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The first confirmation of V-type asteroids among the Mars crosser population [☆]



A.O. Ribeiro ^a, F. Roig ^{a,*}, M. Cañada-Assandri ^{b,c}, J.M.F. Carvano ^a, F.L. Jasmin ^a,
A. Alvarez-Candal ^{a,d}, R. Gil-Hutton ^{b,c}

^a Observatório Nacional, Rua General José Cristino 77, Rio de Janeiro 20921-400, Brazil

^b Universidad Nacional de San Juan, Av. España 1512 sur, San Juan J5402DSP, Argentina

^c Complejo Astronómico El Leoncito (CONICET), Av. España 1512 sur, San Juan J5402DSP, Argentina

^d Instituto de Astrofísica de Andalucía – CSIC, Glorieta de la Astronomía s/n, E18008 Granada, Spain

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ABSTRACT

The Mars crossing region constitutes a path to deliver asteroids from the Inner Main Belt to the Earth crossing space. While both the Inner Main Belt and the population of Earth crossing asteroids contains a significant fraction of asteroids belonging to the V taxonomic class, only two of such V-type asteroids has been detected in the Mars crossing region up to now. In this work, we systematically searched for asteroids belonging to the V class among the populations of Mars crossing asteroids, in order to support alternative paths to the delivery of these bodies into the Earth crossing region. We selected 18 candidate V-type asteroids in the Mars crossing region using observations contained in the Sloan Digital Sky Survey Moving Objects Catalog. Then, we observed 4 of these candidates to take their visible spectra using the Southern Astrophysical Research Telescope (SOAR). We also performed the numerical simulation of the orbital evolution of the observed asteroids. We confirmed that 3 of the observed asteroids belong to the V class, and one of these may follow a path that drives it to an Earth collision in some tens of million years.

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1. Introduction

Mars crosser (MC) asteroids are distributed in the region with $1.3 < q < 1.666$ AU and $a < 3.2$ AU, where q is the perihelion distance and a is the orbital semi-major axis. Together with the Earth-crosser (EC) asteroids ($q < 1.3$ AU and $Q > 0.983$ AU, where Q is the aphelion distance), they have been recognized as the potential sources of the meteorites recovered on the Earth. The origin of these two populations relies on the dynamical interaction between the web of mean motion and secular resonances in the asteroid Main Belt and the thermal re-emission forces acting on the surface of the small asteroids, the so-called Yarkovsky and YORP effects. This interaction produces a continuous loss of asteroids especially from the Inner Main Belt (IMB; $q > 1.666$ AU and $2.0 < a < 2.5$ AU) to the planet crossing region. Therefore, it should be expected that the IMB, MC and EC populations show similarities in their taxonomical distribution. In this work, we

address the occurrence of asteroids belonging to the V taxonomic class among the population of Mars crossers.

Taxonomy allows us to classify the asteroids according to observations related to their surface properties, like colors, spectra and albedos. Although in general there is no direct relation between taxonomic class and mineralogy, taxonomic classification imposes some constraints on the possible mineralogy of the body. Among the recognized taxonomic classes (e.g. Bus and Binzel, 2002b), the V class is particularly interesting. Its spectrum shows a steep slope downwards of $\sim 0.8 \mu\text{m}$ and a deep absorption band long-wards of $\sim 0.8 \mu\text{m}$ and centered at $\sim 1.0 \mu\text{m}$. This band is associated to a mineralogy typical of basalt (e.g. Burbine et al., 2001). The V class is mostly found among the members of a dynamical family in the IMB, the Vesta family (Binzel and Xu, 1993), which originated from a collision that excavated a huge crater on the basaltic surface of asteroid (4) Vesta (McCord et al., 1970; Asphaug, 1997). Recent results from the Dawn mission confirm the origin of the diogenite meteorites from Vesta's Rheasilvia crater (Reddy et al., 2011, 2012, 2013; McSween et al., 2013), and help to interpret the differences between HED meteorites, vestoids and Vesta in terms of grain size and collisional implantation of material on Vesta's surface (Buratti et al., 2013). The spectral peculiarities and the spatial concentration of the V-type asteroids make them especially useful as tracers of the

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* Corresponding author.

E-mail addresses: anderson@on.br (A.O. Ribeiro), froig@on.br (F. Roig).

dynamical paths that may transport asteroids from the IMB to the planet crosser region.

It has been proposed (see Morbidelli et al., 2002 and references therein) that the EC and MC asteroids would be the fragments of large bodies of the Main Belt that after a collision were injected into the J3:1 mean motion resonance or the ν_6 secular resonance. The chaotic evolution inside these resonances excited the fragments' orbital eccentricities driving them to cross the orbits of the terrestrial planets. The flux of asteroids falling into the J3:1, ν_6 and other major resonances might be continuously resupplied by the mobility in semi-major axis caused by the Yarkovsky effect (Farinella et al., 1998; Vokrouhlický and Farinella, 2000). Migliorini et al. (1998) and Michel et al. (2000) also showed that a significant fraction of the IMB asteroids may become MCs over 100 My time scales through weaker resonances other than the J3:1 and the ν_6 .

An analysis of the taxonomical distribution in the planet crossing region has been done by Binzel et al. (2004) using spectroscopic data of 254 EC and MC asteroids taken from the SMASS survey. They found a significant correlation between the distribution of taxonomic classes in the Main Belt and the EC and MC populations, especially for the classes belonging to the S and Q complexes. Their analysis also showed an albedo dependent distribution with heliocentric distance for the classes belonging to the X complex. These results are in line with the proposed origin of the planet crossing asteroids from Main Belt sources, possibly with a minor contribution from other sources like the Jupiter family comets. de León et al. (2010) also used a spectroscopic survey of other 74 EC and MC asteroids to compare their mineralogy with that of the Main Belt asteroids and of the ordinary chondrite meteorites. They found that EC and MC asteroids appear to have less reddish surfaces compared to the Main Belt bodies, and that the main source for these asteroids would be the IMB. Moskovitz et al. (2010) analyzed the near infra red (NIR) spectra of 39 IMB asteroids and compare them to the HED sample of meteorites. They found that the asteroids' mineralogy is not totally compatible with that of the HEDs, and they attribute this to the effect of space weathering, among other possibilities. In their sample, they include two MC asteroids, (1468) Zomba and (33881) 2000 JK66, compatible with a basaltic mineralogy, although the authors did not address these objects as Mars crossers. More recently, Sanchez et al. (2013) analyzed the visible and near infra-red spectra of 14 EC and MC asteroids and found that their composition is consistent with either ordinary chondrites or basaltic achondrites meteorites.

It must be noted, however, that all the above spectroscopic surveys failed, in general, to identify asteroids of the V class among the MC population, whereas about 10% of the IMB population and 4% of the EC population with currently known taxonomy belong to this class. Binzel et al. (2004) argued that the lack of V-type asteroids among the MC asteroids is in line with the idea that these bodies would be directly injected into the J3:1 and ν_6 resonances from low eccentricity and low inclination orbits, compatible with the Vesta family locus. Once inside these resonances, they would rapidly evolve to EC orbits without having any dynamical interaction with Mars. Notwithstanding, long term orbital simulations by Nesvorný et al. (2008) and Roig et al. (2008) indicate that about 8% of the Vesta family members could become MCs over 2 Gy of evolution. Since the Vesta family currently has more than 10,000 members and it is older than at least 1.2 Gy (Carruba et al., 2005), we should expect to find significant traces of V-type asteroids in the MC region.

In this work, we use the observations provided by the 4th release of the Sloan Digital Sky Survey Moving Objects Catalog (SDSS-MOC4, Ivezić et al., 2001; Jurić et al., 2002) to identify MC asteroids with surface colors compatible to those of the V class.

Table 1

Number of asteroids in the three dynamical regions analyzed: N_{Ast} is the number of known asteroids in the ASTORB database, N_{Tax} is the number of asteroids with taxonomic classification in the SDSS-MOC4 (Carvano et al., 2010), N_V is the number of asteroids classified as V-type by these authors.

Number	EC	MC	IMB
N_{Ast}	8268	9912	169,274
N_{Tax}	91	533	19,946
N_V	3	10	2623

Our searching method is summarized in Section 2.1. In Section 2.2, we present the spectroscopic observations of four of these asteroids, made with the SOAR telescope, in order to confirm if they are actual V-type asteroids. An analysis of the dynamical evolution of these bodies is given in Section 3. Finally, Section 4 is devoted to the conclusions.

2. V-type asteroids in the Mars Crosser region

The shortage of V type asteroids among the MC population, when compared to the EC, might be related to an observational bias due to the small fraction of asteroids with observed spectra in the two populations (1% among the MCs and 4% among the ECs). Moreover, different spectroscopic surveys could be affected by selection effects and completeness effects that are difficult to quantify. Nevertheless, we can apply a simple argument to show that a significant amount of V-type asteroids should be spectroscopically detected in the MC region.

This argument is based on the taxonomic classification developed by Carvano et al. (2010) for the observations contained in the SDSS-MOC4. Let N_{Ast} be the number of known asteroids listed, for example, in the ASTORB database (<ftp://ftp.lowell.edu/pub/elgb/astorb.html>).¹ Let N_{Tax} be the number of asteroids in the SDSS-MOC4 that have got a taxonomic class in Carvano et al. (2010); and let N_V be the number of these SDSS-MOC4 asteroids specifically classified as V-type. Table 1 summarizes these numbers for each population of interest. At first glance, it appears that there are more V-type asteroids detected in the MC region than in the EC region. However, we must bear in mind that the detection efficiency of the SDSS, which is given approximately by the fraction N_{Tax}/N_{Ast} , is different in each population, and in particular it is larger in the IMB. Therefore, if we assume that the fraction N_V/N_{Tax} is representative of the actual fraction of V-type asteroids in each population, the actual number \bar{N}_V of V-type asteroids that the SDSS-MOC4 could have detected in either the MC or EC region is

$$\bar{N}_V = \frac{N_V}{N_{Tax}} N_{Ast} \frac{N_{Tax}^{IMB}}{N_{Ast}^{IMB}}$$

This gives $\bar{N}_V = 22$ in the MC population and $\bar{N}_V = 32$ in the EC region, and although there would be less V-type asteroids in the MC than the EC region, their amount should be significant enough to allow their spectroscopic detection provided that a systematic search for these bodies is carried out.

2.1. Selecting candidate V-type observations from the SDSS-MOC4

In this work, we use the five band photometric observations of the SDSS-MOC4 survey to produce a list of potentially interesting targets for further spectroscopic observations among the Mars crossing population. The SDSS-MOC4 provides calibrated

¹ The ASTORB file is produced at the Lowell Observatory, by Edward Bowell.

Table 2

The targets selected for spectroscopic observation. Asteroids marked with an (*) were observed spectroscopically in this work. Columns give osculating perihelion distance (q), semi-major axis (a), eccentricity (e), and inclination (I) correspond to JD 2456000.5 (2012-03-14). Table also gives the absolute magnitude H , the number of SDSS-MOC4 observations considered N_{SDSS} , the average values of the first and second principal components PC_1 and PC_2 , and the average Sloan $i-z$ color. The last column identifies the taxonomic classification according to Carvano et al. (2010); the +NIR flag indicates that the object has also been observed in the near infra red by Moskovitz et al. (2010).

Asteroid name	q [AU]	a [AU]	e	I [deg]	H	N_{SDSS}	PC_1	PC_2	$i-z$	Taxonomy
(1468) Zomba (*)	1.601	2.1958	0.2707	9.9434	13.6	1	-0.1218	-0.2182	-0.21	Q (+NIR)
(16147) Jeanli	1.777	2.2801	0.2206	5.9068	14.2	8	-0.1968	-0.3125	-0.43	V
(28985) 2001 MP5	1.742	2.2493	0.2254	4.1578	14.8	1	-0.1611	-0.2593	-0.41	V
(31415) 1999 AK23 (*)	1.662	2.2751	0.2695	6.8439	14.4	1	-0.1775	-0.3109	-0.40	V
(32008) 2000 HM53 (*)	1.769	2.1918	0.1929	6.3020	14.1	1	-0.2349	-0.2619	-0.42	V
(33881) 2000 JK66	1.567	2.2124	0.2916	11.1721	14.4	1	-0.1167	-0.2277	-0.38	V (+NIR)
(44798) 1999 TL191	1.752	2.2809	0.2318	7.4329	15.0	2	-0.1933	-0.2817	-0.40	V
(60669) 2000 GE4	1.765	2.2066	0.1999	7.6918	15.2	2	-0.1775	-0.2322	-0.34	V
(67621) 2000 SY175	1.760	2.1780	0.1919	5.4648	15.8	2	-0.1784	-0.2992	-0.46	V
(89137) 2001 UD17	1.649	2.1997	0.2501	7.4623	16.6	1	-0.0382	-0.2743	-0.29	-
(100316) 1995 MM2	1.588	2.2117	0.2499	4.8471	16.0	1	-0.1278	-0.1744	-0.13	Q
(102803) 1999 VA169	1.633	2.1359	0.2353	4.8482	16.7	3	-0.2055	-0.1936	-0.19	Q
(130988) 2000 WT141 (*)	1.738	2.4606	0.2938	10.2803	15.3	1	-0.2044	-0.2280	-0.35	V
(265117) 2003 UQ26	1.773	2.1979	0.1932	7.6565	16.8	1	-0.0925	-0.1971	-0.35	V
(276400) 2002 XS45	1.579	2.1937	0.2799	5.6344	16.2	1	-0.2314	-0.1983	-0.19	SQ
(285894) 2001 QV25	1.702	2.2241	0.2346	8.0129	16.8	1	-0.0498	-0.2270	-0.28	-
1999 SO15	1.571	2.2316	0.2960	8.5455	17.4	1	-0.1689	-0.2404	-0.33	V
2005 SF57	1.724	2.2484	0.2334	3.8331	18.1	1	-0.2070	-0.2303	-0.46	V

Table 3

Observational circumstances of the V-type candidates observed with the SOAR telescope. JD indicates the time of the beginning of the observation. Air mass and V apparent magnitude are listed in the second and third columns. ϕ , R and Δ are the solar phase angle, the heliocentric distance and the geocentric distance of the target, respectively.

Asteroid number	JD (2455000+)	Air mass	V	ϕ [°]	R [AU]	Δ [AU]
(1468)	929.78819039	1.46	18.20	19.9	2.79	2.36
(31415)	804.49685336	1.16	18.51	28.6	2.09	1.97
(32008)	929.74843229	1.31	17.19	15.0	2.32	1.47
(130988)	804.80536412	1.14	16.84	9.4	1.83	0.84

magnitudes of 220,101 moving objects in the bands u, g, r, i, z , with their corresponding errors. These observations are effectively linked to 104,409 unique asteroids. The MOC4 is an extension of the 3rd release (MOC3) and contains about twice more observations than its predecessor. However, many of these new observations were obtained in non photometric conditions² and were excluded from our analysis. This clean up results in a final sample of 94,116 observations, corresponding to 70,234 asteroids.

There are different approaches to search for specific taxonomic classes among a large set of observations like the SDSS-MOC4. Roig and Gil-Hutton (2006), for example, selected candidate V-type asteroids by applying a Principal Component Analysis to the distribution of the observations. Carvano et al. (2010) used a method based on comparison of the whole set of colors with templates of the known classes. Moskovitz et al. (2008) compared individual colors to those of known V-type asteroids. Solontoi et al. (2012) selected V-type candidates studying the distribution of the observations in a color-color diagram. It is worth noting that these approaches are all independent and produce results that show a good overlapping. In principle, it is not possible to say that one method should be preferred over another.

In this work, we followed the approach of Roig and Gil-Hutton (2006) that basically consists of the following steps: (i) for each observation in our sample, we computed the photometric reflectance fluxes normalized to the r band with their corresponding errors; (ii) we discarded the observations with errors larger than

10% in any of the fluxes; (iii) we applied the Principal Components Analysis to the remaining observations and chose those with principal components $PC_1 < 0$ and $PC_2 < -0.158$; and (iv) from this last sample, we selected the observations linked to asteroids having osculating $1.3 < q < 1.77$ AU. At this point, it is important to clarify the criteria used to select the observations. The criterion in step (iii) is more relaxed than the one applied by Roig and Gil-Hutton (2006) to select V-type candidates, and the result is probably more contaminated by candidates of other taxonomic classes, especially the S and Q classes that can be mistaken with the V class in the SDSS photometry. Nevertheless, our aim is not to make a precise classification of the observations but to produce a list of potential targets for spectroscopic observations, and a more restrictive selection criterion could discard targets that might be interesting. The criterion in step (iv) is also more relaxed than the actual definition of Mars crossers. However, the choice of 1.77 AU as the upper limit of the population's perihelion distance, instead of the 1.666 AU classical limit, allows us to include some IMB asteroids that may get to $q < 1.66$ AU in a few hundreds of thousand years. In fact, most IMB asteroids currently in the interval $1.67 < q < 1.77$ AU evolve in a Kozai-like regime, which produces large amplitude coupled oscillations of the asteroid's eccentricity and inclination, with periods of the order of 10^5 years, while the semi-major axis remains fixed (e.g. Valsecchi and Gronchi, 2011).

Our procedure led to 30 observations matching the above criteria, which correspond to 18 asteroids listed in Table 2. This table gives the orbital parameters and absolute magnitude of the asteroids, the values of the principal components and the number of Sloan observations used. It also lists the $(i-z)$ color index, which gives an idea of the depth of the absorption band long-wards of $0.75 \mu\text{m}$. Comparing this list with the taxonomy developed by Carvano et al. (2010),³ we found 12 asteroids with at least one observation in the SDSS-MOC4 identified by these authors as belonging to the V class, while 4 candidates were classified by them as Q-type and 2 remain unclassified. We also found the two asteroids reported by Moskovitz et al. (2010) from NIR observations. This information is summarized in the last column of Table 2.

² Observations with declination $|\delta| < 1.26^\circ$ or galactic latitude $|b| < 15^\circ$; see <http://www.astro.washington.edu/users/ivezic/sdssmoc/sdssmoc.html>.

³ Available at the Planetary Data System Node, <http://sbn.psi.edu/pds/resource/sdsstax.html>.

Table 4
Solar analog stars used to obtain the reflectance spectra of the asteroids. The last column indicates the asteroid's spectrum to which the solar analog correction was applied. Note that HD 102365 was observed at different air masses for different asteroids.

Star name	α (J2000)	δ (J2000)	Air mass	V	B–V	Spectral type	Asteroid(s)
HD 102365	11 ^h 46 ^m 31.07 ^s	–40°30′01.27″	1.15/1.32	4.89	0.66	G2V	(1468)/(31415)
HR 3538	08 ^h 54 ^m 17.95 ^s	–05°26′04.06″	1.12	6.00	0.67	G3V	(32008)
HR 8700	22 ^h 53 ^m 37.93 ^s	–48°35′53.83″	1.21	6.03	0.63	G0V	(130988)

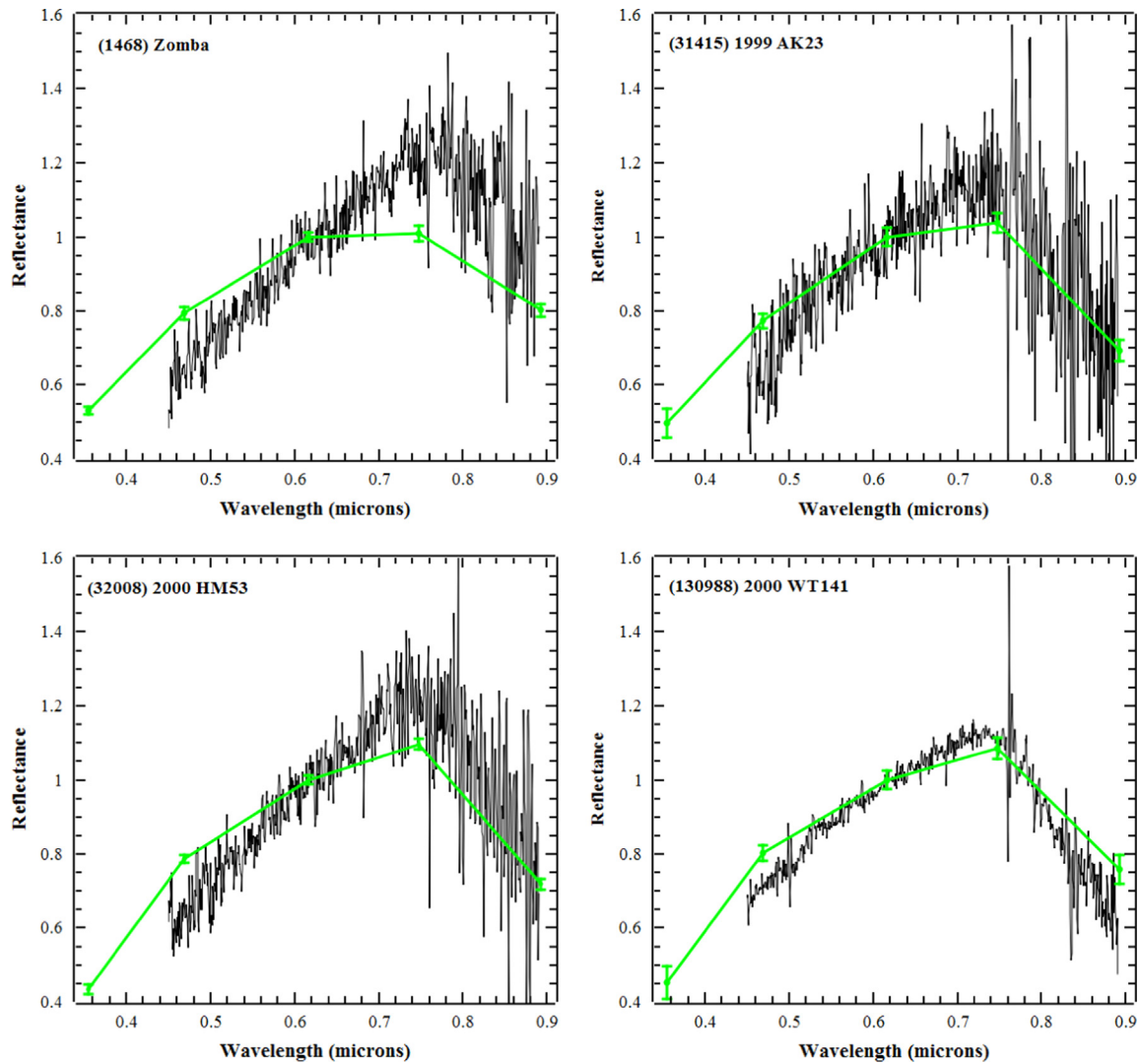


Fig. 1. Spectra (black lines) of the four asteroids observed with the SOAR telescope. Green dots represent the SDSS observations with their corresponding error bars. The reflectance is normalized to 1 at 0.616 μm . (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

2.2. Spectroscopic observations of V-type candidates

Four asteroids in our list of V-type candidates have been observed in service mode using the Goodman HT Spectrograph installed at the 4.1 m Southern Astrophysical Research Telescope (SOAR) in Cerro Pachón, Chile, during semester 2012A. The observational circumstances are summarized in Table 3. The Goodman HT Spectrograph was used in single long slit mode, with a slit of 1.03″ in width. It was equipped with a blocking filter GG-385 and a grating of 300 l/mm, which gives a resolution $R \sim 1390$. The nominal wavelength coverage of the optical system is from 0.39 to 0.91 μm . The exposure time per target varies between 550 and 600 s, which allowed to get a S/N of up to ~ 30 in the best case.

Table 5

Distance d_i between the spectrum of each asteroid and the V class template. Spectra with $d_i \leq 0.038$ are undoubtedly classified as V-type.

Asteroid	d_i
(1468)	0.080
(31415)	0.024
(32008)	0.050
(130988)	0.015

To subtract the solar contribution from the spectra, solar analog stars have also been observed at approximately the same air mass of the asteroids. The exposure time was of 1 s for each star, and the

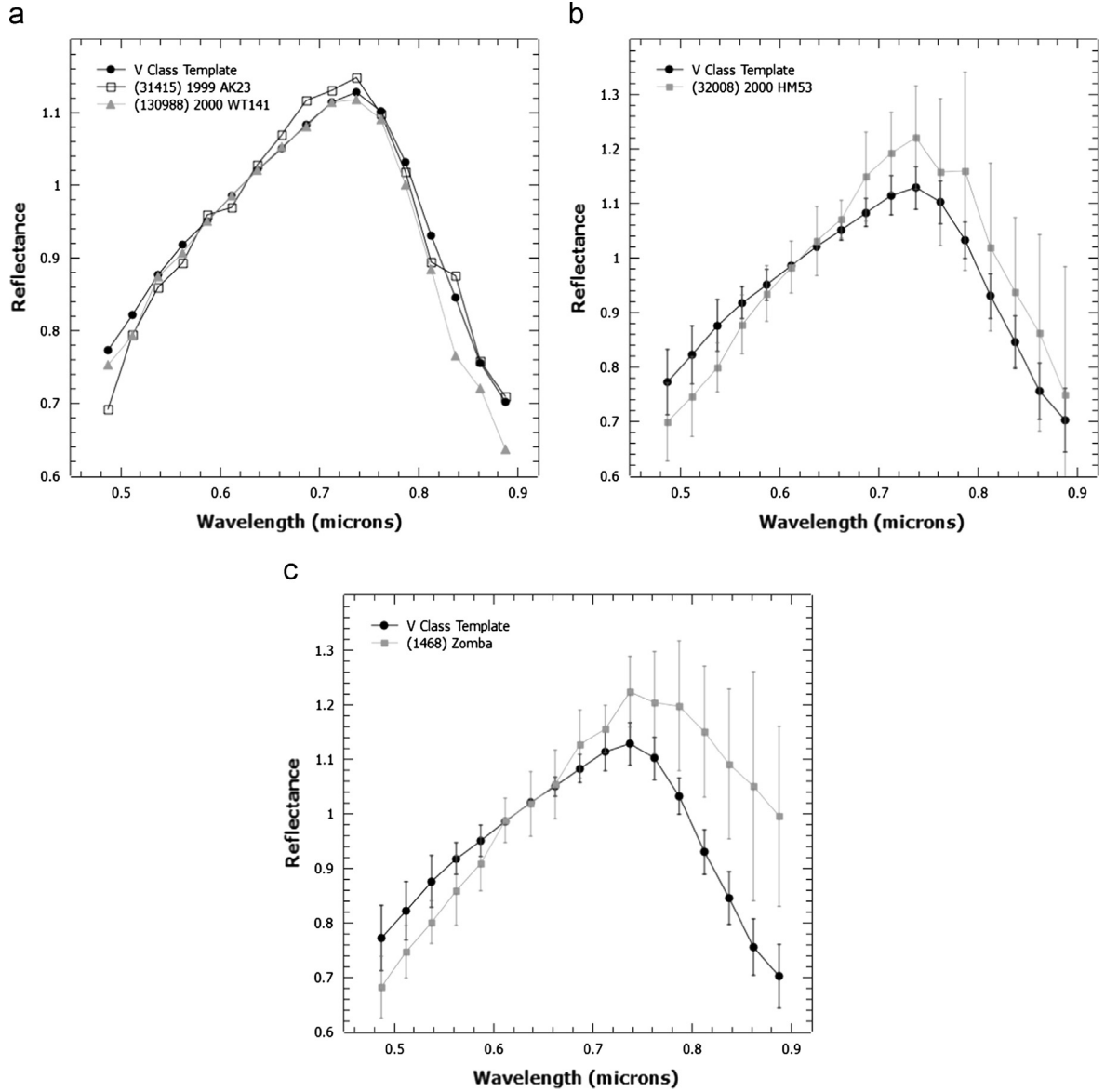


Fig. 2. Comparisons between the V class template (full black dots) and the rebinned spectra of the observed asteroids (other symbols). In panels b and c, we also show the corresponding $1-\sigma$ error bars of the spectra and the template. Note the different vertical scales in panel a.

star spectrum was obtained immediately before or after the asteroid's spectrum. The stars used are listed in Table 4. Bias, dome flat field, and Hg–Ar lamp images have also been obtained for calibration and reduction purposes. The spectra have also been corrected by atmospheric extinction, which introduces some unreddening only for the objects observed at the large air masses, although very well inside the $1-\sigma$ dispersion of the spectra.

The resulting spectra for each of the four asteroids are shown in Fig. 1. The spectra have been normalized to reflectance 1 at the center of the *r* band ($0.616 \mu\text{m}$), instead of the classical value of $0.55 \mu\text{m}$, to make them comparable to the SDSS data. The spectra have also been limited to the interval from 0.45 to $0.89 \mu\text{m}$, since the data below $0.45 \mu\text{m}$ is quite noisy and it is actually irrelevant for taxonomic classification purposes (see the next paragraph), and the data above $0.89 \mu\text{m}$ is extremely noisy and unusable. The small dots linked by green lines represent the SDSS fluxes, with their corresponding error bars. The agreement between the Sloan fluxes and the spectrum is good, except in the case of (1468) Zomba.

In order to verify if the observed spectra belong or not to the V class, we performed a comparison to a template of the class. The

template was synthesized using 37 V-type spectra in the interval from 0.49 to $0.92 \mu\text{m}$ that are available in the SMASS II survey⁴ (Bus and Binzel, 2002a,b) and the S³OS² survey (Lazzaro et al., 2004), according to the following procedure: first, all the spectra were rebinned in wavelength into 18 channels of $0.025 \mu\text{m}$ each. If $f_{i,k}$ denotes the mean flux of the *i*-th spectrum at the *k*-th channel and $\sigma_{i,k}$ is the corresponding standard deviation, then the template's flux at the *k*-th channel is computed by the weighted average

$$\bar{f}_k = \frac{\sum_i f_{i,k} \sigma_{i,k}^{-2}}{\sum_i \sigma_{i,k}^{-2}}$$

where the summation runs over the 37 reference spectra. The corresponding unbiased weighted sample variance and standard deviation $\bar{\sigma}_k$ are also computed. The membership of any spectrum to the template's class is then determined by computing the

⁴ Actually, the SMASS II spectra are in the interval from 0.43 to $0.92 \mu\text{m}$, but they were cut off at $0.49 \mu\text{m}$ to make them compatible with the S³OS² ones.

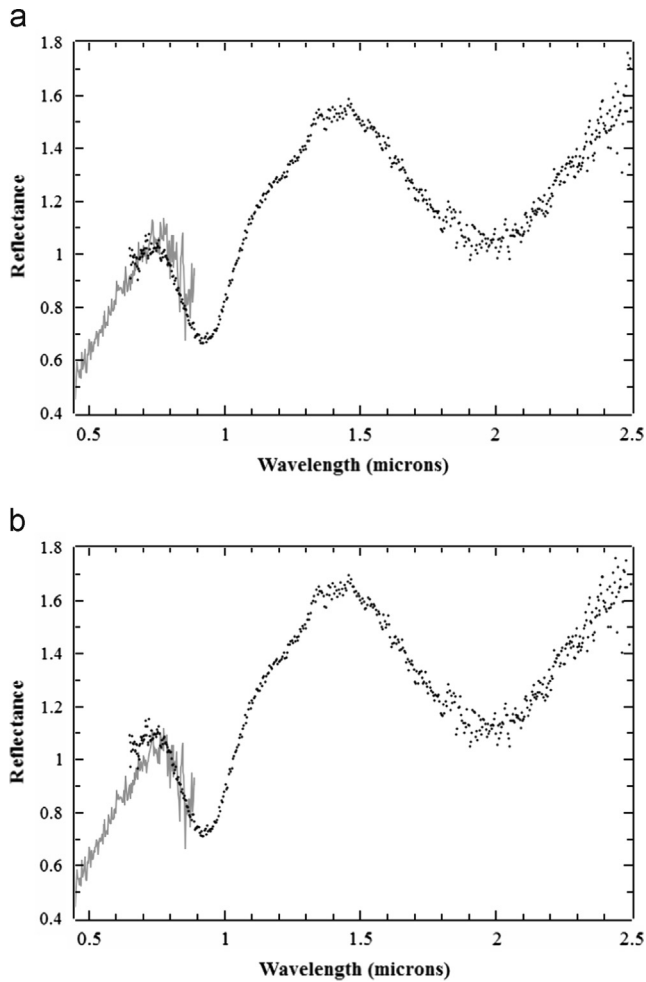


Fig. 3. Spectrum of (1468) in the range 0.45–2.5 μm , obtained by collating our visible spectrum (gray line) with a NIR spectrum of Moskovitz et al. (2010) (black dots). We have applied a 20:1 rebinning in wavelength to the visible spectrum. The reflectance has been normalized to 1 at two common wavelengths: 0.7 μm (panel a) and 0.8 μm (panel b). In either case, it is not possible to find a good match between the visible and NIR spectra.

Table 6
Estimated diameters and maximum Yarkovsky drifts.

Asteroid	D [km]	$ \dot{a} _{\text{max}}$ [AU/y]
(31415)	2.96	8.5×10^{-11}
(32008)	3.40	7.4×10^{-11}
(130988)	1.96	12.8×10^{-11}

weighted distance

$$d_i = \left[\frac{\sum_k (f_{i,k} - \bar{f}_k)^2 (\sigma_{i,k}^2 + \bar{\sigma}_k^2)^{-1}}{\sum_k (\sigma_{i,k}^2 + \bar{\sigma}_k^2)^{-1}} \right]^{1/2}$$

where the summation runs over the 18 channels. Among the 37 reference spectra, the maximum distance to the template is $d_{\text{max}} = 0.038$, therefore any spectrum having $d_i \leq d_{\text{max}}$ can be considered to belong to the V class.

Table 5 gives the distance to the template of the four spectra observed in this work. In the case of (31415) and (130988), we conclude that they can be classified as V-type asteroids. Fig. 2a shows a comparison between the two rebinned spectra and the class template indicating a very good agreement.

In the case of (32008), the value of d_i would indicate that this in principle may not be a V-type. However, the comparison of the

rebinning spectrum to the class template, shown in Fig. 2b, indicates a profile compatible with a V-type spectrum, especially concerning the deep absorption feature long-wards of 0.75 μm . We may also note from this comparison that, even if the spectrum is overestimated with respect to the template beyond the normalization wavelength, all the channels are indistinguishable within the $1 - \sigma$ uncertainties. Thus, (32008) can be marginally classified as a V-type.

In the case of (1468), the distance d_i is incompatible with the class, and the rebinned spectrum is distinguishable from the template within the $1 - \sigma$ uncertainties (Fig. 2c). Therefore, this asteroid cannot be classified as a V-type through this procedure. We recall, however, that Moskovitz et al. (2010) reported two observations of (1468) in the NIR.⁵ These spectra cover the interval 0.65–2.5 μm and 0.82–2.5 μm , respectively, and the latter one allows those authors to perform a mineralogical analysis and a comparison to the HED meteorites, concluding that (1468) has a basaltic composition. In Fig. 3, we show an attempt to join our visible spectrum (rebinning) with this NIR spectrum, using two different common wavelengths for normalization: 0.7 and 0.8 μm . Since it is not possible to find a match, we conclude that our visible spectrum might have been affected by some instrumental problem producing a significant reddening. Among the possibilities, a target partially outside the slit during the acquisition of the spectrum might produce such effect.

Regardless of the issue with (1468), our results provide the first confirmations of V-type SDSS candidates among the Mars crossers. In the cases of (31415) and (32008), unfavorable observational conditions ((31415) was too faint and (32008) was observed at a rather large air mass) produced very noisy spectra, which implies larger uncertainties in the taxonomic classification. Therefore, although these two asteroids can be classified as V-type following our procedure, better spectroscopic observations would be advisable to reinforce this classification.

3. Orbital evolution of V-type Mars crossers

Of the three MC asteroids classified as V-type by our spectroscopic observations, two ((32008) and (130988)) are not currently Mars crossers but they are slightly above the limit in perihelion distance used by the classical definition of this population. The third one, (31415), is currently a Mars crosser but it is also very close to the upper limit of the population's q . In order to check the orbital behavior of these bodies, we have followed their evolution as test particles using the symplectic integrator SWIFT, modified to properly manage close encounters of the asteroids with the planets (SKEEL code; Levison and Duncan, 2000). Our model also includes the effect of Yarkovsky forces on the asteroids using the same approach as in Nesvorný et al. (2008), i.e. we introduce a dissipative force which is parallel to the orbital velocity and produces a prescribed drift da/dt in semi-major axis. The maximum allowed drift for an asteroid is given by

$$\left| \frac{da}{dt} \right| = k \frac{1 \text{ km}}{D}$$

where k is a parameter that for V-type asteroids is approximately 2.5×10^{-10} AU/y (see Nesvorný et al., 2008 for details), and D is the asteroid's diameter in km. Since the albedo of these three asteroids is unknown, the diameter in this case was estimated from the absolute magnitude H assuming an albedo of 0.35. This is compatible with recent estimates of (4) Vesta's albedo (Fornasier et al., 2011), and with the mean albedo of Vesta family members

⁵ Available at the Planetary Data System Node, <http://sbn.psi.edu/pds/resource/irtfspec.html>.

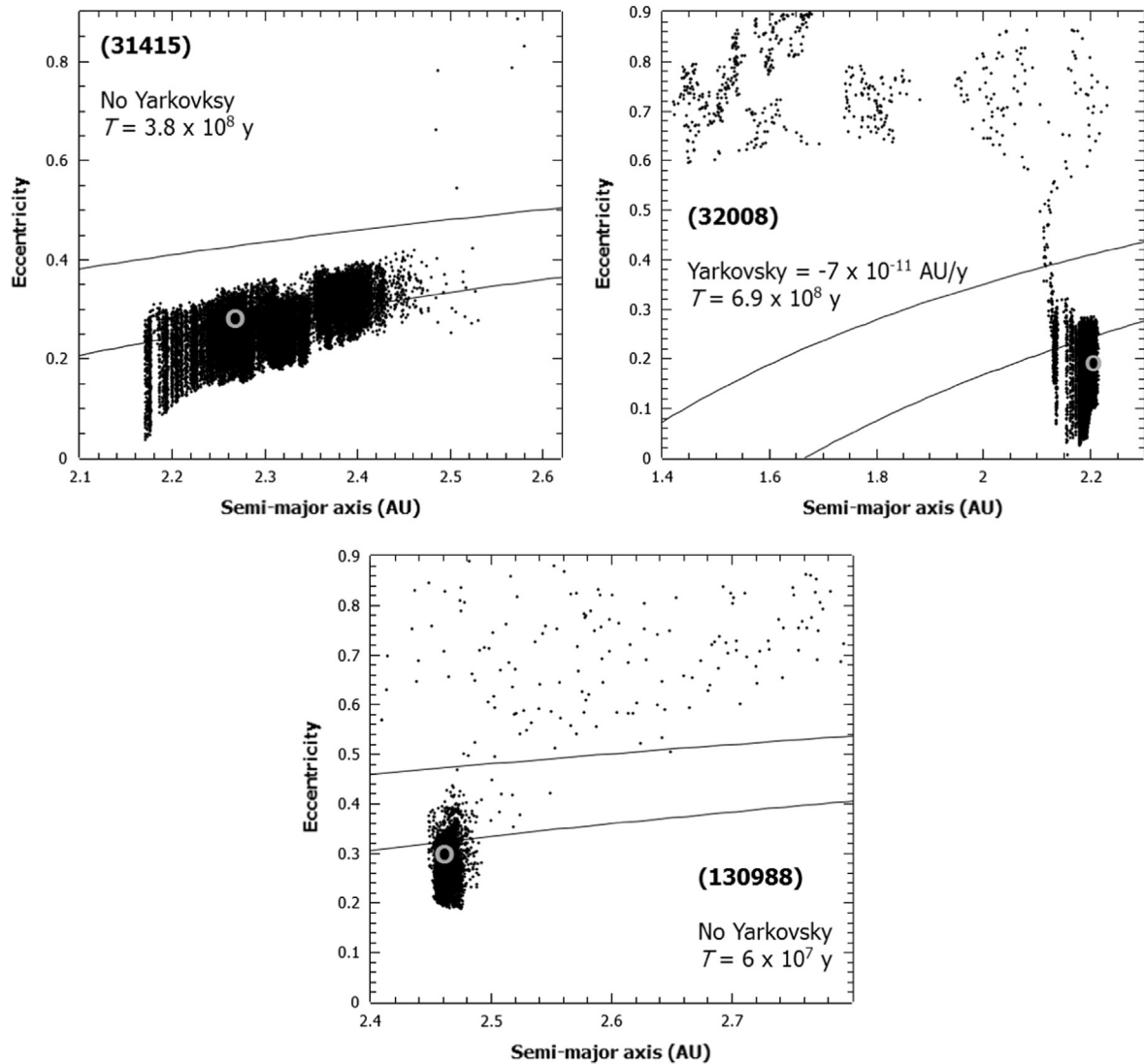


Fig. 4. Examples of the orbital evolution (black dots) of the three V-type asteroids confirmed in this study, in the space of semi-major axis vs. eccentricity. All the examples shown here led to Earth crossing orbits. The corresponding drift in semi-major axis due to the Yarkovsky effect is indicated, when applicable. The time T is the approximate time when the orbit enters the Mars crossing region to be quickly driven to an Earth crossing orbit. The full black lines represent the limits of the MC region. The area above the uppermost line corresponds to the EC region. The gray open circle indicates the current location of the asteroids, which was used as initial condition for the simulations.

from the WISE/NEOWISE survey (Masiero et al., 2012). The values are summarized in Table 6. The Solar System model considered all the 8 planets from Mercury to Neptune, and each simulation covered a time span of at least 200 My, but some simulations were extended up to 1 Gy.

For each of the three asteroids, we performed 11 simulations starting with the same orbital initial conditions: 1 simulation with no Yarkovsky effect, 5 with a Yarkovsky effect causing positive drifts in the semi-major axis (randomly sorted within the maximum allowed drift rate), and 5 with a Yarkovsky effect causing negative drifts. All the simulations show that the asteroids temporarily acquire $q < 1.666$ AU several times during their evolution, jumping in and out of the MCs region. The orbits of (31415) and (32008) appear to be quite stable and at most 18% of the simulations led to paths into the EC region only after several 100 My of evolution, with the subsequent elimination of the asteroid due to close encounters with the Earth or Venus. Examples of such simulations are shown in Fig. 4. In these cases, the transition to the Earth crossing regime is very fast, lasting of the order of 10 My or less.

On the other hand, in the case of asteroid (130988), we found that 72% of the performed simulations led to a behavior that drives

the asteroid to an Earth crossing orbit, eventually discarding it after a close approach to the Earth. The delivery of this asteroid to the EC region may happen as early as after 60 My of evolution. An example of this behavior is also shown in Fig. 4. Asteroid (130988) would be the first confirmed case of a V-type asteroid that originates in the IMB, passes through the MC region and arrives to the near-Earth space. Again in these cases, the evolution in the Mars crossing and Earth crossing regimes lasts ~ 10 My or less.

4. Conclusions

In this work, we applied the method of Roig and Gil-Hutton (2006) to identify candidate V-type asteroids among the populations of Mars crossers, using the photometry of the SDSS Moving Objects Catalog (4th release). We identify 18 asteroids with colors compatible with those of the V class, and performed spectroscopic observations of 4 of these candidates during semester 2012A with the SOAR Telescope. The resulting spectra indicate that

- two candidates are undoubtedly classified as V-type asteroids;

- one candidate can be marginally classified as a V-type;
- the fourth candidate cannot be classified as a V-type according to our observations, although according to [Moskovitz et al. \(2010\)](#) it has a basaltic composition;
- one of the confirmed V-type asteroids fully enters the Mars crossing region after some tens of million years of evolution, and is quickly driven (in less than 10 My) to have a close encounter with the Earth;
- the other two confirmed V-type asteroids temporarily enter the Mars crossing region several times during their orbital evolution, but they have quite stable orbits and are hard to be driven to the Earth crossing region over hundreds of million years of evolution.

Our observations provide the first spectroscopic confirmation of V-type SDSS candidates among the Mars crossers. They help us to enlarge the database of known basaltic asteroids among this population, and give support to the Mars crossing regime as an alternative path to deliver basaltic meteorites to the Earth. However, the actual efficiency of this dynamical path, and the still much lesser amount of V-type asteroids in the MC population relative to the EC population still remain open questions.

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