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Spectral characterization of V-type asteroids: are all the basaltic objects coming from Vesta?

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Abstract. In the last twenty-five years several small basaltic V-type asteroids have been identified all around the main belt. Most of them are members of the Vesta dynamical family, but an increasingly large number appear to have no link with it. The question that arises is whether all these basaltic objects do indeed come from Vesta. In the light of the Dawn mission, who visited Vesta in 2011-2012, recent works were dedicated to the observation of several new V-type asteroids and their comparison with laboratory data (Fulvio et al., (2015)), and to a statistical analysis of the spectroscopic and mineralogical properties of the largest sample of V-types ever collected (Ieva et al., (2015), with the objective to highlight similarities and differences among objects belonging and not belonging to the Vesta dynamical family. Laboratory experiments support the idea that V-type NEAs spectral properties could be due to a balance of space weathering and rejuvenation processes triggered by close encounters with terrestrial planets. Statistical analysis shows that although most of the V-type asteroids in the inner main belt do have a surface composition compatible with Vesta family members, this seem not to be the case for V-types in the middle and outer main belt. For these Middle and Outer V-types (MOVs), their sizes, spectral parameters and location far away from the Vesta dynamical region point to a different origin than Vesta.

Key words. Asteroids: spectroscopy – Vesta – V-type asteroids – basaltic objects– HED meteorites – Space weathering

1. Introduction

Asteroid (4) Vesta is the largest differentiated main belt object showing a basaltic crust. The basaltic composition of its surface has been discovered by McCord et al., (1970), later on confirmed by many observations (e.g., McFadden et al., (1977); Binzel et al., (1997); Gaffey (1997); Vernazza et al., (2005)) and strengthen by the extensive and detailed data provided by the Dawn spacecrafts visible and infrared spectrometer VIR (De Sanctis et al., (2012)). The Dawn spacecraft data show that the 0.9 and 1.9 μm pyroxene signatures (hereafter BI and BII, respectively) are present ubiquitously across Vesta surface and confirm that Vesta surface composition is similar to the one of the Howardite-Eucrite-Diogenite meteorites (HEDs). Nevertheless, HEDs lithologies are present on Vesta with spectral variations at both large and small scale across its surface and Vesta mineralogy indicates a complex geological and collisional history (De Sanctis et al., (2012); Jaumann et al., (2012); Russell et al., (2012)).

In recent years several tens of asteroids have been found to show a surface composition similar to the one of Vesta and have been classified as "V-types". Many of these objects belong to the Vesta dynamical family ("vestoids") and they are believed to derive from the huge collisional event responsible for the large craters near the south pole of Vesta (Thomas et al., (1997); Marchi et al., (2012)). The discovery of V-types outside the limits of Vesta dynamical family (Duffard et al., (2004); Carruba et al., (2005); Alvarez-Candal et al., (2006); Moskovitz et al., (2010)) called this picture into question and, notwithstanding dynamical simulations showed that some "non-vestoids" could be fugitives from the Vesta family (Nesvorný et al., (2008); Roig et al., (2008)), many other non-vestoids do not show any clear dynamical link to Vesta, thus suggesting that they could be fragments of distinct differentiated parent bodies (Lazzaro et al., (2000); Binzel et al., (2006)). Recent measurements on oxygen isotopic composition of HEDs have indicated that, although most of them come from the same basaltic parent body, few others do not match this view (Scott et al., (2009)).

2. Dynamical grouping

In the light of the Dawn mission (De Sanctis et al., (2012)) recent works were dedicated to the characterization of V-type asteroids, belonging ("vestoids") and not belonging to Vesta dynamical family ("V-types non vestoids"). Fulvio et al., (2015) has observed new V-type asteroids not dynamically linked to Vesta and compared V-type spectra with laboratory data for HED meteorites, before and after irradiation. Ieva et al., (2015) has performed a statistical analysis on the largest sample of V-types ever collected, focusing on spectral parameters computed from visible, near-infrared and VNIR spectra. In their works Ieva et al., (2015) and Fulvio et al., (2015) divided V-type asteroids, available in literature, in six groups according to their dynamical properties.

Therefore:

- A **vestoid** is a V-type member of the Vesta dynamical family, as defined by Nesvorný[1] using the Hierarchical Clustering Method (HCM).
- A **fugitive**, following the definition of Nesvorný et al., (2008), is a V-type asteroid with $a < 2.3$ AU and comparable e and i with the Vesta family.
- Also according to Nesvorný et al., (2008) a low-inclination (**low-i**) is a V-type asteroid having $i < 6°$ and $2.3 < a < 2.5$ AU.
- The remaining V-type asteroids in the inner main belt were identified as **IOs.**
- A **NEA** is a V-type asteroid in the near-Earth region (with a perihelium q < 1.3 AU).
- A **MOV** is a V-type asteroid in the middle and outer main belt ($a > 2.5$ AU).

3. Spectral analysis

3.1. Visible range

The principal aim of the statistical analysis is to check if the different V-types across the main belt and near-Earth region share the same spectral properties as those objects that very plausibly come from Vesta (i.e the vestoids). In order to highlight similarities and differences among different dynamical groups Ieva et al., (2015) focused in the visible range on three parameters: the reflectivity gradient in the 5000 - 7500

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[1] http://sbn.psi.edu/pds/resource/nesvornyfam.html

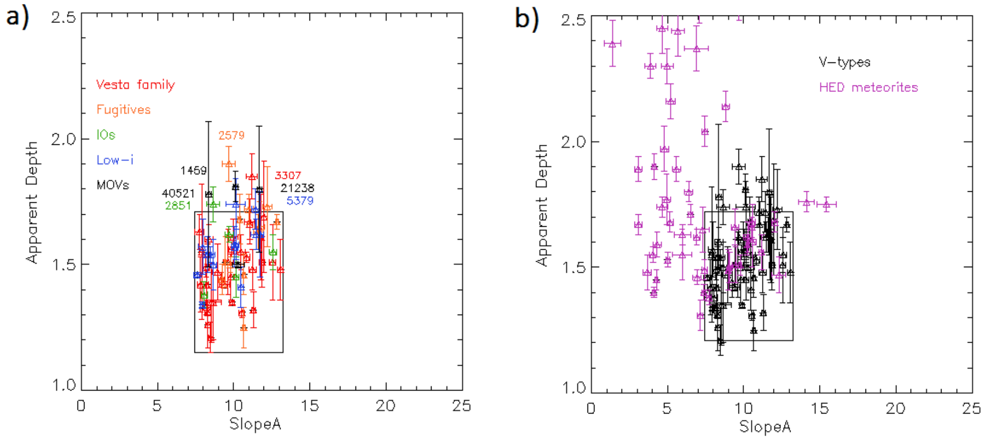

Fig. 1. a) SlopeA/Apparent Depth computed for a sample of V-type objects grouped according to their dynamical properties: Vestoids or Vesta family objects, Fugitives, Inner Others (IOs), Low-inclination and Middle/Outer main belt V-types (MOVs). b) SlopeA/Apparent Depth for a sample of HED meteorites and V-type objects. The box is defined by the values of the spectral parameters for V-types belonging to the control sample: Vesta family members observed in the visible and NIR range under similar observational conditions. From Ieva et al., (2015).

Å range (**slopeA**) and 8000 - 9200 Å range (**slopeB**), and the ratio between the reflectivity at 7500 and 9000 Å (**apparent depth**). Since the slopeA parameter can also depend on the phase angle α, Ieva et al., (2015) corrected their computed values applying an empirical relation found for Vesta by Reddy et al., (2012).

In Fig. 1a is reported slopeA vs apparent depth for the whole sample of V-types, grouped according to their dynamical properties: the rectangular region is a control sample, defined by those vestoids which have both visible and near-infrared spectra and were observed at similar phase angles. Most of the database of V-types cluster in the region defined by the control sample. For few objects the experimental errors in the depth determination, due to the low S/N spectra in this region, are too big to exclude a compatibility with the control sample zone; other V-types outside the control sample (1459, 2579, 3307) have apparent depth higher than 1.80, which could be symptomatic of a bigger grain size, fresh pyroxene or a different mineralogy. V-type NEAs show a great variation of the apparent depth, having depth greater and lower than the control sample, but since no phase angle correction is available for NEAs, observed at $\alpha > 30°$, they aren't shown in Fig. 1.

Spectral parameters computed on V-type asteroids were compared with a sample of HED meteorites collected from the RELAB database[2]: V-types have in general a quite redder slopeA and a lower apparent depth than HED suite, as clearly shown in Fig 1b. This suggests that even after the phase angle correction V-types are intrinsically redder, showing a certain degree of space weathering alteration.

3.2. NIR range

In the near-infrared (NIR) range V-type asteroids are characterized by the presence of two deep absorption features, due to pyroxene minerals, at 0.9 and 1.9 μm (BI and BII). From the comparison of the minimum of the absorption bands (**BI** and **BII center**), which are the most diagnostic parameters to infer mineralogical properties, it is possible to see if different dynamical groups have different spectral parameters, hence a different mineralogy. In

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[2] http://www.planetary.brown.edu/relabdocs/relab

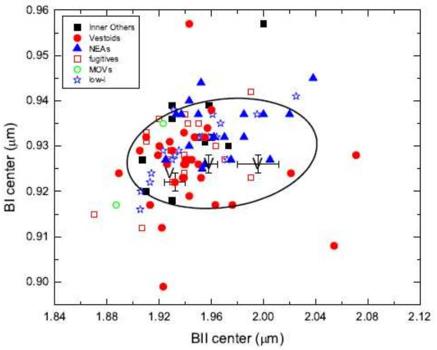

Fig. 2. BI center vs. BII center for the different dynamical classes and subclasses of V-types considered in this work: Vestoids, Fugitives, IOs, Low-i, NEAs and MOVs. The V symbols indicate Vesta ground-based observations from Vernazza et al., (2005) while the oval area delimits the range of values obtained by the Dawn spacecraft (De Sanctis et al., (2012)). From Fulvio et al., (2015)

Fig. 2 from Fulvio et al., (2015) are plotted BI center vs. BII center for all the V-types in the sample. Vesta family members (vestoids) tend to regroup in the region 0.91 μm $\leq$ BI$_{center}$ $\leq$ 0.94 μm and 1.88 μm $\leq$ BII$_{center}$ $\leq$ 1.98 μm, although few asteroids spread out toward higher BII center or lower BI center. One asteroid (3613) shows the highest BI center value, at odds with other vestoids. Fugitives, low-i and IOs show BI and BII center values comparable to those above mentioned for vestoids, with few exceptions. On the contrary, a shift toward higher BI and BII center values seems to be shown by V-type NEAs with respect to the Vesta family. One of the three MOV confirmed in the NIR range (21238) show low BI/BII centre.

4. Comparison with laboratory data and Dawn's Vestan spectra

4.1. Comparison with HED meteorites

To better understand the connection between V-type asteroids, Vesta, and HED meteorites Fulvio et al., (2015) performed a comparison of V-type spectra with laboratory spectra of two eucrites (DaG 684 and Bereba) before and after different stages of Ar^{+} and C^{+} irradiation experiments, simulating space weathering. From Fig. 3 it is clear that space weathering should cause V-type NEAs reflectance spectra to be much redder than they actually appear. V-type NEAs instead show less-weathered spectra than other subclasses. This could could be due in principle to a balance between weathering processes, which tend to redder the spectra, and regardening processes, like a close encounter with a planet, which expose fresh unweathered pyroxene.

4.2. Comparison with Dawn data

In order to confirm or exclude a genetic link between Vesta and the two MOV objects (1459 Magnya and 21238 Panarea) Ieva et al., (2015) look for spots on the surface of Vesta having a composition and a mineralogy compatible with them. The comparison was performed using Dawn spectra collected by the VIR instrument on the south pole region, near the craters which likely produced the Vesta dynamical family. From the comparison of the maps of BI-BII centres and depths produced by the VIR Team (Ammannito et al., (2013)) and the same parameters obtained using the same procedures for the two MOV objects, it is clear that Magnya and Panarea have spectral parameters not compatible with the south pole region of Vesta. Moreover, the excavation of a (17 ± 1) km object like Magnya (Delbò et al., (2006)) from the two deep craters around the south pole of Vesta (which have an estimated depth of 30-45 km) seems rather improbable (For further details see Ieva et al., (2015)).

5. Conclusions

In the statistical analysis NEAs and MOVs show the most extreme spectral parameters of the whole sample, quite different to the Vesta family. Space weathering affects the surfaces of basaltic material, reddening the visibile spectral slope and lowering the 0.9 and 1.9 μm band depths. V-type NEAs seem instead to have experienced "moderate" weathering effects, although they tend to pass closer

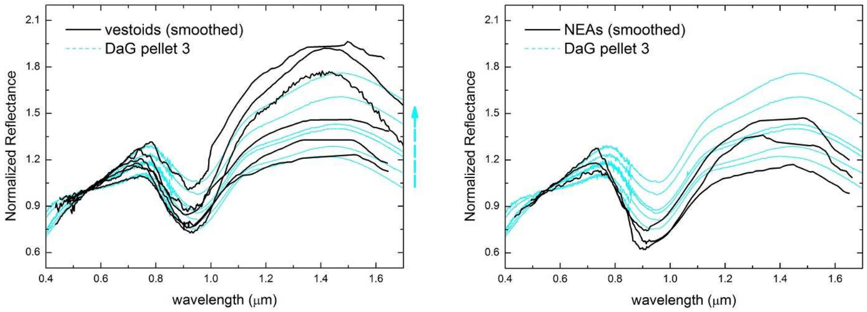

Fig. 3. Comparison between VIS-NIR spectra of (left) vestoids and (right) NEAs with laboratory spectra of meteorite DaG at different stages of ion irradiation. The arrows indicate increasing fluence of irradiation. Adapted from Fulvio et al., (2015)

to the Sun than main belt asteroids, having experienced in principle stronger weathering. For V-type NEAs, the extreme parameters shown and laboratory experiments strongly support the idea that their surfaces testify a balance of weathering processes and a "rejuvenation" of surfaces triggered by regardening processes, like close encounters with terrestrial planets (See Fulvio et al., (2015)).

The two MOV objects Magnya and Panarea show instead different spectral parameters, not compatible with the south pole region on Vesta, which is likely the origin of the Vesta dynamical family. Their location in the main belt strongly points to a different origin from Vesta, since the probability that a 5 km V-type asteroid ejected from Vesta crosses the 3:1 resonance with Jupiter and reaches a stable orbit in the middle/outer belt is almost 1% (Roig et al., (2008)). Magnya has also an estimated diameter too big to be extracted from the south pole of Vesta. Moreover, Hardersen et al., (2004) has claimed for Magnya a different mineralogy. For these two basaltic objects, their peculiar spectral properties, sizes and location in the main belt argue that they could come from a different parent body than Vesta (Ieva et al., (2015)).

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