fig. 3a except that each Vestoid is represented by a filled circle whose size is proportional to its ejection velocity (BINZEL and XU, 1993) from Vesta if it came from Vesta. Three Vestoids with the largest ejection velocities all plot outside the HED-lunar space weathering trend zone (between two broken lines). The probability that such a distribution happens by chance is

$$ {}_{8}C_3 \,/\, {}_{20}C_3 = 0.049, \tag{4} $$

which is about 5%.

5. Origin of Vestoids and HED Meteorites

The following points are suggested regarding the origin of Vestoids and HED meteorites: (1) Most Vestoids in the Vesta family are originally made of HED meteorite materials. (2) Most Vestoids in the Vesta family are more altered than Vesta. (3) Most Vestoids outside the Vesta family are either altered in a different way from other Vestoids or are originally made of different materials from HED meteorites. (4) There is a group of Vestoids which are both dynamically and spectrally distinct from the other Vestoids.

The above suggestions support the traditional view that HEDs came from Vesta (MCCORD *et al.*, 1970) but cast a shadow over the idea that Vestoids outside the Vesta family are the link between Vesta and HEDs (BINZEL and XU, 1993). Because the majority of the Vestoids between Vesta and the 3:1 Kirkwood Gap are off the HED-lunar space weathering trend, if they came from Vesta and are the sources of HED meteorites, their spectral differences from Vesta and HEDs and the correlation between their dynamical and spectral distinction from the other Vestoids must be explained.

One explanaiton is that the Vestoids off the HED-lunar space weathering trend have coarser average grain sizes than those inside the trend, as suggested from two J points in Fig. 3a. If this is the case, the reason why Vestoids with higher ejection velocity tend to have coarser grain size must be explained. It seems not clear whether higher velocity or higher energy impact will cause enrichment or depletion of fine grains.

Another explanation is that the Vestoids off the HED-lunar space weathering trend came from another asteroid, possibly the impactor which collided with Vesta and excavated the other Vestoids. Unless the surface is coated with an optically thick blanket of Vesta debris, the composition of the impactor asteroid must also be basaltic. If various types of iron meteorites and the M asteroids all belong to the cores of the ancient lost asteroids, their surfaces were most likely basaltic. Considering the compositional zoning of the solar system (GRADIE and TEDESCO, 1982), it is no wonder that there were more than one basaltic asteroids near Vesta's orbit.

However, the results of this study will not eliminate the possibility that Vestoids are non-HED asteroids which had a grazing impact with Vesta (WASSON, 1995). In this case, some of such asteroids had greater interaction with Vesta causing themselves coated with HED materials from Vesta and became members of the Vesta family. Other Vestoids had lesser interaction with Vesta, thus were not covered with HED materials so extensively, and escaped toward the 3:1 Kirkwood Gap. The reason why Vesta seems to be fresher than Vestoids, in this case, is that Vestoids have different mineral composition underneath the HED coating, which have been gradually lost, making Vestoids' spectra less similar to HEDs than Vesta.

Third possibility involving mixtures of Vesta debris and impactor material requires more extensive modeling. And this entire issue must be further studied with more evidence from more observations of Vestoids and Vesta and the spectral and mineralogical studies of HED meteorites.

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