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A spectroscopic comparison of HED meteorites and V-type asteroids in the inner Main Belt

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ABSTRACT

V-type asteroids in the inner Main Belt ($a < 2.5$ AU) and the HED meteorites are thought to be genetically related to one another as collisional fragments from the surface of the large basaltic Asteroid 4 Vesta. We investigate this relationship by comparing the near-infrared (0.7–2.5 μm) spectra of 39 V-type asteroids to laboratory spectra of HED meteorites. The central wavelengths and areas spanned by the 1 and 2 μm pyroxene–olivine absorption bands that are characteristic of planetary basalts are measured for both the asteroidal and meteoritic data. The band centers are shown to be well correlated, however the ratio of areas spanned by the 1 and 2 μm absorption bands are much larger for the asteroids than for the meteorites. We argue that this offset in band area ratio is consistent with our currently limited understanding of the effects of space weathering, however we cannot rule out the possibility that this offset is due to compositional differences. Several other possible causes of this offset are discussed.

Amongst these inner Main Belt asteroids we do not find evidence for non-Vestoid mineralogies. Instead, these asteroids seem to represent a continuum of compositions, consistent with an origin from a single differentiated parent body. In addition, our analysis shows that V-type asteroids with low inclinations ($i < 6°$) tend to have band centers slightly shifted towards long wavelengths. This may imply that more than one collision on Vesta's surface was responsible for producing the observed population of inner belt V-type asteroids. Finally, we offer several predictions that can be tested when the Dawn spacecraft enters into orbit around Vesta in the summer of 2011.

1. Introduction

The basaltic howardite, eucrite and diogenite meteorites (HEDs) and the large Main Belt Asteroid 4 Vesta have traditionally been linked due to their spectroscopic similarity and the lack of any other large asteroid with the characteristic spectral signature of magmatic basalts (McCord et al., 1970; Consolmagno and Drake, 1977). The presence of a collisional family associated with Vesta supports this link. Vesta-family members, often referred to as the Vestoids, are spectroscopically classified as V-types and can be dynamically linked to Vesta. The term non-Vestoid commonly refers to any V-type asteroid that originated on a parent body other than Vesta.

The Vestoids extend from the ν_6 secular resonance at the inner edge of the Main Belt to the 3:1 mean motion resonance with Jupiter at 2.5 AU (Fig. 1, Binzel and Xu, 1993). These resonances act as a dynamical escape hatch from the Main Belt and can transport fragments removed from the surface of Vesta (or one of the Vestoids) to the Earth as HED meteorites (Gladman et al., 1997). Resolved images of Vesta reveal a large crater (~460 km in diameter) on its south pole (Thomas et al., 1997), supporting a scenario of collisional formation for the Vesta family.

Hydrocode simulations of the collision that formed the Vesta family (Asphaug, 1997) suggest that km-size fragments would have been removed with ejection velocities (Δv) of no greater than approximately 0.6 km/s. Simplified versions of Gauss's equations can be used to quantify the distance from Vesta in orbital element space corresponding to this ejection velocity (Zappala et al., 1996).[1] The maximum range of semi-major axes accessible to collisionally-produced fragments can be estimated by assuming that

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[1] The following calculations assume that the true anomaly and argument of perihelion at the time of formation of the Vesta family were equal to those calculated by Zappala et al. (1996). However, these authors did not consider the effects of orbital migration due to the Yarkovsky force (Bottke et al., 2006). Therefore, the calculations presented here are approximations accurate to ~20%.

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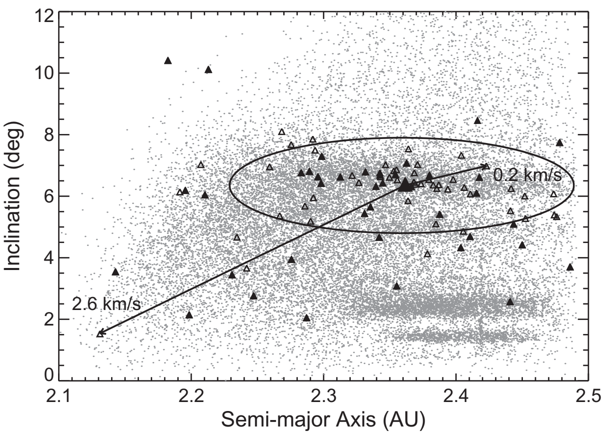

Fig. 1. Dynamical map in proper element space of V-type asteroids in the inner Main Belt. The filled triangles represent the V-type asteroids with NIR spectra included in this study. The open triangles are all spectroscopically confirmed V-types based solely on visible wavelength data (Xu et al., 1995; Bus and Binzel, 2002b; Lazarro et al., 2004; Alvarez-Candal et al., 2006; Moskovitz et al., 2008a). Vesta is denoted by the large filled triangle at 2.36 AU, 6.35°. The gray dots in the background are all objects from the 4th release of the SDDS MOC (Parker et al., 2008). The ellipse traces the 0.6 km/s ejection velocity relative to Vesta. The relative ejection velocities for two objects are indicated by the arrows.

a hypothetical Vestoid was ejected with a 0.6 km/s velocity vector aligned exclusively in a direction tangential to its orbit (Eq. (4) in Zappala et al. (1996)). This calculated range is 2.23–2.49 AU, centered on the semi-major axis of Vesta (2.36 AU). Similar calculations can be done for both eccentricity and inclination, producing ranges of 0.06–0.13° and 4.8–7.9° respectively. This region of orbital element space is enclosed by the ellipse in Fig. 1.

Fig. 1 shows numerous V-type asteroids in the inner Main Belt with values of Δv much larger than 0.6 km/s, some with values in excess of 2 km/s. When these objects were first discovered (e.g., Binzel and Xu, 1993; Burbine et al., 2001; Florczak et al., 2002; Lazarro et al., 2004; Alvarez-Candal et al., 2006) it was unclear how they could have reached such orbits. However, recent progress in the use of numerical integrators has helped to clarify this issue. Carruba et al. (2005) showed that three-body and weak secular resonances could lead to the migration of some Vestoids to orbits with $\Delta v > 0.6$ km/s. Nesvorný et al. (2008) showed that a combination of these resonances and the Yarkovsky effect could disperse the orbits of Vestoids to nearly the full extent of the inner Main Belt. However, these authors found that the observed number of V-type asteroids at low inclination ($i < 6°$) was too large to be explained by their model of Vestoid migration.

Three possibilities exist to explain this over-abundance of low-i V-types. First, these objects could be fragments of basaltic crust from a non-Vestoid differentiated parent body. In this case these objects could be spectroscopically distinct from the Vestoids, as is the case for non-Vestoid V-types in the outer Main Belt (e.g., Lazzaro et al., 2000; Moskovitz et al., 2008b). Second, they may be from Vesta, but were removed from the surface before the Late Heavy Bombardment (LHB), before the primary family-forming collision, and were scattered to their current orbits as mean motion and secular resonances swept through the Main Belt during the LHB (Gomes, 1997). In this case these objects would represent an older population of Vestoids, removed from a different region on Vesta's surface and thus might be spectroscopically distinct. Third, these objects may have been ejected from the Vesta parent body at the time of family formation and have since migrated to their current orbits by some unexplored dynamical mechanism. In this case these objects should not appear spectroscopically different from other V-type asteroids in the inner Main Belt.

A similar line of reasoning motivated Hiroi and Pieters (1998) to investigate the visible-wavelength spectral features (namely the slope and 1 μm band depth) of 20 V-type asteroids in the inner Main Belt as a function of their orbital elements. These authors found that V-type asteroids with large values of Δv tended to have steeper spectral slopes than V-types with smaller Δv. However, the largest value of Δv considered by these authors was 0.65 km/s, very close to the expected ejection velocity of Vestoid fragments. Furthermore, all of the objects that were studied have since been incorporated into the Vesta dynamical family as detection completeness has increased in the last decade. Thus it is surprising that this spectroscopic trend was observed as a function of orbital parameters for objects that plausibly originated at the same time from the same parent body.

Duffard et al. (2004) attempted a similar investigation into the spectroscopic diversity of Vestoids at NIR wavelengths. This study produced unexpected results: the Band II to Band I area ratios and the Band I and Band II centers for the majority of the V-types in their sample did not agree with those of the HEDs (Band I and Band II refer to the 1 and 2 μm absorption bands common to basaltic material, see Section 2 for definitions of these parameters). Although it has been suggested that band area ratios are sensitive to variations in grain size, temperature and space weathering (Ueda et al., 2002), band centers should be less sensitive to these effects and thus comparable between genetically related populations (i.e. the HEDs and Vestoids).

In light of recent advances in dynamical simulations (Carruba et al., 2005; Nesvorný et al., 2008) and improvements in NIR spectroscopic instrumentation (Rayner et al., 2003), we revisit the issue of the diversity of basaltic asteroids by measuring the NIR spectral properties of 39 inner Main Belt V-type asteroids. The goals of this study are threefold: (1) address the reported spectro-dynamical correlation amongst V-type asteroids in the inner Main Belt (Hiroi and Pieters, 1998) by extending our analysis out to NIR wavelengths and by including V-types across a wider range of orbital element space; (2) address the findings of Duffard et al. (2004) to look for spectroscopic differences between inner belt V-type asteroids and HED meteorites; (3) determine if any of the V-type asteroids in the inner Main Belt have spectroscopic properties suggestive of a non-Vestoid mineralogy. It is important to note that we do not attempt to extract detailed mineralogical information for individual asteroids. Instead we characterize our relatively large data set using band analysis techniques (e.g., Cloutis et al., 1986) with the intent of making statistically significant statements about the gross spectral properties of V-type asteroids relative to those of the HED meteorites.

2. Spectral band analysis

The reflectance spectra of minerals contain absorption features that are diagnostic of properties such as composition, albedo, grain size and crystal structure. A variety of analytic tools have been developed to interpret such information from remotely obtained spectra (e.g., Sunshine et al., 1990; Hiroi et al., 1993; Shkuratov et al., 1999; Lawrence and Lucey, 2007). Band analysis techniques (e.g., Cloutis et al., 1986) are useful for characterizing spectral data and can be used as a starting point for deriving mineralogical information (Gaffey et al., 2002). As a characterization tool, band analyses are completely objective, requiring no knowledge or assumptions about mineralogy, and can be implemented quickly for a large number of spectra. The primary goal of this work is to use band analysis techniques to facilitate a comparison between HEDs and V-type asteroids. We perform this band analysis with attention to the following parameters: the minima and central wavelength of the 1 and 2 μm olivine–pyroxene absorption features (Band I and Band II respectively) and the ratio of areas within