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Selecting candidate V-type asteroids from the analysis of the Sloan Digital Sky Survey colors

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Abstract

We present a systematic method to identify possible basaltic (V-type) asteroids using the Moving Objects Catalog (MOC) of the SDSS. The method is based on the Principal Components Analysis of the MOC colors combined with some refined criteria of segregation of the taxonomic classes. We found several V-type candidates outside the Vesta family, most of them in the inner asteroid belt. We also identified a few candidates in the middle/outer belt. Notwithstanding, their basaltic nature still needs to be conformed by spectroscopy, and these candidates are potential targets for observation using large telescopes.

Keywords: Asteroids, composition; Asteroids, dynamics; Data reduction techniques

1. Introduction

Asteroids families are groups of asteroids that originated in the collisional break-up of a large parent body. Usually, they are identified as clusters of bodies in the space of orbital proper elements (Milani and Knežević, 1990), and in this case they are referred to as "dynamical" families (e.g., Zappalà et al., 1995). Several recent studies indicate that members of the same asteroid family tend to be quite homogeneous in terms of their surface mineralogy (e.g., Mothé-Diniz et al., 2005). This may be interpreted as a consequence of the lack of mineralogically differentiated parent bodies in the asteroid belt. We recall that mineralogy may be inferred from both low resolution spectroscopy or multi-band photometry, and this allow to classify the asteroids in different "taxonomic" classes or types (e.g., Tholen, 1984; Bus, 1999).

Among the most interesting asteroid families there is the Vesta family. It is located in the inner asteroid belt and was originated from a collisional event that excavated a large crater in the surface of Asteroid (4) Vesta (Asphaug, 1997). The presence of such crater in the south hemisphere of the asteroid has been recently confirmed by HST images (Thomas et al., 1997), and the latest estimates indicate that this cratering event occurred more than at least 1.2 Gyr ago (Carruba et al., 2005). Asteroid (4) Vesta is particularly interesting because it is the only large asteroid showing a basaltic crust (McCord et al., 1970). This is interpreted as the result of a differentiation process caused by an active heating and melting of the asteroid interior. Spectroscopic studies indicate that many Vesta family members also show a basaltic composition (Xu et al., 1995; Bus and Binzel, 2002; Lazzaro et al., 2004) consistent with their link to Vesta's crust.

In the visible range, the spectrum of a basaltic asteroid is mainly characterized by a steep slope short-wards of 7000 Å and a deep absorption band long-wards of 7500 Å. Asteroids with this kind of spectrum are classified as V-type. A few years ago, the only known V-type asteroids were members of the Vesta dynamical family. Nowadays, several V-type asteroids are know to reside outside the Vesta family.[1] Most of these as-

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[1] Binzel and Xu (1993) already pointed out the existence of eight V-type asteroids outside the Vesta family, but their result was biased by the poor def-

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teroids are located in the inner asteroid belt (e.g., Florczak et al., 2002). Their origin has no clear explanation yet, although the possibility of being fragments from Vesta's crust cannot be totally ruled out. Actually, a dynamical mechanism has been recently proposed to explain a few of these V-type asteroids as fugitives from the Vesta family (Carruba et al., 2005).

The most intriguing case is that of (1459) Magnya, a basaltic asteroid in the outer asteroid belt which is too far away form the Vesta family to have a real probability of being a fragment from Vesta's crust (Lazzaro et al., 2000). It has been proposed that Magnya could be a fragment from a large differentiated asteroid other than (4) Vesta that existed in the outer asteroid belt (Michtchenko et al., 2002). If the collisional break-up of this hypothetic parent body occurred more than 1 Gyr ago, the chaotic nature of the orbits in that region of the outer belt would have disperse the fragments, making it impossible to detect today the family associated to this collisional event. But even if this is true, we should expect to find other fragments with a basaltic composition in the outer belt, and up to now no other V-type asteroid has been identified beyond 2.5 AU. The eventual discovery of such objects would provide important evidence to support the idea that more than one large differentiated asteroid existed in the belt (Yamaguchi et al., 2002), something which is still a matter of controversy.

It would be possible to search for yet unknown V-type asteroids using data from large photometric surveys, like the Sloan Digital Sky Survey (SDSS). A sub-product of this survey is the Moving Objects Catalog (MOC), which in its third release provides five band photometry for 43424 asteroids of which 15472 have been observed twice or more (Ivezić et al., 2001; Jurić et al., 2002). In order to analyze the surface composition of asteroids and to perform taxonomic classification, multi-band photometry is not as precise as spectroscopy. But the amount of data of the SDSS-MOC significantly contrast with the only ∼2300 asteroids observed by the major spectroscopic surveys presently available: the SMASS (Xu et al., 1995; Bus and Binzel, 2002; Burbine and Binzel, 2002) and the S^3OS^2 (Lazzaro et al., 2004). Moreover, while these spectroscopic surveys reached an average absolute magnitude of $H \simeq 11$, the SDSS-MOC pushed this value to $H \simeq 15$, providing taxonomic information of a huge population of very small asteroids for which spectroscopic observations can only be assessed using very large telescopes. Therefore, the SDSS-MOC becomes a powerful tool for statistical analyses of asteroid taxonomy.

In this paper we introduce a systematic method to identify possible candidate V-type asteroids using the SDSS-MOC data. Our method is based on the Principal Components Analysis (PCA) of the data, combined with some refined criteria of segregation based on direct comparison to the available spectroscopic data. Since the spectral characteristics of V-type asteroids are so peculiar, we expect to easily distinguish them among the other types. However, we must note that due to the intrinsic limitations of the few band photometry, this analysis provides only an indication that an asteroid could be a V-type, and the actual taxonomy must be confirmed by its spectrum. Then, the idea is to use our method to select targets for spectroscopic observations on large telescopes.

This paper is organized as follows: In Section 2 we introduce the main outlines of our method. In Section 3 we present the results, and in Section 4 we discuss the orbital distribution of the selected candidates.

2. Methodology

The SDSS photometry is based on the u, g, r, i, z system of filters (Fukugita et al., 1996; Stoughton et al., 2002), with band centers at $\lambda_u \simeq 3540$, $\lambda_g \simeq 4770$, $\lambda_r \simeq 6230$, $\lambda_i \simeq 7630$ and $\lambda_z \simeq 9130$ Å, and band widths of $\Delta\lambda_u \sim 570$, $\Delta\lambda_g \sim 1380$, $\Delta\lambda_r \sim 1380$, $\Delta\lambda_i \sim 1530$ and $\Delta\lambda_z \sim 1350$ Å (see SDSS Project Book, Photometric Camera: http://www.astro.princeton.edu/PBOOK/camera/camera.htm). The photometric observations are performed almost simultaneously in the five filters. Each entry in the MOC corresponds to a single observation of a moving object and provides the apparent magnitudes u, g, r, i, z with their corresponding errors. Of the 204305 entries contained in the third release of the MOC, we only considered 67637 observations that are effectively linked to know asteroids (Jurić et al., 2002). These observations correspond to 43424 unique bodies.

In order to analyze these observations, we proceeded as follows: (i) we computed the reflectance flux or albedo $F(\lambda)$ at each band center, and we discarded all the observations with errors in albedo larger than 10%; (ii) we performed a Principal Component Analysis of the remaining data; (iii) we identified the region in principal components space where the different taxonomic types are located; and (iv) we made a selection of V-type candidates giving suitable constraints in principal components and comparing albedos to reflectance spectra of known V-type asteroids. In the following, we describe each of these steps.

2.1. Albedos

To compute the albedos we adopted the following system of "reflectance" colors, i.e., already corrected by the solar colors: $c_{u-r} = (u-r) - 1.77$, $c_{g-r} = (g-r) - 0.45$, $c_{r-i} = (r-i) - 0.10$, $c_{r-z} = (r-z) - 0.14$, where the values of the solar colors were taken from Ivezić et al. (2001). The albedos at each band center, normalized to the albedo at the r band, were defined as: $F_u = 10^{-0.4c_{u-r}}$, $F_g = 10^{-0.4c_{g-r}}$, $F_i = 10^{0.4c_{r-i}}$ and $F_z = 10^{0.4c_{r-z}}$.

To estimate the relative errors $\Delta F/F$, we used a second order approach[2]:

$$\Delta F/F = 0.9210\Delta c(1 + 0.4605\Delta c),$$

where Δc are the color errors computed as the root squared sum of the corresponding magnitude errors, e.g., $\Delta c_{u-r} =$

inition of the Vesta family know by that time. At present, these eight asteroids are family members.

[2] This formula is based on a simple Taylor expansion of the function $F(c) = 10^{0.4c}$. It overestimates the usual first-order relative error by $\sim 0.4241(\Delta c)^2$ and provides a better approach to the error, especially for $\Delta c > 0.1$.

$\sqrt{(\Delta u)^2 + (\Delta r)^2}$. Then, we proceeded to discard what we consider as "bad" observations, i.e., those observations for which $\Delta F/F$ was larger than 10% at any band. It is worth noting that, even if $F_r = 1$ for all the observations, $\Delta F_r/F_r$ varies from one observation to another and this error must also be taken into account in discarding bad observations. This error was estimated using $\Delta c_{r-r} = \sqrt{2}\Delta r$.

We further verified that some observations may show quite unusual albedos at one or more bands, if compared to the typical range of variation of asteroid spectral reflectance. This may happens even if the error in albedo is less than 10%. Therefore, we also discarded the observations for which any of the following conditions held: $F_u > 1.0$, $F_g > 1.3$, $F_i > 1.5$, $F_z > 1.7$, $F_g \leqslant F_u$ or $F_g < 0.6$. After this cleanup, we ended up with a sub-sample of 17957 "best" observations corresponding to 13290 unique asteroids, which represents about 30% of the original sample.

2.2. Principal Components Analysis (PCA)

The above sub-sample of "best" observations was analyzed through the PCA. In short, each observation in the sub-sample may be represented by a single point in the 4D space of albedos F_u, F_g, F_i, F_z. The whole sub-sample forms a cloud in this 4D space, having maximum dispersions along certain preferred directions. The idea of the PCA is to rotate the coordinate system so as to align it with these preferred directions. The projections of each point over this new coordinate system are the principal components (PC). In practice, the rotated system is spanned by the eigenvectors of the covariance matrix of the data. Besides the rotation, it is also usual to translate the origin of the coordinate system to the barycenter of the cloud. Then, for each observation, the first PC gives an idea of the overall variation of the albedo $F(\lambda)$, the second PC gives an idea of the overall variation of the albedo after the variation related to the first PC was removed, and so on. In this way, the most relevant information of each observation is usually contained in the first PCs, making the analysis of the data much simpler.

This approach has been already used by Jedicke et al. (2004) to analyze the data from the second release of the MOC. The main difference between their work and this paper is that Jedicke et al. computed PCs directly from the reflectance colors, while here the PCs are derived from the reflectance fluxes. We believe that working with reflectance fluxes allows an easier interpretation of the data, that can be directly compared to the known asteroid spectra.

The explicit transformation between the albedos $\mathbf{F} = \{F_u, F_g, F_i, F_z\}$ and the principal components $\mathbf{PC} = \{PC_1, PC_2, PC_3, PC_4\}$ is given by $\mathbf{PC} = \mathbf{E}\,\mathbf{F} - \mathbf{B}$, where $\mathbf{E}$ is the eigenvectors matrix and $\mathbf{B}$ is the barycenter vector of the data:

$$\mathbf{E} = \begin{pmatrix} 0.8474 & 0.4793 & -0.2141 & 0.0795 \\ 0.0028 & -0.0150 & 0.3281 & 0.9445 \\ 0.3866 & -0.2622 & 0.8336 & -0.2948 \\ -0.3639 & 0.8374 & 0.3894 & -0.1209 \end{pmatrix},$$

$$\mathbf{B} = \begin{pmatrix} 0.8412 \\ 1.3126 \\ 0.6243 \\ 0.7852 \end{pmatrix}.$$

The corresponding errors may be obtained as $\mathbf{\Delta PC} = \sqrt{\mathbf{E}^2 \mathbf{\Delta F}^2}$, where $\mathbf{E}^2 = \{E_{jk}^2\}$ and $\mathbf{\Delta F}^2 = \{\Delta F_u^2, \Delta F_g^2, \Delta F_i^2, \Delta F_z^2\}$. However, we must warn the reader that this transformation is specific for our dataset of 17955 "best" observations from the third release of the MOC. If a different dataset is used, for example, considering all the albedos with relative errors less than 20%, the covariance matrix of the data and its eigenvectors need to be recomputed, and the coefficients of $\mathbf{E}$ and $\mathbf{B}$ will adopt other values.

2.3. Distribution of taxonomic types

Fig. 1 shows the distribution of the "best" observations (gray dots) projected onto the planes PC_1–PC_2 (a) and PC_3–PC_2 (b). The figure also highlights those observations corresponding to asteroids with known taxonomy from spectroscopic surveys (SMASS and S^3OS^2). In particular, we found 338 observations in the MOC that are related to known numbered asteroids belonging to any of the three major taxonomic complexes (Bus, 1999):

- 158 observations corresponding to 109 different S-type asteroids;
- 99 observations corresponding to 65 different X-type asteroids;
- 81 observations corresponding to 60 different C-type asteroids.

We also found:

- 1 observation related to 1 known R-type asteroid: (5111);
- 11 observations related to 8 different known V-type asteroids: (2442), (2640), (2704), (3782), (3869), (3968), (4055) and (5481).

Using these 11 observations, it is possible to define the approximate limits of the region in the space of PCs where we should expect to find other V-type asteroids. This represents a major advance with respect to the second release of the MOC which only observed one V-type asteroid, thus making it difficult to limit the distribution of these objects in principal components (e.g., Fig. 3 of Nesvorný et al., 2005).

In Fig. 1a, the data are segregated such that observations showing absorption bands (e.g., S- and V-type) have $PC_1 \lesssim 0$. In these cases, PC_2 is somehow related to the band depth such that the deepest bands occur for $PC_2 \lesssim 0$. On the other hand, band-less observations (e.g., C- and X-type) have $PC_1 \gtrsim 0$, and in these cases PC_2 is somehow related to the average slope of the flux such that positive slopes occur for $PC_2 \gtrsim 0$. Note however that this segregation is only approximate and the taxonomic classes actually show some degree of overlap. This is related to the actual errors of the SDSS photometry. For example, the C and X classes cannot be totally segregated since the

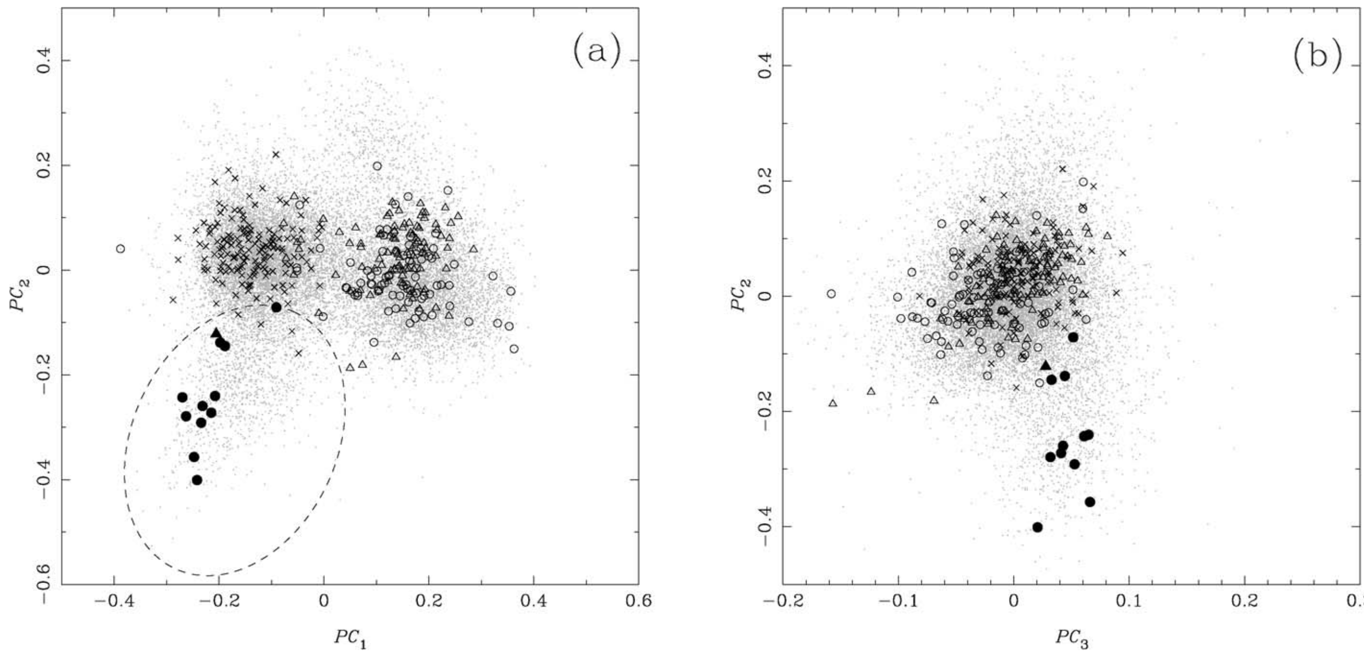

Fig. 1. The distribution of 17957 observations from the SDSS-MOC (gray dots) on the space of the first three principal components. Observations corresponding to asteroids with known taxonomy are indicated by crosses (S complex), triangles (X complex), open circles (C complex), full circles (V-type), and full triangle (R-type). The dashed ellipsis indicate the region where V-type observations are expected to be found.

differences between the typical SDSS albedos of both classes are in most cases within the 10% error of the data. In other words, the SDSS photometry is not accurate enough to unambiguously distinguish between C- or X-type asteroids in more than 50% of the cases.

On the other hand, the S-type is better segregated from both the C- and X-types, except for the overlap of some observations for which the albedos do not match the known taxonomy. In most cases, these mismatches are caused by unusual values of the albedos, if compared to the known reflectance spectra, in one or two bands. We estimated that about 10% of the MOC entries that are linked to asteroids with known taxonomy show albedos remarkably incompatible with the corresponding taxonomic classes, i.e., the differences between SDSS albedos and reflectance spectra are beyond 2-σ uncertainty.[3]

2.4. Selection of V-type candidates

In Fig. 1a, the V-type asteroids appear quite well segregated from all the other taxonomic classes. They form a cluster whose projection onto the (PC_1, PC_2)-plane is contained within the dashed ellipsis. This ellipsis defines our main criterion to search for V-type candidates in the principal components space. It is centered at $PC_1 = -0.170$, $PC_2 = -0.325$, has major axes $a = 0.270$, $b = 0.195$, and is rotated by 65° with respect to the PC_1 axis. However, the ellipsis partially overlaps with the S-type region and the criterion is not enough to unambiguously segregate the V-type from the S-type observations. The analysis of PC_3 and PC_4 does not provide any additional criterion to totally segregate the observations either, although we restricted our search for candidates to the range $-0.05 \leqslant PC_3 \leqslant 0.13$ since all the observations of known V-type asteroids fall within this interval (Fig. 1b).

In view of this, we decided to complement our searching criteria with the analysis of the albedos F_z and F_i. The first one measures the depth of the absorption feature at the z band, which is the most remarkable characteristic of V-type spectra. The second one gives a measure of the spectrum maximum at ~7500 Å, which is also a relevant characteristic of V-type and of S-type spectra. We expect that these two parameters help to better segregate the S and V-type observations.

Considering the 158 observations of S-type asteroids contained in the MOC, we verified that all they have $F_z > 0.88$ and $F_i/F_z < 1.25$. Therefore, we proposed that a *safe* criterion to exclude any possible S-type observation from inside the ellipsis in Fig. 1a is to require $F_z \leqslant 0.83$ and $F_i/F_z \geqslant 1.31$. This in turn becomes a *sufficient* condition to identify a MOC entry as a V-type observation, but not a necessary one since there are 3 known V-type asteroids in the MOC—(2640), (3782) and (3968)—that do not fulfill it. Caution must be taken with asteroids that have more than one entry in the MOC. In these cases, it may happen that only some entries, but not all of them, fulfill the above criterion. Thus, we adopted to discard an asteroid from our selection whenever it has at least one entry with $F_z > 0.88$ or $F_i/F_z < 1.25$, i.e., compatible with an S-type observation.

It is interesting to compare Fig. 1a with a color–color plot like those from Figs. 8–9 of Ivezić et al. (2001). Fig. 2 is a plot of a vs $(i–z)$ colors, where the a color has been estimated using a similar approach as in Ivezić et al. (2001): $a = 0.9285(g–r) +$

[3] Among these cases, it is worth mentioning asteroids (520), (1605), (1758), (3104), (3214), (3702) and (6410).

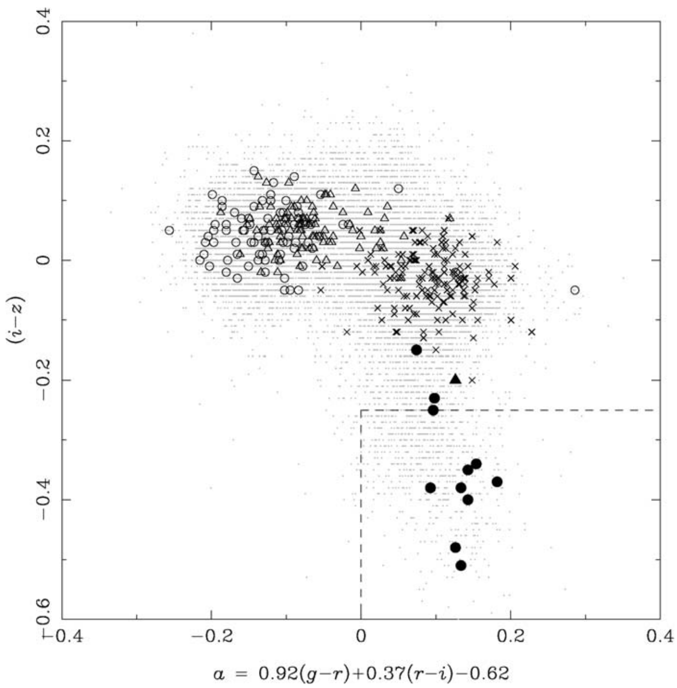

Fig. 2. The distribution of 17957 observations from the SDSS-MOC (gray dots) on the a vs $(i\text{–}z)$ plane (see text). Symbols have the same meaning as in Fig. 1. Most observations showing V-type colors would be approximately located inside the dashed square.

$0.3713(r\text{–}i) - 0.6204$ (note that the colors here do not include the solar correction). We wish to stress that this formula differs from Eq. (4) of Ivezić's paper which was derived using the first release of the MOC. In fact, the a color is nothing but the first principal component of the data in the $(g\text{–}r)$ vs $(r\text{–}i)$ plane, and therefore its definition depends on the specific dataset under analysis. In principle, the a color should be redefined for each new release of the MOC. The definition used here is specific for our sub-sample of 17957 "best" observations from the third release.

In Fig. 2, the taxonomic types also appear segregated in the sense that most observations with absorption bands have $a \gtrsim 0$ while most band-less observations have $a \lesssim 0$. However, the S, C and X-type observations appear much more mixed up than in Fig. 1a. This is because neither the a color is as good as the PC_1 to segregate observations, nor the $(i\text{–}z)$ color is suitable to distinguish between observations with shallow bands or with no bands. On the other hand, the V-type asteroids appear again well segregated, forming a cluster in the region $a \gtrsim 0$ and $(i\text{–}z) \lesssim -0.20$. This is expected since the V-type spectrum is so peculiar that only two colors would be enough to characterize it. It is worth noting that our sufficient condition $F_i/F_z \geqslant 1.31$ to identify a V-type observation is equivalent to require $(i\text{–}z) \leqslant -0.25$. We can say that, concerning the selection of candidate V-type asteroids, the analysis of the a vs $(i\text{–}z)$ colors should produce roughly the same results than the analysis of principal components applied here. This would not be the case for a more general study of the other taxonomic classes, for which PCA would be a richer and more refined approach than a simple color–color analysis.

Table 1
List of candidate V-type asteroids that are members of the Vesta dynamical family (see Section 4)

(5481)	20437	30834	45532	55719	70513	1999 TH115
5969	20921	30918	46696	56055	73114	2000 DM62
6093	21673	31574	46698	56097	73174	2000 EJ77
6944	22354	31663	46833	56122	73381	2000 GM125
6985	23758	34189	47338	56412	73987	2000 JQ41
7794	23804	34534	47347	56419	74971	2000 QL24
9748	24172	34784	47417	56463	75011	2000 SB72
10157	24177	34876	47441	56622	75120	2000 TM12
10619	24764	35721	47477	57321	75302	2001 EO20
10724	24839	35820	47852	57806	75603	2001 SD47
12157	24920	35831	48060	57929	77085	2001 SH315
12405	25378	35974	48102	57930	78670	2001 TF14
12407	25540	36811	48460	58244	79169	2001 TG134
13162	25645	38700	48626	59320	79277	2001 XG117
13333	26064	38732	48939	59522	80417	2001 YZ110
13465	26145	38922	48977	60275	84077	2002 GM165
13638	26202	39218	49101	61104	84150	2002 GR117
14322	26475	39468	49946	61638	84165	2002 GR87
14463	27025	39767	49948	62296	86466	2002 GV76
14568	27805	39949	50084	62636	86775	2002 PG57
14602	27939	40364	50489	64213	90179	2002 SG49
14956	27959	40693	50626	65695	92547	2002 TV16
15553	28143	41534	51562	66393	92561	2003 QG36
15554	28256	41586	52454	66396	92803	2003 QG92
15608	28291	42979	52991	66462	93394	2003 QS23
15634	28693	43300	53001	67118	97966	2003 SJ190
16452	29367	43306	53034	67162	98086	2003 SP52
17409	29714	43388	53736	67616	98128	2003 SP90
17469	30000	43507	54084	68703	99564	2003 UE118
17641	30167	44196	54324	68787	1995 VV12	
17815	30177	44772	54374	69153	1998 SB127	
18253	30237	45073	54747	69596	1998 UT45	
19383	30282	45195	54877	69742	1999 JH74	
19979	30751	45435	55376	70510	1999 RE209	

Asteroids within parenthesis are the only ones with observed spectra, in all cases corresponding to the V-type.

3. Results

Using our method we identified 680 MOC entries, corresponding to 505 different asteroids, exhibiting V-type colors. We discarded from this sample 6 unnumbered asteroids that were observed in only one opposition. The remaining 499 asteroids are listed in Tables 1 and 2.

In order to check the reliability of our selection criteria, we made a direct comparison of the albedos of these MOC entries to the reflectance spectra of known V-type asteroids. In principle, the right way to make this comparison would be to convolve the available spectra with the u, g, r, i, z system of filters and to compare the resulting convolved signal with the SDSS albedos. Unfortunately, the available visible reflectance spectra usually do not cover the whole wavelength range spanned by the system of filters. An alternative approach is to normalize the available spectra to the corresponding reflectance flux at the center of the r band, and to directly compare these normalized spectra with the SDSS albedos.

Proceeding this way, we considered the reflectance spectra of 35 V-type asteroids taken from the SMASS II survey (Bus and Binzel, 2002). Each of these spectra was normalized to the

Table 2
List of candidate V-type asteroids that are not members of the Vesta dynamical family (see Section 4)

2168	10892	23330	36938	55613	70252	2000 AW130
2247	11504	23631	37705	55737	70477	2000 CK66
(2442)	11764	24024	40521	55998	71340	2000 GU111
2614	11871	24280	40733	56026	71381	2000 KK82
(2704)	12027	24604	41485	56381	74601	2000 KO41
2823	12543	25354	41910	56425	74759	2000 OM40
3331	12723	25677	42253	56570	74877	2000 QH126
3648	12851	25992	42829	57342	77215	2000 RR87
(3869)	14323	26433	43302	58470	79629	2000 SH97
4383	14326	26468	43948	60506	79735	2000 ST217
5498	15481	26886	43964	60669	80351	2000 SY47
5560	15630	27239	44496	61068	80413	2000 UU33
5599	15895	27638	44798	61201	81128	2001 EB19
6081	15989	28160	45915	61235	81233	2001 FU126
6224	16352	28280	46690	61281	81448	2001 JR
6504	16491	28517	46751	61507	84036	2001 MO11
6550	16703	28985	46762	62521	84038	2001 QV25
6563	17496	29386	47089	63649	84524	2001 QZ131
6976	17899	29862	47189	64243	86630	2001 RE54
7472	18110	30081	47203	64276	87201	2001 SO254
7484	18386	30893	48191	64308	88321	2001 SV173
7798	18651	31415	48629	64311	89570	2001 TE47
8149	19165	31692	49132	65507	90127	2001 XP100
8645	19432	31953	49226	65824	91300	2002 AE179
8646	19660	32050	49990	66264	93250	2002 AF20
8703	19738	32073	50098	66905	94685	2002 BB18
8761	19809	32449	50666	67408	94686	2002 BH27
8805	20341	32940	51507	67587	97930	2002 JY57
9147	20436	33807	51742	67598	98105	2002 PK
9254	20529	33810	52041	67621	98286	2002 RS123
9481	20551	33881	52863	67652	1998 OA15	2002 SB57
9531	21049	33949	52886	67734	1998 RX48	2003 AA41
9553	21238	35062	53646	68064	1998 VT7	2003 RS10
10129	21412	35082	53702	68143	1999 RL164	2003 SC202
10537	21506	35261	53870	68407	1999 TS25	2004 BF58
10544	22327	35718	53950	70051	1999 TY103	(4055)*
10666	22539	36412	54873	70069	1999 VG21	2002 TM135*
10750	22759	36767	54925	70163	2000 AM150	2003 ST271*

Asteroids within parenthesis are the only ones with observed spectra, in all cases corresponding to the V-type. An * indicates that the object has no proper elements computed.

corresponding average reflectance flux at 6230 Å, that was estimated by interpolating a straight line fit to the spectrum in the interval 6030–6430 Å. In Fig. 3, we compare the normalized spectra to the SDSS albedos of 50 candidates V-type asteroids taken at random from our sample. In general, the SDSS albedos fit well within the limits of the reflectance spectra. At the z band, the upper limit of the reflectance spectra is ∼0.80. We have verified that about 80% of the SDSS albedos of the whole sample of V-type candidates are below this value, thus reproducing quite well the typical depth of the absorption feature at this band. The remaining 20% are between $0.80 < F_z < 0.88$, thus reproducing the band depth only marginally but still within the 2-σ uncertainties.

We have also detected a weak tendency of the SDSS albedos to systematically overestimate the reflectance spectra at the z band. This seems to be related to the bandwidth of the z filter, as we explain in the following. In general, if the spectrum

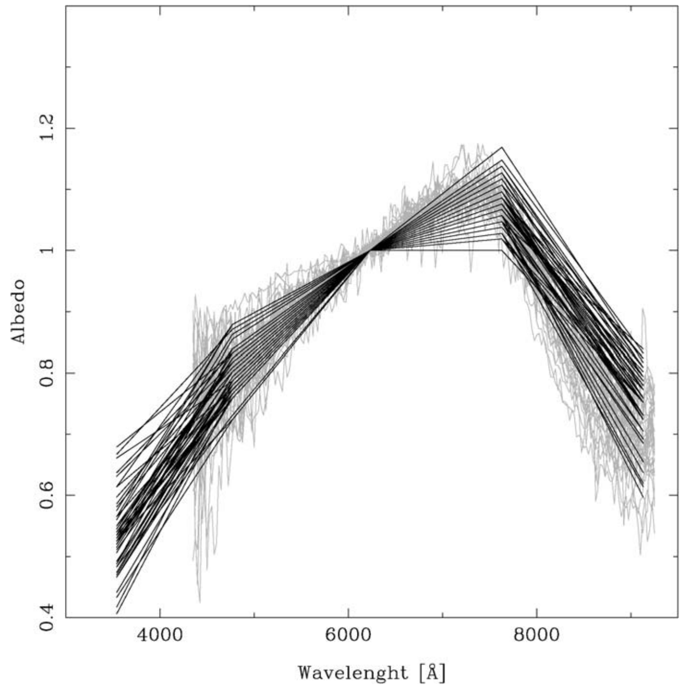

Fig. 3. SDSS albedos of 50 V-type candidates chosen at random from our sample (black lines) compared to the reflectance spectra of 35 V-type asteroids from the SMASS II survey (gray lines). All the data have been normalized to 1 at the center of the r band (6230 Å).

shows an absorption feature that is narrower than or comparable to the filter bandpass, then the photometric albedo, obtained by convolving the spectrum with the filter, will underestimate the absorption feature's depth, especially if the filter's effective wavelength falls close to the center of the absorption feature. This is precisely what happens with the SDSS albedos of V-type candidates. The effective wavelength of the z-band filter is very close to the center of the 0.90 μm absorption band typical of V-type spectra, and the filter width is comparable to the width of this absorption band that runs from ∼0.85 to ∼1.05 μm. This may explain the existence in the MOC of three V-type asteroids—(2640), (3782) and (3968)—with $F_z > 0.83$ that do not fulfill our selection criteria. Unfortunately, since all the visible spectroscopic surveys stop at ∼0.92 μm, we are unable to test this hypothesis.

In a recent work, Willman and Jedicke (2005) presented spectroscopic observations of 6 asteroids that would be V-type candidates. They selected these candidates based on the analysis of colors from the second release of the SDSS-MOC, as described by Nesvorný et al. (2005). Surprisingly, the 6 asteroids showed an S-type rather than a V-type spectrum. This probably means that the selection criteria applied by the authors was not rigorous enough to exclude the S-type observations from their sample of V-type candidates. On the other hand, using the method presented here, these 6 asteroids were clearly excluded from our sample. Therefore, we believe that our selection criteria provide a good sufficient condition to get a sample of very probable V-type asteroids.

4. Discussion

Once we arrived to a set of candidate V-type asteroids, we proceeded to analyze their orbital distribution in the space of proper elements. We eliminated from this analysis 3 candidates for which proper elements are not available. One of this objects is the near-Earth Asteroid (4055) Magellan, which is known to have a V-type spectrum (Lazzaro et al., 2004).

The remaining 496 V-type candidates in our sample are main belt asteroids for which analytic proper elements are available at the Asteroids Dynamic Site (http://hamilton.dm.unipi.it/cgi-bin/astdys/astibo). We primarily divided them in those that are members of the Vesta dynamical family and those that are not. In order to define the Vesta dynamical family, we applied the Hierarchical Clustering Method (HCM) to the database of analytic proper elements of 188204 asteroids known by August 2005. We defined the dynamical family with ∼9500 members at a cutoff value of 60 m/s (for more details on how to apply the HCM and how to choose the cutoff see Mothé-Diniz et al., 2005). We found 233 V-type candidates in our sample that are members of the Vesta family defined in this way (see Table 1). Of these, only (5481) is known to have a V-type spectrum (Lazzaro et al., 2004). The remaining ones have no spectrum observed and are waiting for confirmation.

We also found 263 V-type candidates that are not members of the Vesta dynamical family (see Table 2). Their orbital distribution is shown in Fig. 4. It is clear from this figure that almost all of these asteroids are located in the inner asteroid belt, and this provides a strong indication that *V-type asteroids outside the Vesta family are likely to come from (4) Vesta*.

However, the most interesting result is the presence of 6 V-type candidates in the middle/outer asteroid belt with $a > 2.7$ AU: (7472), (10537), (44496), (55613), (66905) and 2000 KO41. These asteroids are quite isolated in proper elements space and do not belong to any of the major dynamical families. They are not close in proper elements space to (1459) Magnya either. In fact, they are much less eccentric and inclined than Magnya, and it is almost impossible to establish a dynamical/collisional link among them. We might think that they are fragments of other parent bodies different form that of Magnya. However, their lower eccentricities and inclinations imply that the orbital neighborhoods of these asteroids would be relatively stable in the long term. Thus, the same dynamical mechanism proposed by Michtchenko et al. (2002) to explain the origin of Magnya may not work in these cases. A more detailed study of the long term orbital evolution and stability of these bodies would be necessary before elaborating any conclusions. But first, their basaltic character needs to be confirmed by spectroscopic observations.

Another interesting result is the presence of 2 V-type candidates in the middle asteroid belt with $2.5 < a < 2.6$ AU: (21238) and (40521). These asteroids are beyond the 3:1 mean motion resonance (MMR) with Jupiter, that defines the edge of the Vesta dynamical family at larger semi-major axes. However, they might still be fragments from Vesta's crust that were ejected at very high ($\gtrsim$700 m/s) velocities. We know that such large ejection velocities may occur in craterization events as the one that originated the Vesta family (Asphaug, 1997).

Of the 255 V-type candidates in the inner asteroid belt ($a <$ 2.5 AU) that are not members of the Vesta family, only (2442), (2704) and (3869) have observed spectra (Xu et al., 1995; Bus and Binzel, 2002), in all cases corresponding to the V-type. The orbital distribution of the remaining candidates shows some interesting features:

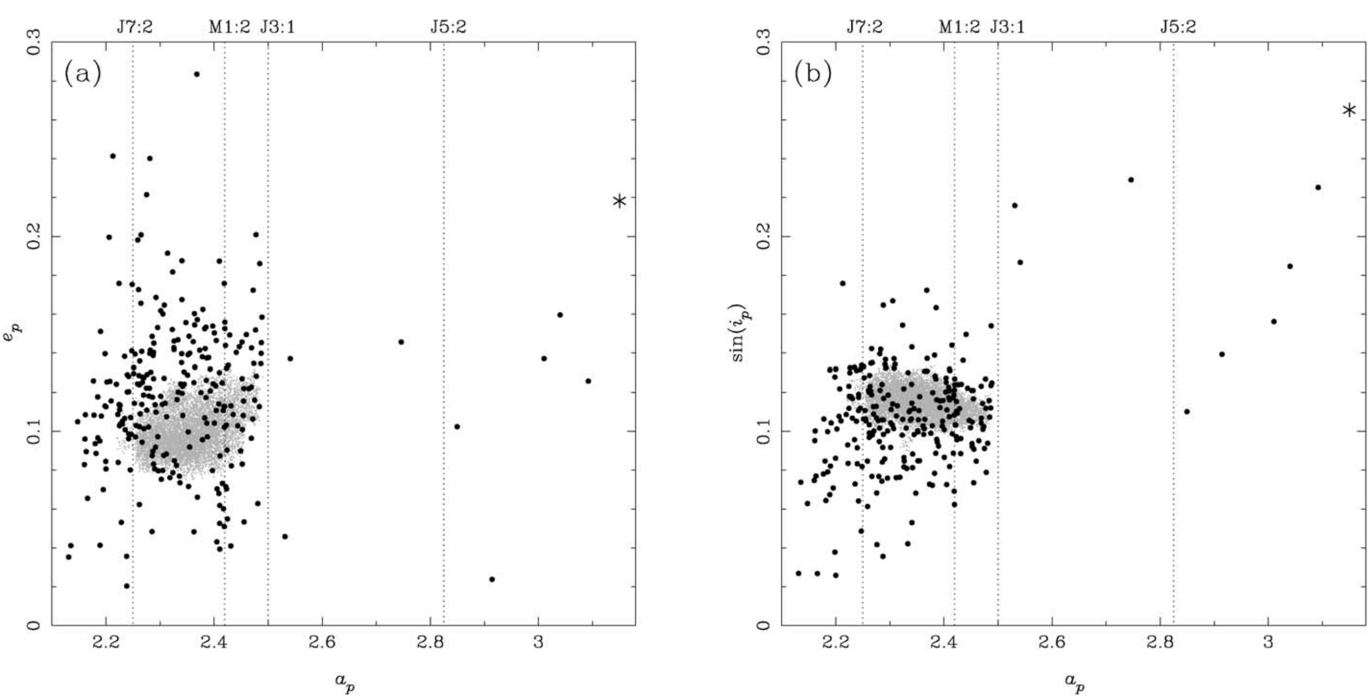

Fig. 4. The distribution in proper elements space of the 263 V-type candidates (full dots) that are not members of the Vesta dynamical family (gray dots). (1459) Magnya is indicated by a star. The vertical dotted lines mark the location of the main mean motion resonances labeled above (J ≡ Jupiter, M ≡ Mars).

(i) We identified 30 V-type candidates with $a < 2.22$ AU. We recall that the Vesta dynamical family is limited at the smaller semi-major axes by the 7:2 MMR with Jupiter, located between 2.23–2.27 AU. Until now, only two V-type asteroids were known to have semi-major axes smaller than 2.22 AU: (2579) and (3850) (Bus and Binzel, 2002). If the basaltic nature of our candidates is confirmed, this number would rise significantly. The origin of these asteroids might also be explained by very large ejection velocities generated during the craterization event that originated the Vesta family. However, they show a large dispersion in proper eccentricities and inclinations, indicating that their long term orbital evolution would have been strongly affected by some still unknown dynamical mechanism.

(ii) The V-type candidates outside the Vesta family show a systematic tendency to smaller proper inclinations (∼3 deg less) than the Vesta family members (Fig. 4b). This tendency has been already noted in the known V-type asteroids outside the Vesta family (see Fig. 1 of Carruba et al., 2005). It is difficult to believe that this happens by chance, but we are far from providing a possible explanation.

(iii) Several asteroids appear distributed along some MMRs, in particular, the 7:2 MMR with Jupiter and the 1:2 MMR with Mars (Fig. 4a). Since we mainly concluded that most *V-type asteroids outside the Vesta family probably come from the Vesta family itself*, the presence of these resonant asteroids supports the idea that they might have evolved from the Vesta family by slowly drifting in eccentricity and inclination along the weak MMRs. This is a well known mechanism in which slow changes in the semi-major axes due to thermal dissipative forces, like the Yarkovsky effect (Bottke et al., 2002), may push the Vesta family members to reach these MMRs where they follow chaotic paths outside the Vesta family. For example, Carruba et al. (2005) showed that asteroids entering the 7:2 MMR may evolve to planet crossing orbits in time scales of the order of 100 Myr, and may significantly contribute to the production of V-type near-Earth asteroids (Burbine and Binzel, 2002). We are also carrying out numerical simulations showing that the evolution of Vesta family members along the 1:2 MMR with Mars is significant in time scales of the order of 500 Myr.

Finally, let us recall that Carruba et al. (2005) proposed a list of possible V-type candidates selected on the basis of pure dynamical criteria. These authors found a plausible dynamical mechanism that might explain the presence of some known V-type asteroids outside the Vesta dynamical family, like (809) Lundia and (956) Elisa. The mechanism involves a complex interaction between the Yarkovsky effect, several weak three-body MMRs, and the non linear secular resonance $z_2 = 2(g - g_6) + (s - s_6)$ (Milani and Knežević, 1992). They proposed that this mechanism may have also affected several bodies that might be found nowadays close in proper elements space to (809) Lundia and (956) Elisa. Their list of candidates includes 32 asteroids of which 13 have been observed by the SDSS-MOC. Of these, only one was identified as a possible V-type using our selection criteria: (19738) Calinger. This asteroid is then the most probable V-type candidate in our sample.

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