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Spectral characterization of V-type asteroids outside the Vesta family

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ABSTRACT

We present new near-infrared (NIR) reflectance spectra of 10 V-type candidate asteroids obtained at the 3.6 m Telescopio Nazionale Galileo covering the spectral range of 0.7–2.5 μm. The observed objects were selected from diverse data sets of putative V-type asteroids in order to characterize them, and hence better understand their relationship with (4) Vesta. We derive spectral parameters from NIR spectra to infer mineralogical information of the observed asteroids. All the spectra of the asteroids here reported show two prominent absorption features at 1 and 2 μm that are typical of V-class objects. The comparison of spectral parameters such as band centres and band separation, among our observations, Howardites, Eucrites, Diogenites meteorites, and (4) Vesta from Visible and Infrared Spectrometer (VIR) data on Dawn reveals that there is a strong correlation between these objects. From our analysis, four objects are compatible with Howardites, three are more similar to a eucritic-like composition, and two are compatible with Diogenites. Asteroid 26145, which is the only member of the Vesta dynamical family observed in 2012 March, is compatible with Vesta's surface, and shows a composition close to the Eucrites.

Key words: techniques: spectroscopic – minor planets, asteroids: individual: Vesta.

1 INTRODUCTION

(4) Vesta is one of the smallest differentiated objects of the Solar system. Its composition has been extensively studied in the past decades (McCord, Adams & Johnson 1970; McFadden, McCord & Pieters 1977; Binzel et al. 1997), revealing the presence of a basaltic crust. (4) Vesta is spectroscopically similar to the basaltic achondrite suite of meteorites, collectively known as Howardites, Eucrites, Diogenites (HED; McCord et al. 1970; Burbine et al. 2001; Drake 2001; De Sanctis et al. 2013) for which it is thought to be the parent body (Binzel et al. 1997; Moskovitz et al. 2010; De Sanctis et al. 2012). The discovery of a large basin in the Southern hemisphere of the object from *Hubble Space Telescope* observations (Li et al. 2010) and subsequently confirmed by the NASA Dawn mission observations (Russell et al. 2012), strengthened the hypothesis that fragments originated after a collisional event might have been ejected into orbits dynamically linked to (4) Vesta, thus forming its family. According to the recent review on asteroid families by Nesvorný, Brož & Carruba (2015), the Vesta family counts 15 252 members, assuming a cutoff distance of 50 $\mathrm{ms^{-1}}$, confined between (4) Vesta's orbit and the 3:1 mean motion resonance. The analysis of these asteroid spectral properties reveals that they are compatible with basaltic material, although differences among them have also been observed (Burbine et al. 2001; Duffard et al. 2004; Moskovitz et al. 2010). Recent high-resolution observations of a selected number of V-type asteroids belonging to Vesta's family clearly showed this diversity (Hardersen et al. 2014), and allowed inferring an origin from different regions on (4) Vesta's surface for these objects.

The identification of many V types, located in the inner Main Belt but not members of the Vesta dynamical family (Xu et al. 1995; Florczak et al. 1999; Burbine et al. 2001; Alvarez-Candal et al. 2006), raised the question whether they originated from another differentiated parent body. Numerical simulations of the dynamical evolution of Vesta's fragments have shown that a relatively large fraction might evolve out of the family borders (Nesvorný et al. 2008). On the other hand, these results also indicate that for the low-inclination objects, with $i < 5°$, a link with (4) Vesta is more difficult to confirm and a different origin is plausible. The analysis of a subset of these objects (Moskovitz et al. 2010; De Sanctis et al. 2011b) seems to indicate a composition closer to Eucrites than Vesta's dynamical family members. The discovery of a second more ancient basin in the (4) Vesta Southern hemisphere further complicated the ejection scenario from (4) Vesta (Schenk et al. 2012).

Moreover, the identification of small basaltic asteroids, 1459 Magnya, 10537 1991RY16, and 21238 1995WV7 (Lazzaro et al. 2000; Binzel et al. 2006; Hammergren, Gyuk & Puckett 2007; Moskovitz et al. 2008), in the outer and intermediate Main Belt, strongly points to the possibility of the catastrophic disruption of other differentiated objects. The main reason being that it is not yet

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Table 1. Observational and physical data for the observed asteroids. The columns indicate, respectively: (1) the asteroid, (2) the observation date, (3) the total exposure time, (4) the proper semimajor-axis, (5) the proper eccentricity, (6) the proper inclination, (7) the absolute magnitude, (8) the diameter, (9) the visual magnitude at the observing date. The proper elements are obtained from the Asteroids Dynamic Site (http://hamilton.dm.unipi.it/~astdys2/catalogs/allnum.pro), while the diameter has been computed assuming an albedo of 0.361 (Masiero et al. 2013).

Asteroid	Date	Exp time (s)	a_p (au)	e_p	i_p (°)	H (mag)	Diam (km)	V (mag)
2614 Torrence	2012-March-17	4230	2.338 10	0.1244	6.0675	12.920	5.773	17.12
6550 Parler	2012-March-17	2700	2.409 74	0.1873	6.1712	13.350	4.736	16.30
7798 (1996 CL)	2012-March-15	2240	2.478 33	0.1283	4.5253	13.500	4.419	17.60
10544 Horsnebara	2012-March-17	3140	2.226 07	0.1133	7.4696	14.130	3.306	17.29
19165 (1991 CD)	2012-March-15	3360	2.291 08	0.1137	7.7181	13.650	4.124	16.18
26145 (1994 PG18)	2012-March-15	2240	2.453 65	0.1032	6.1309	13.710	4.012	16.76
33949 (2000 MP4)	2012-March-17	3140	2.135 03	0.0412	4.2323	14.550	4.725	17.60
36938 (2000 SA234)	2012-March-17	3360	2.247 75	0.1412	7.6892	15.480	1.776	18.39
37705 (1996 GD20)	2012-March-17	4480	2.179 99	0.0936	4.8588	15.360	1.877	17.98
67408 (2000 QS4)	2012-March-16	3360	2.200 00	0.0805	1.4841	15.260	1.965	17.76

clear what mechanism could transport Vesta's fragments to beyond the 3:1 mean motion resonance. It is noteworthy that the mineralogy of these three asteroids seems to present differences with respect to that of other V-type asteroids in the inner belt (Hardersen, Gaffey & Abell 2004; De Sanctis et al. 2011b, 2012). Considering the properties of the previously analysed objects, those with an inclination less than 5° show a composition closer to Eucrites (Moskovitz et al. 2010; De Sanctis et al. 2011b). Two outer belt asteroids, classified as V types, were observed at Telescopio Nazionale Galileo in 2010 (observing program number AOT21, principal investigator De Sanctis M.C.). The spectral investigation indicates that they clearly show the 1 μm band, typical of the pyroxene material, while the band at 2 μm is less evident, because of the strong telluric bands, not well removed (De Sanctis et al. 2011c). The detailed analysis of these outer belt asteroids will be discussed in a separate paper.

In a recent review, Ieva et al. (2016) try to identify peculiar properties for different V-type asteroids across the Main Belt with respect to vestoids, i.e. asteroids that are likely to come from (4) Vesta, basically members of its dynamical family. The studied data set includes, among others, 44 vestoids, 15 V types with a < 2.3 au, and 23 V types with inclination i <6° and 2.3 au < a < 2.5 au. The main result from Ieva et al. (2016) is that the inner Main Belt asteroids show spectral properties similar to those identified on Vesta's surface, thanks to the NASA/Dawn observations. In addition, the majority of the asteroids included in that work present a composition compatible with a Howardite lithology, which is the most common lithology found on Vesta surface by the Dawn data (De Sanctis et al. 2012; Ammannito et al. 2013; De Sanctis et al. 2013), although few objects are more similar to Diogenites and Eucrites.

The spectral investigation of the basaltic asteroids in the Main Belt can help understanding if there are V-type asteroids that show distinct mineralogy with respect to (4) Vesta and its family members.

We present new near-infrared (NIR) reflectance spectra of 10 V-type candidate asteroids obtained at the 3.6 m Telescopio Nazionale Galileo, covering the spectral range of 0.7–2.5 μm. The observed objects were selected from diverse databases of putative V-type asteroids aiming their characterization and hence better understand their relationship with (4) Vesta.

The paper is organized as follows: a description of data selection, observations, and reduction techniques is provided in Section 2; in Section 3, the important parameters to characterize the asteroids are derived and discussed. Finally, our main conclusions are summarized in Section 4.

2 DATA SELECTION, OBSERVATIONS, AND REDUCTION

10 potential V-type asteroids have been observed during a three-nights programme at Telescopio Nazionale Galileo, in 2012 March. The period of observations was not particularly favourable because of weather problems and sand storms from the desert (calima). For this reason, the observed spectra present strong atmospheric features, sometimes not well removed. However, the characteristic basaltic bands at 1 and 2 μm are clearly identified in the derived spectra.

The observed asteroids were selected from the lists of possible V types, classified in this way on the basis of their photometric colours from the Sloan Digital Sky Survey (SDSS; Roig & Gil-Hutton 2006; Moskovitz et al. 2008; Roig et al. 2008; Carvano et al. 2010); we focused on those which are not members of the Vesta dynamical family, in order to characterize their mineralogy and better infer their relationship, or not, with (4) Vesta.

The list of the observed data is reported in Table 1. Four asteroids with inclinations lower than 5° and located outside the typical Vesta region were observed. We focused on these targets because there are dynamical (Nesvorný et al. 2008) and observational (Moskovitz et al. 2010; De Sanctis et al. 2011a,b) indications that asteroids located in this region might be compositionally different with respect to the rest of the V types. Six more asteroids falling in the Vesta region were also observed from comparison reasons. Proper elements of the selected asteroids are provided in Table 1. Diameters range between 1.8 and 5.8 km, as estimated considering an albedo of 0.361, which is the mean value of the Vesta dynamical family as determined by Masiero et al. (2013).

The above-listed asteroids were observed with the Near-Infrared Camera Spectrometer (NICS) on the Telescopio Nazionale Galileo. NICS was equipped with the Amici grism, which yields a complete 0.8–2.5 μm spectrum in one single acquisition. The low resolution (RS = 50–500) together with the high efficiency of the Amici grism (90 per cent in all the infrared range) allowed us to obtain spectra of faint objects like small V-type asteroids with the advantage of having the whole NIR range measured simultaneously. For calibration, three well-known solar analogue stars (Land 98-978, Land 107-998, and Land 102-1081) were also observed during the nights. Data reduction was carried out according to standard-reduction techniques, which include flat-field correction and sky subtraction. The asteroid spectra were, as usual, normalized in order to have a reflectance value equal to 1 at 1.6 μm.

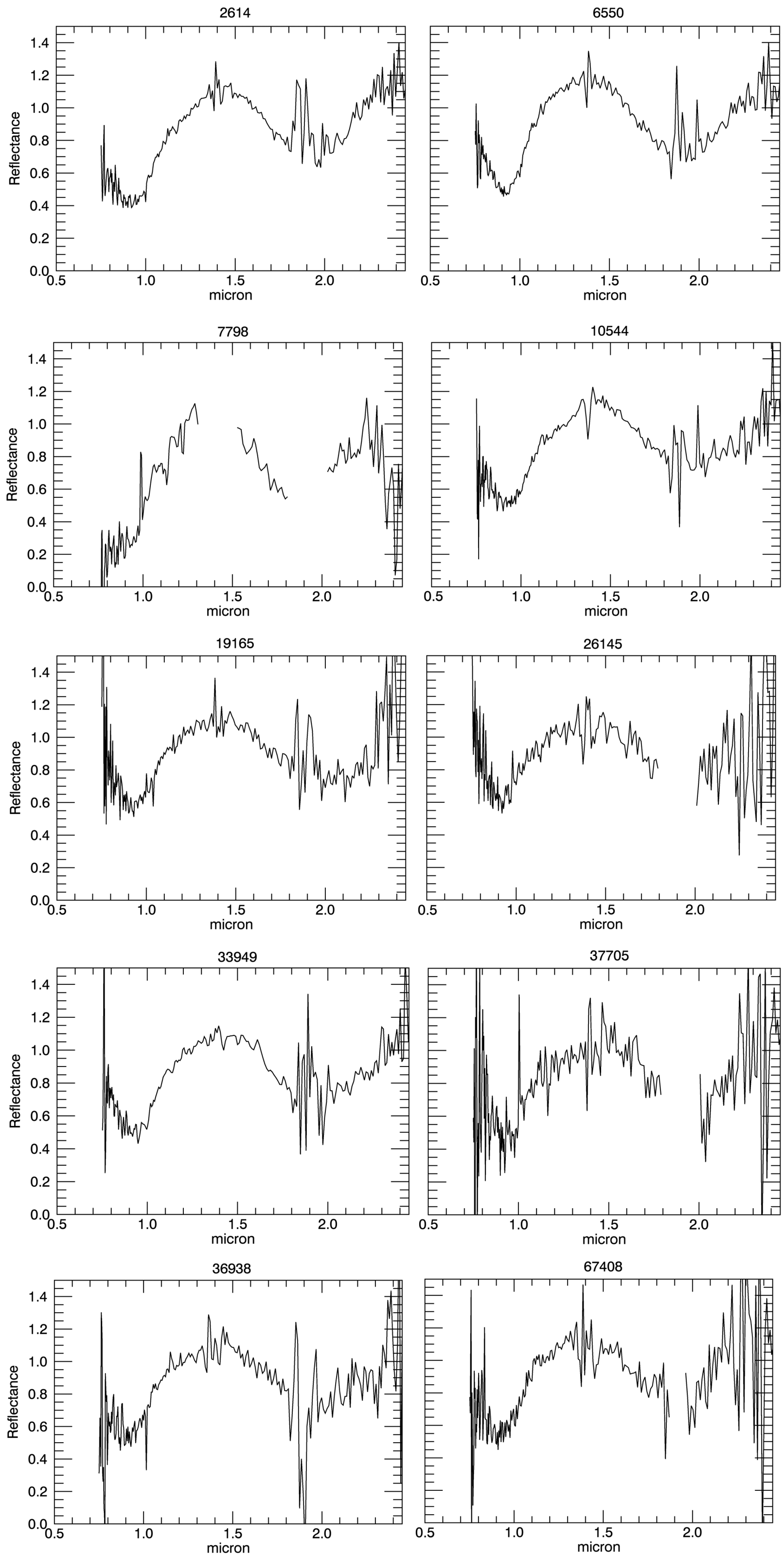

Figure 1. Spectra of the observed asteroids, normalized at 1 at 1.6 µm. The region between 1.8 and 2.0 µm is not included because of issues with the telluric band correction.

The obtained spectra are presented in Fig. 1. The spectral region between 1.8 and 2.0 µm was removed for some asteroids because of problems with the atmospheric correction, as mentioned above. The asteroids considered in this work are characterized by the typical absorption bands, near 1 and 2.0 µm, hereafter called BI and BII, respectively, indicative of the presence of pyroxene. All the observed asteroids are classified as V types, following the Bus–DeMeo method [available at http://smass.mit.edu/cgi-bin/

busdemeoclass-cgi (DeMeo et al. 2009)]. Most of the spectra present an inflection at about 1.25–1.3 μm, which is an absorption band attributed to feldspar (Gaffey 1976). This band is more pronounced in asteroids 10544, 37705, 36938, and 67408 although too weak to compute its area which could give hints on the abundance of feldspar (Gaffey, Bell & Cruikshank 1989). Despite the poor quality of the spectra of asteroids 26145 and 7798 beyond 1.8 μm, the band centred at 2.0 μm is observed; however, the determination of BI and BII is quite difficult for asteroid 7798, which is not included in the following discussion. It is noteworthy that a visible spectrum of asteroid 19165 (1991 CD) is reported in Hicks et al. (2014), which confirms the 1 μm band present in our spectrum. The method to derive the spectral parameters is described in the following section.

3 ANALYSIS OF THE DATA

The obtained data were analysed using the standard techniques to derive spectral parameters, basically the centres of the bands at about 1.0 μm (BI) and at 2.0 μm (BII), as described by Gaffey et al. (2002). Band minima were calculated on a smoothed spectrum, obtained by applying a second-order polynomial fit to the observed spectra, in the regions 0.8–1.1 μm and 1.6–2.3 μm for BI and BII, respectively. To minimize the effect of noise, we calculated the band minima on the spectra obtained by comparing the asteroids with each of the solar analogues observed during the nights, with an approach similar to the one adopted by Storm, Bus & Binzel (2007). The BI and BII minima are obtained as the average of the values resulting from this procedure. Due to a characteristic of our spectra, which do not encompass the complete region between 0.7 and 1.4 μm, necessary to determine the BI centre, laboratory calibrations were used to transform computed BI minima to BI centres:

$$\text{BI center} = \text{BI minimum} + 0.007 \pm 0.004\ \mu\text{m}. \quad (1)$$

We finally verified that the removal of continuum does not alter the position of BII centre, and hence it is possible assuming that BII centre and minimum coincide.

This approach was already used by our team in previous papers (Duffard et al. 2004; De Sanctis et al. 2011a,b) and we thus refer the reader to those papers, and references therein, for further details and discussion on the applicability of the method. In Table 2 are given the computed parameters, i.e. the band I minimum (BI min), the band I centre (BI centre), the band II minimum (BII min) and the band separation. In what follows, we will first discuss the distribution of the obtained parameters with respect to the orbital parameters and the HED meteorites, then derive the mineralogy of the observed asteroids and, finally, compare the results with (4) Vesta's surface properties.

3.1 Band centres distributions

The derived values for the spectral parameters span, within the errors, the same range of those obtained by our team in previous observing campaigns (Duffard et al. 2004; De Sanctis et al. 2011a,b). To check the existence of trends with respect to the proper orbital parameters for the observed asteroids, we plotted the spectral parameters versus the semimajor axis, the eccentricity, and the inclination. In order to have a more representative data set, we also included data obtained during the above-mentioned campaigns (Duffard et al. 2004; De Sanctis et al. 2011a,b). The results are given in Figs 2(a)–(c), where the BI centre values are shown with respect to the orbital parameters; the same plots are provided for BII centres in Figs 2(d)–(f). Asteroids belonging to the Vesta family are identified with the open circles, while those not belonging to the Vesta family with the green filled circle; the dimension of each symbol is proportional to the estimated asteroid diameters, reported in Table 1. Asteroids observed in this work are also identified with a cross.

The V-type asteroids not belonging to the Vesta family seem to show a wider spread in the plane of BI: 0.915–0.955 μm and 0.890–0.955 μm for family and non-family members, respectively. The mean BI centre value is equal to 0.926 μm for both family and non-family members, with a spread of 0.004 and 0.01 μm for family and non-family members, respectively. In addition, for similar-sized objects, the error associated to the BI determination seems to be higher for the non-family members. However, the data set is still too small to drive secure conclusions on this trend and the fact is attributed to noisier spectra obtained in worse observing conditions, for the time being.

In Figs 2(d)–(f), BII values are provided in comparison with the orbital parameters. In this case, the mean BII centre is 1.958 μm with a standard deviation of 0.044 μm for asteroids belonging to the Vesta family, and 1.938 μm with a standard deviation equal to 0.038 μm for the non-family members. In addition, few asteroids belonging to the Vesta family present a BII value higher than 2.05 μm. It must be recalled, on the other hand, that the BII determination is often difficult because of the telluric lines at 1.8 μm. In the overall, however, it is not evident any peculiar trend of neither BI nor BII with the considered dynamical parameters which could highlight differences in the distribution of the basaltic material in the Main-Belt region.

To furthermore constrain the composition of the observed asteroids and analyse the possible link with (4) Vesta and the HED meteorites, we compared our results with those of meteorites. The BI and BII are computed from spectra of HEDs available on the online RELAB data base (http://www.planetary.brown.edu/relab/), and are taken from De Sanctis et al. (2013). All the asteroids observed by our team in previous campaigns are included in Fig. 3, the total data set consisting of 19 V-type asteroids belonging to the Vesta dynamical family and 34 V-types non-family members. Most of the V-types family members present spectral properties similar to Howardites, except for few cases where the BII centre parameter is higher. The V-types not belonging to the Vesta family show conversely a composition more similar to Eucrites and Howardites, while very few cases are compatible with Diogenites. Among the asteroids observed in 2012 March , also identified by a square in Fig. 3, four agree with the distribution of HED, with the unique exception of asteroid 36938, which plots slightly below the Howardite region. Three asteroids are compatible with the Eucrite meteorites, among which the Vesta family asteroid 26145, observed in the March 2012 programme. Two asteroids fall in the region of Howardites, while three are more compatible with the Diogenites. The asteroids showing the inflection at 1.25–1.3 μm, mentioned in Section 2, do not cluster in a common region; on the other hand, they seem to be only partly compatible with HEDs mineralogies. Just one asteroid, 10544, is completely located inside the Howardite region. However, the data set is still too small to derive robust conclusions on the distribution of object presenting or not presenting the 1.25–1.3 μm inflection.

3.2 Inferred mineralogy

The relationship between the spectral parameters, BI and BII centres, and the mineralogy, particularly pyroxene and olivine, has been

Table 2. Spectral parameters for the observed asteroids. The columns indicate, respectively: (1) the asteroid, (2) the band I minimum, (3) the band I centre, (4) the Band II centre (equal to the band II minimum, see the text), (5) the band separation, (6) if member of the Vesta family. The suffix after the asteroid name indicates data from: (a) present work, (b) De Sanctis et al. (2011c), (c) De Sanctis at al. (2011a), and (d) Duffard et al. (2004).

Asteroid	BI min (μm)	BI centre (μm)	BII min = BII centre (μm)	Band separation (μm)	Vesta Family
2614 Torrence[a]	0.921 ± 0.0025	0.9285 ± 0.0065	1.9270 ± 0.0020	1.000	No
6550 Parler[a]	0.919 ± 0.0035	0.9265 ± 0.0075	1.9125 ± 0.0025	0.993	No
10544 Horsnebara[a]	0.924 ± 0.0045	0.9313 ± 0.0085	1.9693 ± 0.0020	1.045	No
19165 (1991 CD)[a])	0.932 ± 0.0035	0.9395 ± 0.0075	2.0090 ± 0.0130	1.076	No
26145 (1994 PG18)[a]	0.929 ± 0.0030	0.9360 ± 0.0070	1.9940 ± 0.0040	1.065	Yes
33949 (2000 MP4)[a]	0.932 ± 0.0045	0.9395 ± 0.0085	1.9740 ± 0.0030	1.042	No
36938 (2000 SA234)[a]	0.913 ± 0.0080	0.9200 ± 0.0120	1.9643 ± 0.0035	1.051	No
37705 (1996 GD20)[a]	0.941 ± 0.0015	0.9485 ± 0.0055	2.0070 ± 0.0015	1.065	No
67408 (2000 QS4)[a]	0.918 ± 0.0075	0.9255 ±0.0155	1.8850 ± 0.0010	0.967	No
1929 Kollaa[b]	0.923 ± 0.004	0.930 ± 0.004	1.947 ± 0.005	1.025	Yes
1933 Tinchen[b]	0.915 ± 0.004	0.922 ± 0.004	1.936 ± 0.006	1.022	Yes
2011 Veteraniya[b]	0.921 ± 0.005	0.928 ± 0.005	1.956 ± 0.0008	1.035	Yes
2912 Lapalma[b]	0.922 ± 0.003	0.929 ± 0.003	1.932 ± 0.01	1.010	No
3944 Halliday[b]	0.912 ± 0.002	0.919 ± 0.002	1.943 ± 0.02	1.030	Yes
3968 Koptelov[b]	0.920 ± 0.005	0.927 ± 0.005	1.922 ± 0.02	1.002	Yes
4147 Lennon[b]	0.919 ± 0.0035	0.926 ± 0.003	1.926 ± 0.005	1.007	Yes
4993 Cossard[b]	0.921 ± 0.003	0.928 ± 0.003	2.071 ± 0.02	1.151	Yes
6406 (1992 MJ)[b]	0.916 ± 0.003	0.923 ±0.003	1.990 ± 0.02	1.074	No
7148 Reinholdbien[b]	0.923 ± 0.003	0.930 ± 0.003	1.948 ± 0.02	1.025	No
8693 Matsuki[b]	0.892 ± 0.005	0.899 ± 0.003	1.923 ± 0.02	1.031	No
21238 (1995 WV7)[b]	0.908 ± 0.002	0.915 ± 0.003	1.900 ± 0.005	0.992	No
4383 Sugura[c]	0.913 ± 0.005	0.920 ± 0.009	1.91 ± 0.01	1.00	No
5498 Gustafsson[c]	0.920 ± 0.002	0.927 ± 0.006	1.92 ± 0.01	1.00	No
5560 Amytis[c]	0.905 ± 0.005	0.912 ± 0.009	1.90 ± 0.01	0.99	No
6563 Steinheim[c]	0.924 ± 0.006	0.930 ± 0.01	1.91 ± 0.01	0.99	No
6976 Kanatsu[c]	0.911 ± 0.003	0.918 ± 0.007	1.93 ± 0.01	1.02	No
8761 Crane[c]	0.925 ± 0.005	0.932 ± 0.009	1.95 ± 0.01	1.02	No
9147 Kourakuen[c]	0.908 ± 0.001	0.915 ± 0.005	1.987 ± 0.01	0.98	No
9531 Jean Luc[c]	0.930 ± 0.001	0.937 ± 0.006	1.94 ± 0.01	1.01	No
10614 (1997 UH1)[c]	0.919 ± 0.003	0.926 ± 0.007	1.95 ± 0.01	1.03	Yes
11764 Benbaillaud[c]	0.920 ± 0.005	0.927 ±0.009	1.97 ± 0.01	1.05	No
17064 (1999 GX16)[c]	0.919 ± 0.005	0.926 ± 0.009	1.94 ± 0.01	1.02	Yes
28160 (1998 VC11)[c]	0.900 ± 0.01	0.907 ± 0.014	2.02 ± 0.03	1.12	No
28517 (2000 DD7)[c]	0.908 ± 0.005	0.915 ± 0.009	1.90 ± 0.02	0.98	No
31692 (1999 JQ31)[c]	0.920 ± 0.003	0.927 ± 0.007	1.93 ± 0.01	1.01	No
31953 (2000 GZ125)[c]	0.929 ± 0.005	0.936 ± 0.009	1.92 ± 0.01	0.99	No
32940 (1995 UW4)[c]	0.926 ± 0.001	0.933 ± 0.005	1.91 ± 0.01	0.98	No
61235 (2000 OT15)[c]	0.932 ± 0.002	0.939 ± 0.006	1.93 ± 0.02	0.99	No
64276 (2001 TW218)[c]	0.925 ± 0.002	0.932 ± 0.006	1.96 ± 0.01	1.04	No
809 Lundia[d]	0.923 ± 0.005	0.930 ± 0.005	1.935 ± 0.03	1.012	No
956 Elisa[d]	0.912 ± 0.003	0.919 ± 0.003	1.912 ± 0.03	1.000	No
2468 Repin[d]	0.922 ± 0.004	0.929 ± 0.004	1.930 ± 0.03	1.008	Yes
2763 Jeans[d]	0.923 ± 0.003	0.930 ± 0.003	1.957 ± 0.03	1.034	No
2851 Harbin[d]	0.910 ± 0.003	0.917 ± 0.003	1.904 ± 0.03	0.994	No
3268 De Sanctis[d]	0.910 ± 0.004	0.917 ± 0.004	1.976 ± 0.02	1.066	Yes
3498 Belton[d]	0.920 ± 0.005	0.927 ± 0.005	1.968 ± 0.03	1.048	Yes
3782 Celle[d]	0.927 ± 0.01	0.934 ± 0.01	1.951 ± 0.01	1.024	Yes
4796 Lewis[d]	0.919 ± 0.005	0.926 ±0.005	1.935 ± 0.03	1.016	No
4815 Anders[d]	0.931 ± 0.005	0.938 ± 0.005	1.960 ± 0.03	1.029	Yes
6631 (1992 FZ1)[d]	0.912 ± 0.004	0.919 ± 0.004	1.972 ± 0.03	1.060	Yes
10285 (1982 QX1)[d]	0.921 ± 0.003	0.928 ± 0.003	2.077 ± 0.02	1.156	Yes
10320 (1990 TR1)[d]	0.917 ± 0.005	0.924 ± 0.005	2.021 ± 0.03	1.104	Yes
10349 (1992 LN)[d]	0.911 ± 0.003	0.918 ± 0.003	1.923 ± 0.01	1.012	Yes

studied in various papers over the last years (Adams 1974; King & Ridley 1987; Cloutis & Gaffey 1991; Gaffey et al. 2002; Klima, Pieters & Dyar 2007). From these works, it has been possible to derive formulas allowing us to compute the molar Ca [Wo] and Fe [Fs] contents, representative of the pyroxene composition, from laboratory calibrations. In particular, Gaffey et al. (2002) used pyroxenes to derive their set of equations while, more recently, Burbine et al. (2009) used HED meteorites. In this work, we decided to apply both set of equations in order to obtain a better insight on the mineralogy of our sample. It is noteworthy that although the two formulations give slightly different values, they agree within the errors, as can be seen in Table 3.

The derived wollastonite (Wo) and ferrosilite (Fs) contents span the same range as HEDs meteorites, as derived in De Sanctis et al.

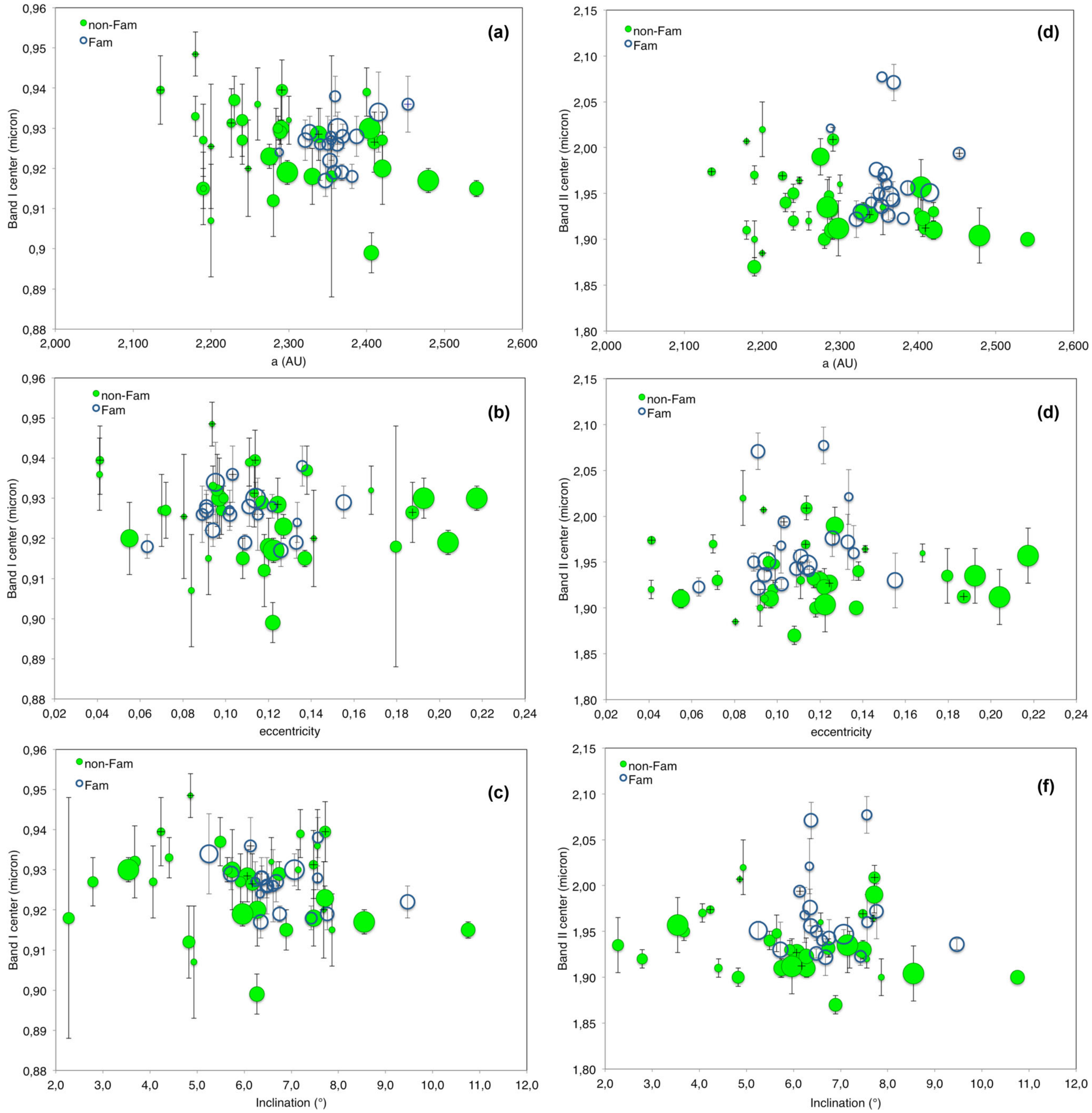

Figure 2. Band I centre versus orbital parameters: proper semimajor axis (a), proper eccentricity (b), proper inclination (c). Band II centre versus orbital parameters: semimajor axis (d), eccentricity (e), inclination (f). Vesta-family members and non-members are indicated, respectively, by blue and green dots. Dot dimension indicates the calculated asteroid diameter, while crosses identify asteroids discussed in this work.

(2011a), going from lower values of [Wo] and [Fs] for Diogenites to higher values for Eucrites and Howardites, respectively. Indeed, the lowest values are for asteroid 67408, which in Fig. 3 is clearly located in the Diogenite region. It is noteworthy that asteroids 19165, 26145, and 37705 likely present a eucritic composition. These asteroids have the [Wo] contents between 11 and 12 (equations from Burbine et al. 2009), or between 11 and 16 (equations from Gaffey et al. 2002); the fact that [Wo] content estimations, obtained independently with the two methods, are quite close, makes the mineralogy assignation more evident. Such values are only partly obtained for non-Vesta family members observed in previous campaigns (Duffard et al. 2004; De Sanctis et al. 2011a,b), where asteroids 9531, 31953, and 61235 show [Wo] contents higher than 10, but only retrieved by using the formulas from either Burbine et al. (2009) or Gaffey et al. (2002) (De Sanctis et al. 2011b). In the latter case, it is not possible to firmly conclude the presence of a eucritic composition of these asteroids.

As mentioned in Section 2, asteroids with inclination lower than 6° might present a different surface composition with respect to (4) Vesta and the other vestoids. According to Nesvorný et al. (2008), asteroids in the region defined by $2.32 < a < 2.48$, $0.05 < e < 0.2$, $2 < i < 6$ could represent a population not derived from Vesta.

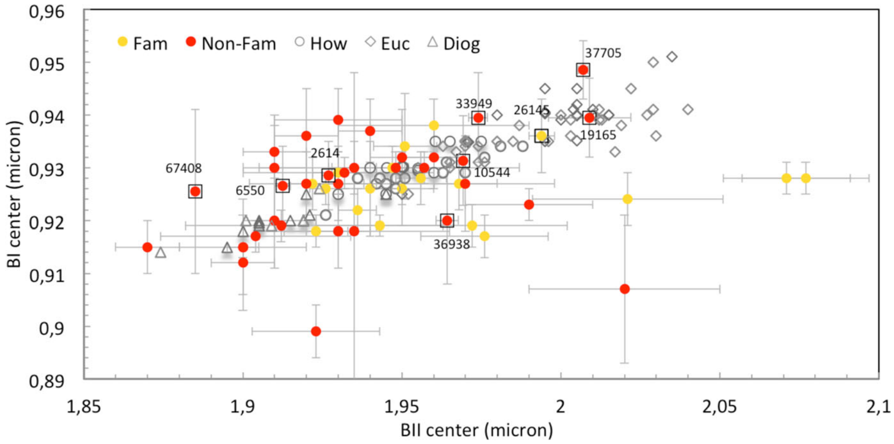

Figure 3. Values of BI centre versus BII centre for the observed asteroids and the HED. Eucrites are shown with triangles, Howardites with circles and Diogenites with diamonds. All V-type asteroids observed in this program and during previous runs from 2004 to 2010 are included in plot. Yellow circles indicate the Vesta-family members, while the red ones indicate non-Vesta family. Asteroids observed in 2012 March are identified also with a square.

Table 3. Molar Ca, Fe, and Mg contents derived for the observed asteroid. The columns indicate, respectively: (1) the asteroid, (2) the calcium [Wo], (3) iron [Fs], (4) magnesium [Mg] content using the Burbine et al. (2009) formulation, (5) the calcium [Wo], (6) iron [Fs] content using the Gaffey (2002) formulation.

Asteroid	[Wo] ±1	[Fs] ±4	[Mg] ±5	[Wo] ±4	[Fs] ±5
2614 Torrence	6–7	32–36	60–65	8	33
6550 Parler	4–6	29–34	63–69	7	29
10544 Horsnebara	8–9	39–41	54–56	9	44
19165 (1991 CD)	11–12	48–49	44–46	13	43
26145 (1994 PG18)	10–11	44–46	48–50	11	42
33949 (2000 MP4)	9–12	42–48	46–53	13	41
36938 (2000 SA234)	4–9	28–40	55–71	4	43
37705 (1996 GD20)	12	49–57	34–44	16	43
67408 (2000 QS4)	2–6	24–33	64–76	5	22

By using extensive numerical simulations, the authors investigated the dynamical evolution of Vesta's fragments over time-scales of gigayear, compatible with the age of the family. Although most of the inner belt V-type asteroids located outside the limits of the dynamical family are likely fugitives from (4) Vesta, the objects in the low-inclination orbits are not obtained with sufficient efficiency. Observational indications on possible mineralogical differences regarding objects of this population were presented by Moskovitz et al. (2010) and in our previous work, De Sanctis et al. (2011b), but with no conclusive results due to the small sample. In the present data set, asteroids 33949, 37705, and 67408 have an inclination lower than 6°, eccentricity lower than 0.2, but they are located at 2.1–2.25 au, slightly outside of the region identified by Nesvorný et al. (2008). Among these three asteroids, only 67408 is characterized by an unusually low [Wo] and [Fs] contents. These values are, on the other hand, compatible with asteroid 6550, which has a higher orbital inclination, being located outside the region under study.

3.3 Comparison with Vesta's surface properties

The VIR instrument on board the NASA Dawn mission has provided an insight on the Vesta surface properties, through observations in the 0.25–5.1 µm spectral range, from the approach phase

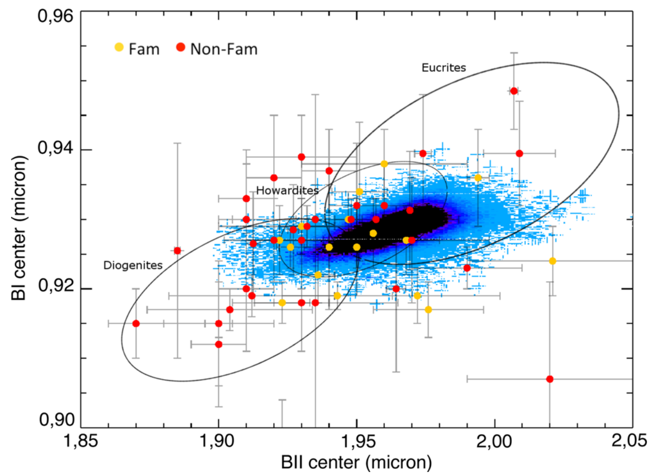

Figure 4. Comparison of the BI and BII centres calculated for V-type asteroids, observed in several runs in the period 2007–2012, HEDs and values derived in the Vesta surface, observed with VIR on DAWN mission (from De Sanctis et al., 2013). All asteroids observed during this run and previous programs (from Duffard et al. 2004; De Sanctis et al. 2011a, b) are included for the statistics. V-types members of the Vesta family are indicated with a yellow circle, while those not belonging to the Vesta family with the red symbol.

(2011 May) until departure, occurred in 2012 August. The derived BI and BII in the available spectra, acquired with VIR, are shown in Fig. 4 in comparison with the same parameters calculated for ground-based observations. HEDs regions are indicated with ellipses. To increase the statistical investigation, previously observed asteroids by our team, and published in Duffard et al. (2004) and De Sanctis et al. (2011a,b), are included, together with the data given in this paper.

Most of the (4) Vesta data reported in Fig. 4 (from De Sanctis et al. 2013) are compatible with Howardites, while the Diogenite and Eucrite regions are only partly filled. However, authors underline that the statistics is based considering only the BI and BII values that occur at least 10 times in the VIR spectra, and hence less frequent values are not taken into account. Moreover, the Vesta surface is only partly mapped with VIR due to orbit constraints, and hence some regions cannot be represented in the plot. Finally, the VIR spatial resolution might play a role in masking *pure* small diogenite regions that could occur in coherent sub-pixel areas. Despite these limitations, we note that most of the observed asteroids are compatible with the Vesta's surface characteristics even if the observed V-types show a larger spread of the BI versus BII values with respect to (4) Vesta data. Most of our data plot in the Howardite region, and partly in the Diogenite one. The Eucrite region is less populated by the V-type data reported here, and only four asteroids, notably not belonging to the Vesta family, are compatible with the Eucrites. It is interesting to note that some asteroids present BI and BII values that are outside the region identified for (4) Vesta using the VIR data, showing a BI centre value lower than 0.92 μm (diogenitic-rich asteroids). Asteroid 26145, the only one observed in this run and belonging to the Vesta family, is compatible with the Vesta's surface, although at the border of the identified region, in the sector of the Eucrites (Fig. 3).

The observed differences between V-type and (4) Vesta data can be ascribed to real mineralogical differences, but we also have to note the large error bars associated with ground-based observations. Most of the data here reported are from asteroids not belonging to Vesta-family, thus mineralogical differences can be intrinsic to the lithologies of the observed objects. Moreover, the Vesta-family asteroids show more clustered BI and BII values, compatible with the Dawn (4) Vesta data (Fig. 4), while the non-family objects show more extreme values of BI and BII, spanning the entire set of HED values. Space-weathering effects can also be considered to explain the observed differences. Space weathering on (4) Vesta has been recently studied (Pieters et al. 2000; Marchi et al. 2010; Fulvio et al. 2012, 2016). (4) Vesta has its own space weathering, different from S type or other asteroids, resulting in band depths reductions without any sensitive increase of spectral slopes (Pieters et al. 2000). Marchi et al. (2010) reported the trend for space weathering on V-type asteroids, showing that visible spectral slopes of V types are systematically redder with respect to HEDs. More recently, Fulvio et al. (2012, 2016) demonstrated that space weathering can be responsible for only small displacement of band centres (effects are of the order of 0.01 μm for BI and BII band centres), and hence it cannot be considered responsible for the observed behaviour.

We finally recall that it is quite difficult to link the asteroids observed from ground with mineralogy in the Vesta's surface observed from space, due to the different spatial resolution. However, the vast basin in the Southern hemisphere of (4) Vesta shows a higher mineralogical variability, which is compatible with the HEDs suite composition (Ammannito et al. 2015).

4 CONCLUSIONS

10 small basaltic asteroids have been observed in the VIS-NIR spectral range, and for 9 of them, it was possible to derive mineralogical related parameters. With just one exception, they do not belong to the Vesta dynamical family and are on orbits with inclination lower than 6°, which, according to Nesvorný et al. (2008), are not easily dynamically linked to (4) Vesta.

The spectroscopic properties of all the observed asteroids confirm their taxonomic classification as V-types. However, no peculiar trends with respect to dynamical parameters could be identified. The comparison with HEDs meteorites suggests that four of the observed asteroids present a mineralogical composition compatible with Howardites. They are also in agreement with features identified on the Vesta surface, as observed with VIR spectrometer on board the Dawn mission. Among the other five observed asteroids, three have a composition more similar to Eucrites and two to Diogenites, and these are not represented in the Vesta surface.

Comparison with asteroids previously observed by our team at the same telescope shows that we were able to identify asteroids whose composition, although compatible with HED meteorites, do not seem to be present on the surface of Vesta. This obviously does not mean that the composition is totally different from (4) Vesta, but could be representative of regions not mapped with VIR due to orbit constraints. It is noteworthy that as we increase the number of asteroids with mineralogical characterization, we constantly enlarge the region of spectral parameters spanned by V-type objects. Moreover, this enlargement is mostly due to the asteroids that are not members of the Vesta dynamical family, as a quick look to Fig. 4 indicates. It should be stressed, however, that since we are dealing with small asteroids, their spectra are quite noisy and, consequently, the derived parameters have large error bars. Additional data can provide new clues regarding the existence of V-type asteroids with a mineralogy incompatible with an origin from (4) Vesta.

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