Spectral characterisation of 14 V-type candidate asteroids from the MOVIS catalogue

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ABSTRACT

Most of the currently known basaltic (V-type) asteroids are believed to be past or present members of the Vesta dynamical family. The rising discoveries of V-type asteroids that are not linked to the Vesta family dynamically suggest that a number of major basaltic bodies may have been present during the early stages of the solar system. Using the near-infrared (NIR) colour data in the Moving Objects from VISTA Survey (MOVIS) catalogue, a list of 477 V-type candidates was compiled, with more than half of them outside the Vesta family. In this work, we aim to provide a spectral analysis of 14 V-type candidates of various dynamical types. The computed visible and NIR spectral parameters are used to investigate evidence of space-weathering or mineralogical differences from the expected basaltic composition. Based on the analysis of their visible spectra, we confirm 11 new V-type asteroids: six low-i asteroids – (3188) Jekabsons, (3331) Kvistaberg, (4693) Drummond, (7223) Dolgorukij, (9007) James Bond, and (29733) 1999 BA4; along with four inner-other asteroids – (5524) Lecacheux, (19983) 1990 DW, (51742) 2001 KE₅₅, and (90023) 2003 BD₁₃; as well as one fugitive – (2275) Cuitlahuac. Additionally, we analysed three peculiar outer main belt V-type candidates based on their visible + NIR spectra. We confirm the diogenite-like composition of (2452) Lyot. The spectrum of asteroid (7302) is not consistent with a basaltic composition and likely reflects an S-type body. The spectrum of (14390) 1990 QP₁₀ is similar to a V-type but it shows unique spectral features that suggest a peculiar composition. Overall, our results demonstrate the efficiency of the MOVIS catalogue in identifying V-type objects, with a success rate of over 85%. The identification of V-types in the inner main-belt is more likely due to the presence of the Vesta family and other nearby asteroids that had escaped from the family. In the middle and outer main belt, where the amount of data is more limited, the proportion of false positives increases.

Key words. minor planets, asteroids: general – techniques: spectroscopic

1. Introduction

V-type asteroids are basaltic bodies that are rich in pyroxene and are believed to represent the crust of larger differentiated bodies. Their taxonomic classification is derived from asteroid (4) Vesta, which is the largest “small body” (530 km in diameter) to show a basaltic crust (McCord et al. 1970). The visible and near-infrared (NIR) spectra of V-type asteroids exhibit two characteristic absorption bands positioned near 1 and 2 μm . Due to the spectroscopic similarities with basaltic achondrites, Vesta is also considered the parent body of howardites, eucrites, and diogenites, also known as HEDs (Drake 2001). Eucrites are composed of Ca-pyroxene and Ca-plagioclase, the fundamental minerals of basalts. They are one of the extremes in a series that has diogenites (Ca-poor pyroxenes) on the other side. In the middle of this series are the howardites, considered to be breccias composed of debris from both eucrites and diogenites (Hutchison 2004).

Most of the discovered V-type asteroids belong to the Vesta collisional family in the inner main belt. Two craters in the south pole of Vesta identified by the Dawn mission (Marchi et al. 2012) most probably represent the origin of the Vesta dynamical

family. Since the first discovery of asteroids with spectra similar to Vesta near the 3:1 mean motion resonance with Jupiter (Binzel & Xu 1993), numerous other asteroids with V-type spectra were identified beyond the nominal borders of the family. Based on the dynamical models, these past members of the Vesta family were injected into resonances and moved to different orbits (Cruikshank et al. 1991; Farinella et al. 1994). Today, we know of basaltic asteroids all over the main belt (e.g. Nesvorný et al. 2008; Moskovitz et al. 2008; de Sanctis et al. 2011; Ieva et al. 2016; Hardersen et al. 2018; Licandro et al. 2017; Medeiros et al. 2019; Mansour et al. 2020). Some of them can be traced back to Vesta through various dynamical pathways (Nesvorný et al. 2008; Carruba et al. 2005, 2014; Brasil et al. 2017).

Since the discovery of asteroid (1459) Magnya located in the outer main belt (Lazzaro et al. 2000) and with an interpreted bulk composition different from Vesta (Hardersen et al. 2004), the presence of at least another large differentiated object is directly implied. Nowadays, several other basaltic asteroids are known in the middle and outer main belt (Ieva et al. 2016; Medeiros et al. 2019, and references therein). The analysis of oxygen isotopes is particularly useful in meteorites experiencing melting processes at large scales, such as the HEDs. This group typically

presents very similar O-isotopic values, which provides a basis for defining an average value and assessing whether deviating values from this average come from having a different parent body as that of the group (Greenwood et al. 2020). In this regard, additional evidence arguing in favour of the formation of another HED-like differentiated body in the belt is offered in the discovery of at least two eucrites having distinct, non-HED oxygen isotopic compositions (Yamaguchi et al. 2002; Burbine et al. 2002; Benedix et al. 2017).

In this work, we analyse the visible spectra of V-type candidate asteroids selected by Popescu et al. (2016) and Licandro et al. (2017), which are presented in Sect. 2, along with a confirmation of their classification and characteristic spectral properties in Sect. 3. We further focus on the compositional study of three peculiar asteroids from the outer main belt, for which visible and NIR spectra are analysed in Sect. 4. Finally, our conclusions are presented in Sect. 5.

2. Observations and data reduction

2.1. Target selection from the MOVIS catalogue

For the selection of targets for our study, we used the list of V-type candidates identified by Licandro et al. (2017), Popescu et al. (2018), and Mansour et al. (2020) in the Moving Objects from VISTA survey (MOVIS, Popescu et al. 2016). This is a set of three catalogues that include near-infrared colours of 39 947 objects recovered from the Visible and Infrared Survey Telescope for Astronomy (VISTA, Cross et al. 2012) and, in particular, its Hemisphere Survey (VISTA-VHS). The VISTA-VHS survey includes three different programs that observe the sky in four filters: *Y* (1.02 μm), *J* (1.25 μm), *H* (1.65 μm), and *Ks* (2.15 μm).

It was previously found that the colour–colour plots generated using MOVIS data included clusters that can be associated with different taxonomic classes (Popescu et al. 2016). In particular, the (*Y*–*J*) versus (*J*–*Ks*) colour–colour plot appears to be very efficient in the identification of V-type candidates. The first spectral analyses of V-type candidates from the MOVIS catalogue (Licandro et al. 2017; Medeiros et al. 2019) have shown high success rates (87 and 83%, respectively) for confirmation of the candidate V-types. Approximately half of the proposed V-type candidates selected by Licandro et al. (2017) are not members of the Vesta dynamical family.

In the scope of this work, we acquired visible spectra of 14 asteroids from the list of V-type candidates, in particular, those that are not members of the Vesta collisional family. This sample includes 11 asteroids with no previous spectral data and three interesting outer main-belt asteroids with previously analysed NIR spectra. The asteroids studied in this work originate from various dynamical groups, categorised according to the definitions from Nesvorný et al. (2008) and Ieva et al. (2016). The majority of our sample is found in the inner main belt: six low-*i* asteroids ($i < 6^\circ$, $2.3 < a < 2.5$ au), one fugitive ($a < 2.3$ au and comparable *e* and *i* with the Vesta family), and four inner-other asteroids (IOs – asteroids from the inner main belt, which are not members of the Vesta family, low-*i* or fugitives). The studied sample also includes three outer main-belt bodies categorised as middle and outer main-belt asteroids (MOVs, $a > 2.5$ au). The orbital and physical parameters of the analysed asteroids are given in Table 1.

2.2. Data acquisition and reduction

The visible spectra presented here were mostly obtained using the Intermediate Dispersion Spectrograph (IDS) instrument

Table 1. Orbital elements and physical properties of the asteroids analysed in this work.

Asteroid	<i>a</i> (au)	<i>e</i>	<i>i</i> ($^\circ$)	Group $\pm$	<i>p_V</i>
2275	2.296	0.170	6.393	Fugitive	0.177 ± 0.035
2452	3.164	0.113	11.769	MOV	0.380 ± 0.063
3188	2.290	0.134	4.694	Low- <i>i</i>	0.425 ± 0.071
3331	2.419	0.087	3.566	Low- <i>i</i>	–
4693	2.279	0.083	4.866	Low- <i>i</i>	0.366 ± 0.070
5524	2.366	0.027	7.488	IOs	0.034 ± 0.102
7223	2.351	0.175	1.557	Low- <i>i</i>	0.391 ± 0.073
7302	2.807	0.181	9.959	MOV	0.298 ± 0.026
9007	2.474	0.153	5.868	Low- <i>i</i>	0.329 ± 0.043
14390	3.244	0.103	6.560	MOV	0.220 ± 0.057
19983	2.390	0.058	6.379	IOs	0.335 ± 0.044
29733	2.447	0.087	5.542	Low- <i>i</i>	0.214 ± 0.119
51742	2.340	0.143	8.078	IOs	–
90223	2.459	0.114	7.149	IOs	–

Notes. Columns are: semi-major axis *a*, eccentricity (*e*), inclination (*i*), dynamical group (following Nesvorný et al. 2015), and – when available – visible albedo (*p_V*) retrieved from the WISE/NEOWISE database (Masiero et al. 2011, 2012, 2014; Nugent et al. 2016). The orbital and physical parameters were extracted from the JPL Small-Body Database¹.

mounted on the 2.54 m *Isaac Newton* Telescope (INT), as part of standard programs C67/2018B and C94/2019A as well as the Alhambra Faint Object Spectrograph and Camera (ALFOSC) at the 2.5 m Nordic Optical Telescope (NOT), under the service program SST2016-346, both located at the El Roque de Los Muchachos Observatory (ORM) in La Palma (Canary Islands, Spain). A summary of the observational circumstances for each studied asteroid is given in Table 2.

For the acquisition of the visible spectra with the IDS spectrograph, we used the RED+2 CCD detector with the low-resolution R150V grating, which covers the 0.40–0.95 μm spectral interval. A 1.2'' slit was employed, oriented along the parallactic angle to correct for differential refraction effects. The tracking was set at the asteroid's proper motion, extracted from the corresponding ephemeris. Observations with the ALFOSC spectrograph were performed using the CCD#14, a 2048 × 2064 back illuminated detector providing a 0.214''/pixel scale, and the Grism#4 (0.32–0.91 μm). A second-order blocking filter (GG420) was used to avoid contamination at red wavelengths. The final set-up covered a wavelength range from 0.42 to 0.91 μm . A 2.5'' slit was used, oriented in the parallactic angle, and the tracking was also set at the asteroid's proper motion, as in the case of observations with the IDS.

A total of two to four spectra were obtained for each target and subsequently averaged to increase the quality of the final spectra. Several solar analogue stars were observed each night at airmass similar to those of the targets. Data reduction followed the standard procedures and was done using IRAF tasks (Tody 1986). The spectra of both the target asteroids and solar analogues were bias- and flat-field-corrected, extracted from the sky background and collapsed to one dimension. Then, the spectra were wavelength-calibrated using the CuAr+CuNe lamps (IDS) or ThAr+Ne+He lamps (ALFOSC). Finally, each asteroid spectrum was divided by all available solar analogue spectra and the results were normalised to unity at 0.55 μm and averaged to

¹ <https://ssd.jpl.nasa.gov/sbdb.cgi>

Table 2. Observational circumstances of the asteroids analysed in this work.

Asteroid	Telescope	Date and UT start	T_{exp} (s)	Airmass	m_V	α (°)	r_h (au)	Solar analogues
2275	INT	20/11/18 04:35	3x300	1.346	15.0	6.5	2.120	SA93-101, Hyades64, SA98-978
2452	NOT	08/12/18 04:50	3x300	1.436	16.3	4.8	3.306	SA98-978, SA102-1081
3188	INT	23/04/19 23:21	3x1200	1.904	16.8	5.0	2.504	SA107-998, SA110-361
3331	NOT	08/12/18 05:28	3x600	1.112	17.7	26.2	2.222	SA98-978, SA102-1081
4693	INT	23/04/19 21:18	3x1200	1.141	17.2	20.2	2.258	SA107-998, SA110-361
5524	NOT	08/12/18 06:13	3x600	1.254	17.6	24.7	2.357	SA98-978, SA102-1081
7223	INT	27/08/18 05:02	2x900	1.023	17.0	27.9	1.957	SA112-1333, SA115-271, HD 5495 HD 9761, HD 10861, HD 167221, HD 204433
7302	INT	27/08/19 00:56	3x600	1.483	15.7	3.4	2.567	SA112-1333, SA115-271
9007	INT	27/08/18 02:40	3x900	1.108	17.2	21.8	2.117	SA112-1333, SA115-271, HD 5495 HD 9761, HD 10861, HD 167221, HD 204433
14390	INT	27/08/19 00:17	3x600	1.524	16.4	4.4	2.915	SA112-1333, SA115-271
19983	INT	20/11/18 05:37	4x500	1.195	16.5	13.5	2.251	SA93-101, Hyades64, SA98-978
29733	INT	23/05/19 01:54	3x1200	1.510	16.4	2.4	2.265	SA107-998, SA112-1333, HD 89165
51742	INT	23/05/19 01:03	3x1200	1.305	17.2	4.9	2.030	SA107-998, SA112-1333, HD 89165
90223	INT	23/05/19 03:08	2x1800	1.468	17.6	6.1	2.182	SA107-998, SA112-1333, HD 89165

Notes. Columns are: telescope used for the observations, date and starting time of the first exposure (UT start), total exposure time (T_{exp}), airmass, apparent magnitude (m_V), phase angle (α), and heliocentric distance at the time of the observation (r_h). The last column includes information on the solar analogue stars used to obtain the asteroid reflectance spectra.

obtain a final reflectance spectrum. The resulting visible spectra for the 14 V-type candidates are displayed in Fig. 1.

3. Visible spectra analysis

3.1. Spectral parameters and taxonomy

To analyse the visible spectra of our target asteroids, we computed three parameters which characterise the position and shape of the 0.9 μm absorption band: the reflectance gradient in the 0.50–0.75 μm range (Slope A), the reflectance gradient in the 0.80–0.92 μm range (Slope B), and the ratio between the reflectance at 0.75 and 0.90 μm (apparent depth). These parameters were defined in Ieva et al. (2016) and computed for a sample of V-types in the Vesta collisional family (also called vestoids), V-type near-Earth asteroids (NEAs), and another four dynamical groups that were described in the previous section: fugitives, low-i, IOs, and MOVs. Their statistical results provided characteristic values of these parameter for the different populations.

The errors of Slope A and Slope B were obtained as a difference between the values obtained in the predefined wavelength ranges (0.50–0.75 μm and 0.80–0.92 μm respectively) and restricted wavelength ranges of 0.55–0.72 μm for Slope A and 0.80–0.90 μm for Slope B, thus accounting both for the spectra noisiness and subtle wavelength calibration errors. The error of the apparent depth was obtained as a standard deviation of five independent manual measurements.

We also calculated the Slope A parameter corrected for the phase angle effect (Slope A corr), following the empirical relation by Reddy et al. (2012):

$$S_c = S - \gamma\alpha, \quad \alpha \lesssim 25^\circ, \quad (1)$$

where S is the measured spectral slope, α is the phase angle, and γ is the reddening coefficient $\gamma = 0.0198\% \mu\text{m}^{-1} \text{deg}^{-1}$.

The phase angle effect can cause some objects to appear redder as the phase angle increases, affecting the observed reflectance slopes. All of the studied asteroids in this work were

observed at phase angles $\alpha \lesssim 30^\circ$, compatible with the Reddy et al. (2012) relation. We note that this relation was inferred for Vesta and we assume that V-types present a similar mineralogy. As we cannot discard that some of the target asteroids might present differences in composition when compared to asteroid 4 Vesta, both values of Slope A and Slope A corr were considered for the analysis. The determined spectral parameters for each asteroid are given in Table 3.

A taxonomical classification of the presented asteroids was performed independently based on the measured visible spectra parameters and using the on-line tool M4AST² developed for asteroid spectra modelling (Popescu et al. 2012). The M4AST tool fits a polynomial curve to the observed asteroid spectrum and finds the closest taxonomical type based on the smallest mean squared error from the average representative spectra from the Bus-DeMeo taxonomy (DeMeo et al. 2009). For those asteroids having NIR spectra (2452, 7302, and 14 390), we used both the M4AST tool and the on-line classification tool available at the web page of the Planetary Spectroscopy Group of the MIT³. The classification procedures are slightly different: while the M4AST uses a curve-matching approach, the MIT tool applies a spline fit to smooth the spectrum, samples the 0.45–2.45 μm range into 41 data points, computes and removes the continuum (or slope), and, finally, applies a principal component analysis (PCA). The results are shown in the last column of Table 3.

While near-infrared spectra are necessary for a mineralogical characterisation of asteroid surfaces (Cloutis et al. 1986; Gaffey et al. 1993, 2002), some information can be also inferred from visible spectra parameters. The effects of meteoroid and micrometeoroid impacts, irradiation and sputtering of solar wind particles and cosmic rays, altogether referred to as space weathering, can cause an alteration of the surface mineralogy of asteroids. Basaltic asteroids generally respond to these effects by exhibiting a redder spectral slope, lower albedo, and shallower spectral bands. Therefore, the detection of a steeper Slope A

² <http://spectre.imcce.fr/m4ast/index.php>

³ <http://smass.mit.edu/>

Fig. 1. Visible spectra of studied V-type candidate asteroids (grey points). The red and green lines represent reflectance gradient fits used for the computation of the Slope A and Slope B parameters. We also plot the average spectrum corresponding to the V-type taxonomic class and its standard deviation (in blue) as defined by DeMeo et al. (2009). In some cases, average R-type (in orange) or S-type (in brown) spectrum from DeMeo et al. (2009) are also plotted for comparison.

can indicate surfaces affected by space weathering (Fulvio et al. 2012, 2016), while greater apparent depth could reflect a larger grain size, the presence of unweathered pyroxene, or a different mineralogy (Cloutis et al. 2013; Fulvio et al. 2017).

3.2. Results and discussion

Figure 2 displays the measured slopes and apparent depths of the studied asteroids and their comparison to V-type asteroids as analysed by Ieva et al. (2016). The box regions displayed in Fig. 3 delimit the spectral parameters for V-type control sample from Ieva et al. (2016): $7.26\%/0.1\mu\text{m} < \text{Slope A} < 18.51\%/0.1\mu\text{m}$, $-18.41\%/0.1\mu\text{m} < \text{Slope B} < -35.98\%/0.1\mu\text{m}$, $7.45\%/0.1\mu\text{m} < \text{Slope A corr} < 13.25\%/0.1\mu\text{m}$, and the apparent depth between 1.15 and 1.72.

For comparison, Fig. 2 also shows the centers of regions characteristic for different taxonomic classes based on the measured Slope A, Slope B, and apparent depths of the mean spectra from the Bus-DeMeo catalogue (DeMeo et al. 2009). The diameter of these regions was estimated from the Slope A error

based on the one-sigma of the mean S-type spectrum and serves only to improve the visual interpretation. The region sizes are not variable because not all of the mean spectra in the Bus-DeMeo catalogue have defined characteristic standard deviations.

It was found that the majority of our targets have visible spectra parameters consistent with expected V-type properties. Four asteroids in our sample are dynamically classified as inner-other (IOs): (5524) Lecacheux, (19983) 1990 DW, (51742) 2001 KE₅₅, and (90223) 2003 BD₁₃. The orbital elements of these bodies are close to the Vesta family (Table 1). While all four asteroids show spectral properties associated with the V-type taxonomic class, their visible parameters are quite dispersed, particularly in Slope A and the apparent depths (Fig. 2).

The spectrum of asteroid (5524) Lecacheux shows slightly higher reflectance in the 0.7–0.9 μm region than expected for a V-type asteroid. The overall shape of the spectrum and the visible parameters are nevertheless fully consistent with V-type taxonomy. Asteroid (5224) presents a low albedo value for a V-type asteroid. However, the albedo determination was based on just four observations using only one of the four filters of

Fig. 1. continued.

Table 3. Visible spectra parameters of the analysed asteroids.

Asteroid	Slope A (%/0.1 μm)	Slope A corr (%/0.1 μm)	Slope B (%/0.1 μm)	App. depth	Tax.	M4AST	SMASS
2275	15.28 ± 0.70	13.99 ± 0.70	-29.59 ± 1.57	1.468 ± 0.026	V	R or Sa	
2452	14.66 ± 0.46	13.71 ± 0.46	-26.50 ± 3.64	1.532 ± 0.047	V	V	V
3188	13.40 ± 1.21	12.41 ± 1.21	-25.02 ± 9.44	1.743 ± 0.123	V	V	
3331	15.36 ± 0.67	10.17 ± 0.67	-35.19 ± 4.57	1.841 ± 0.122	V	V	
4693	14.84 ± 0.37	10.84 ± 0.37	-31.21 ± 6.45	1.597 ± 0.160	V	V	
5524	17.73 ± 0.86	12.84 ± 0.86	-33.24 ± 5.07	1.609 ± 0.036	V	R or Sa	
7223	20.69 ± 0.43	15.17 ± 0.43	-34.65 ± 5.57	1.664 ± 0.128	V	R or V	
7302	11.37 ± 0.24	10.70 ± 0.24	-12.78 ± 1.78	1.157 ± 0.030	S	S	S
9007	12.88 ± 1.15	8.56 ± 1.15	-33.64 ± 4.75	1.558 ± 0.155	V	V	
14390	6.31 ± 1.40	5.44 ± 1.40	-24.78 ± 1.97	1.685 ± 0.043	?	V or O	V
19983	19.21 ± 2.87	16.54 ± 2.87	-27.20 ± 1.39	1.426 ± 0.105	V	R or Sa	
29733	10.24 ± 1.07	9.76 ± 1.07	-24.80 ± 3.27	1.761 ± 0.093	V	V	
51742	10.34 ± 0.52	9.37 ± 0.52	-24.01 ± 6.07	1.710 ± 0.066	V	V	
90223	7.94 ± 0.72	6.73 ± 0.72	-25.73 ± 4.89	1.985 ± 0.101	V	V	

Notes. Columns are: Slope A, Slope B, Slope A corr – which is Slope A corrected for the phase angle effect, and the apparent depth. The closest taxonomic type is given based on the measured parameters (Tax.), using the M4AST tool (Popescu et al. 2012) and for asteroids with NIR spectra also using the SMASS tool.

WISE (W1). According to Masiero et al. (2012), in such cases, the derived albedo may be underestimated.

Asteroid (19983) 1990 DW is found with very high Slope A, which could indicate a weathered surface for the asteroid. Slope A is determined with high uncertainty for this case, due to deviating results when applying different solar analogue stars for the spectrum reduction. Nevertheless, all of the spectral parameters are within an error bar that is consistent with a V-type

body, as confirmed by the taxonomic classification using the M4AST tool (Table 3). The visible spectra parameters of asteroid (51742) 2001 KE₅₅ are comparable to the control sample region (Fig. 2) of Vestoids identified by Ieva et al. (2016). A surprisingly large apparent depth (1.985 ± 0.101) found in the spectrum of the asteroid (90223) 2003 BD₁₃ could indicate presence of fresh unweathered pyroxene. This is also supported by the low slope in the 0.50–0.75 μm region (Slope A corr = 6.73 ± 0.72).

Fig. 2. Slope A versus Slope B (a) and apparent depth (b) of the analysed V-type candidate asteroids (triangles). The same parameters are represented versus Slope A corr in (c) and (d), respectively. The studied samples are plotted along with the results from the statistical analysis of V-type asteroids by [Ieva et al. \(2016\)](#) (squares). The box region delimits parameters of a V-type control sample from [Ieva et al. \(2016\)](#). Colour coding differentiates between the dynamical groups of asteroids. Circles in the *top panels* represent average positions of other taxonomic types based on the mean spectra from the Bus-DeMeo catalogue ([DeMeo et al. 2009](#)), with diameter of the circle estimated from the Slope A error based on the one-sigma of the mean S-type spectrum.

The six low-*i* asteroids in our sample, (3188) Jekabsons, (3331) Kvistaberg, (4693) Drummond, (7223) Dolgorukij, (9007) James Bond, and (29733) 1999 BA4, were all identified as V-types. The majority of them, based on their visible spectra parameters (Fig. 2), fall within the V-type control sample region. For three cases, (3188), (3331) and (29733), we obtained slightly increased apparent depths of their spectra, potentially indicating unweathered surfaces. On the other hand, asteroid (7223) Dolgorukij was found with steep Slope A = 20.69 ± 0.43 , suggesting a more weathered surface.

One asteroid in our sample has been classified as a fugitive, that is, a dynamical group of basaltic asteroids defined by [Nesvorný et al. \(2008\)](#) as having $a < 2.3$ au and e and i comparable to the Vesta family. The asteroid (2275) Cuitlahuac with $a = 2.296$ au is near the limit of this definition and shows spectral properties similar to most Vesta family asteroids (Fig. 2). The shape of the spectrum differs slightly from the average V-type spectrum (Fig. 1), with a higher reflectance observed in the

0.75–0.90 μm region. A similar effect can be seen in the spectrum of asteroid (19983) obtained on the same observing night and could be caused by an unsuitable solar analogue star used for the reduction, as deviating results were obtained for different solar analogue stars (an average of the spectra was used for the analysis). Nevertheless, the determined visible spectra parameters are fully consistent with V-type taxonomy.

Overall, our results suggest that in the visible range, low-*i*, inner-other, and fugitive V-type asteroids do not show recognisable differences when compared to Vesta family bodies. This is in agreement with the results of [Ieva et al. \(2016\)](#), who also did not find significant deviations in NIR spectra between the inner main belt dynamical groups. [Mansour et al. \(2020\)](#) came to a similar conclusion by analysing the distribution of NIR colours of the V-type candidates. It is, therefore, plausible that these bodies originate from (4) Vesta. For fugitives, the dynamical pathways were previously described by [Nesvorný et al. \(2008\)](#). Their simulations, however, did not predict low-*i*

Fig. 3. Visible and near-infrared spectra of the three middle and outer main belt asteroids (MOVs) studied in this work (grey points). The blue and brown curves represent average spectra corresponding to the V-type and S-type taxonomic classes, respectively, and their standard deviation as defined by DeMeo et al. (2009). The green curves are fourth-order polynomial fits to the maxima and the minima used to compute Slope I and II (straight black lines).

vestoids, meaning that if they originated in Vesta, they were liberated from its surface before or during the Late Heavy Bombardment epoch ~ 3.8 Gy ago (Nesvorný et al. 2008).

4. Visible + NIR spectra analysis of outer main belt asteroids

One of the main interests of this work is the characterisation of V-type asteroids from the middle and outer main belt (MOVs) with no dynamical link to the Vesta family. Therefore, we focus in more detail on asteroids (2452) Lyot, (7302) 1993 CQ, and (14390) 1990 QP₁₀, which are all identified as outer main belt asteroids with $a > 2.8$ au. These asteroids have been identified as atypical cases based on NIR spectra analyses by other authors. Here, we attempt to infer new information about the nature of these bodies based on the acquired visible spectra. In addition to the visible spectra parameters discussed in the previous section, we combined the visible spectra with NIR spectra obtained from the literature (Fig. 3) to provide a further compositional analysis based on the determined band centre positions.

4.1. Parameters

For the analysis of the composite visible and NIR spectra, we focused on determining the parameters of absorption features near 0.9 and 1.9 μm caused by the presence of pyroxene minerals,

following the methodology first outlined by Cloutis et al. (1986) (also see Gaffey et al. 2002 and references therein). These bands (hereafter Band I–BI and Band II–BII) result from the Fe^{2+} electronic transitions in the M1 and M2 crystallographic sites of pyroxene structure (Burns 1993) and their positions are sensitive to both mineral abundance and chemistry (Cloutis et al. 1986). The band centre positions of BI and BII can then be used to determine the molar contents of calcium (Wollastonite) and iron (Ferrosilite), following the equations derived by Burbine et al. (2009).

First, we computed Slopes I and II defined as straight lines tangent to the relative maxima (black lines in Fig. 3) determined from a fourth degree polynomial fit to the spectrum between 0.7 and 1.4–1.7 μm and between 1.4–1.7 and 2.4–2.5 μm , respectively (green curves in Fig. 3). The last available data point, typically positioned between 2.4 and 2.5 μm , was used to delimit Band II and compute the Slope II. The slopes were then used to remove the continuum of the spectrum and the wavelength positions of the BI and BII minima were determined as centres of Gaussian fits to the bands using the Fityk software⁴ (Wojdycr 2010). The errors of resulting parameters (Table 4) were determined as standard deviations of individual measurements obtained by adjusting the wavelength range and polynomial degree used to fit the relative maxima.

Finally, we applied a temperature correction to the determined band positions following the procedure from Burbine et al. (2009). This allows for a direct comparison to properties of HED meteorites measured in laboratory at room temperature. The mean surface temperature of an asteroid at the time of the observation was derived from the energy conservation equation:

$$T = \left[\frac{(1 - A)L_0}{16\eta\epsilon\sigma\pi r_h^2} \right]^{1/4}, \quad (2)$$

where A is the bolometric Bond albedo (with mean value of $A = 0.15$ for V-types from Hicks et al. 2014 and mean value of $A = 0.09$ for S-types, following the phase integral values from Shevchenko et al. 2019), L_0 is the solar luminosity (3.827×10^{26} W), η is the thermal beaming parameter (assumed to be unity), ϵ is the infrared emissivity (assumed to be 0.9), σ is the Stefan-Boltzmann constant ($5.67 \times 10^{-8} \text{ J s}^{-1} \text{ m}^{-2} \text{ K}^{-4}$), and r_h is the heliocentric distance of the asteroid at the time of the observation. Then, following Reddy et al. (2012), the band centre positions for howardites and eucrites need to be corrected using:

$$\Delta BI(\mu\text{m}) = 0.01656 - 0.0000552 * T(\text{K}), \quad (3)$$

$$\Delta BII(\mu\text{m}) = 0.05067 - 0.00017 * T(\text{K}), \quad (4)$$

while for diogenites, the correction is given as

$$\Delta BI(\mu\text{m}) = 0.0000000017 * T^3(\text{K}) - 0.0000012602 * T^2(\text{K}) + 0.0002664351 * T(\text{K}) - 0.0124 \quad (5)$$

$$\Delta BII(\mu\text{m}) = 0.038544 - 0.000128 * T(\text{K}). \quad (6)$$

As in other works (e.g. Moskovitz et al. 2010), we found that the temperature correction for Band I position is negligible. The computed temperatures and corrections for Band II centre position, along with the resulting band parameters for studied asteroids are given in Table 4. Since we found that the taxonomy of asteroid (7302) is closer to an S-type (see discussion in Sect. 4.2), the correction equations valid for ordinary chondrites

⁴ <https://fityk.nieto.pl/>

Table 4. Visible and near-infrared spectral parameters based on Cloutis et al. (1986) and Gaffey et al. (1993).

Asteroid	T (K)	ΔBII (μm)	Band I centre (μm)	Band II centre (μm)	Slope I (%/ μm)	Slope II (%/ μm)
2452	147	0.029	0.915 ± 0.005	1.840 ± 0.015	0.91 ± 0.07	0.06 ± 0.01
7302	170	0.027	0.963 ± 0.011	1.893 ± 0.018	0.31 ± 0.05	-0.15 ± 0.04
14390	157	0.024	0.990 ± 0.012	1.977 ± 0.014	0.30 ± 0.09	0.09 ± 0.04

Notes. The information includes the derived asteroid temperature and the corresponding correction (ΔBII), the Band I and Band II centres (Band II centre includes temperature correction ΔBII) and the slopes.

(Sanchez et al. 2012) were used for the final values, presented in Table 4.

The methodology introduced by Cloutis et al. (1986) also allows for the determination of the olivine-orthopyroxene abundances based on the ratio of BII and BI areas (BAR). The computed BAR value is also used as an additional check for the basaltic nature of the asteroid, based on its location in the region defined by Gaffey et al. (1993) for a sample of basaltic achondrites in the BAR versus Band I centre space. Considering that the band area ratios are heavily dependent on whether the continuum is subtracted before the computation (Medeiros et al. 2019), we do not provide an analysis of BAR in this work.

4.2. Results and discussion

Asteroid (2452) Lyot is located in the outer main belt, close to another major confirmed V-type asteroid, namely, (1459) Magnya. Lyot was confirmed as a V-type by Medeiros et al. (2019), who found that it to be of a diogenite-like composition and significantly different from Vesta and Magnya. The visible spectra analysis confirmed properties consistent with basaltic composition (Table 3, Fig. 2). Three out of four middle and outer main belt asteroids with visible spectra studied by Ieva et al. (2016) exhibited increased apparent depths, which could suggest presence of unweathered pyroxene, large grain sizes, or different mineralogies. This is not, however, the case with Lyot, which exhibits an apparent depth of 1.532 ± 0.047 , close to the average V-type values. Furthermore, we combined our visible spectrum with NIR spectrum from Medeiros et al. (2019) and computed band centre positions that are consistent with the results obtained by these authors (Table 4). The obtained Band II position is shifted slightly ($1.840 \mu\text{m}$ compared to $1.873 \mu\text{m}$), just below the assumed limit for diogenites (Klima et al. 2007; Moskovitz et al. 2010). Still, the determined properties are within the error bar consistent with the diogenite-like composition (Fig. 4).

The NIR spectrum of asteroid (7302) 1993 CQ was previously studied as a V-type candidate by Jasmim et al. (2013) and Hardersen et al. (2018), both finding that the determined band parameters were not consistent with a basaltic composition. The computed slopes and apparent depth from its visible spectrum are indeed not characteristic for V-types but they are, rather, very close to the parameters of an S-type asteroid (Fig. 2). This is consistent with the results of Jasmim et al. (2013), who suggested an ordinary chondrite analogue for (7302). Furthermore, we combined our visible spectrum with the NIR spectrum from Hardersen et al. (2018) to provide a band parameter analysis. The resulting values (Table 4) are consistent with the results of Jasmim et al. (2013) and Hardersen et al. (2018), plotted well outside the region associated to V-type asteroids and HEDs in the Band I centre versus Band II centre space, thus ruling out the possibility of a basaltic composition. The overall spectrum fits well with the average S-type spectrum from DeMeo et al. (2009) (Fig. 3). It can be therefore concluded that (7302) is an S-type asteroid.

Fig. 4. Band II centre versus Band I centre for the objects studied in this work (grey). Regions outlined by the values computed for Howardites, Eucrites, and Diogenites (from Moskovitz et al. 2010) are plotted for comparison. The ellipse represents the region occupied by the surface of Vesta as measured by the Dawn mission (De Sanctis et al. 2013).

Overall, three NIR spectra have been obtained for asteroid (14390) 1990 QP₁₀, all pointing to the conclusion that (14390) is an object difficult to classify and, perhaps, representing a new taxonomic type (Migliorini et al. 2017; Leith et al. 2017; Hardersen et al. 2018). Here, we present the first visible spectrum of this body. The spectrum shows a Slope A flatter than expected for V-type asteroids (Table 3, Fig. 2), even more so when corrected for the phase angle effect (Slope A corr = $5.44 \pm 1.40\%/0.1 \mu\text{m}$). The very low value for Slope A could indicate fresh unweathered surface material. The other visible parameters (Slope B = $-24.78 \pm 1.97\%/0.1 \mu\text{m}$ and apparent depth of 1.685 ± 0.043) are compatible with V-type asteroids.

The visible spectrum of (14390) was then combined with the NIR spectrum from Leith et al. (2017), which was chosen as the least noisy from the published NIR spectra. The overall spectrum differs significantly in the NIR region from the expected V-type shape (Fig. 3). The spectrum exhibits a very broad band around $1 \mu\text{m}$ (Band I) and a shallow band near $2 \mu\text{m}$ (Band II), similarly to the results of Migliorini et al. (2017). The computed Band I centre is at $0.990 \pm 0.012 \mu\text{m}$, which is even higher than the one reported by Hardersen et al. (2018) ($0.966 \pm 0.004 \mu\text{m}$) or Leith et al. (2017) ($0.973 \pm 0.001 \mu\text{m}$). These values are inconsistent with the usual orthopyroxene mineralogy of V-type asteroids (de Sanctis et al. 2011; Ieva et al. 2016), suggesting a substantial abundance of olivine (Fig. 4). Furthermore, the spectrum has a very flat Slope I = 0.304 ± 0.088 , which is more similar to an S-type body than to other V-types (Medeiros et al. 2019). Overall, while the V-type is the closest found taxonomic class to fit the visible spectrum of (14390), the spectral differences in NIR are significant and suggest different mineralogy from all other known basaltic asteroids. Therefore, this asteroid remains as unclassified and could represent a new taxonomic class.

Following the work of Medeiros et al. (2019), our results confirm the high success rate of the MOVIS catalogue in identifying

V-type objects. Twelve out of fourteen asteroids studied in this work were confirmed as V-types, yielding an identification success rate of approximately 86%. As expected, the confirmation of the inner main-belt V-types is more likely due to the presence of the Vesta family and other nearby asteroids which escaped from the Vesta family. In the middle and outer main belt, where the amount of data is more limited, the fraction of false positives increases. Still, as is evident from the results of Medeiros et al. (2019), a large proportion of the MOVIS candidates from the middle and outer belt includes V-type objects.

5. Conclusions

Based on the analysis of their visible spectra, we confirm 11 new V-type asteroids that are not members of the Vesta collisional family. With respect to their orbital properties, four of these represent inner-other dynamical type: (5524) Lecacheux, (19983) 1990 DW, (51742) 2001 KE₅₅, and (90023) 2003 BD₁₃. Six V-types have low-*i* orbits: (3188) Jekabsons, (3331) Kvistaberg, (4693) Drummond, (7223) Dolgorukij, (9007) James Bond, and (29733) 1999 BA4; and one is classified as a fugitive from the Vesta family: (2275) Cuitlahuac. The determined visible spectra parameters suggest presence of fresh surface pyroxene in asteroids (3188), (3331), (29733), and (90223). On the other hand, the spectra of asteroids (7223) and (19983) indicate weathered surfaces.

In addition, we analysed three peculiar outer main belt V-type candidates based on their visible + NIR spectra. We confirm the previously reported diogenite-like composition of (2452) Lyot, which differs from the bulk composition of Vesta and Magnya. The spectrum of asteroid (7302) is inconsistent with a basaltic composition, as previously suggested from NIR analyses. We report that (7302) is likely an S-type body.

We provide the first visible spectrum of asteroid (14390) 1990 QP₁₀. Three previous NIR studies reported this asteroid as an unusual object of an unclassified taxonomic type. The visible spectrum has apparent depth and slope in the 0.80–0.92 μm region, similar to the properties of V-type asteroids, but it has flatter slope in the 0.50–0.75 μm region. The overall visible + NIR spectrum is significantly different from V-type taxonomic type, with a very broad band near 1 μm and a shallow band near 2 μm . The spectrum of asteroid (14390) suggests a different mineralogy from other known basaltic asteroids, potentially representing, therefore, a new taxonomic type.

Overall, our results demonstrate the efficiency of the MOVIS catalogue in identifying V-type objects, with a success rate of over 85%. The identification of V-types in the inner main-belt is more likely due to the presence of the Vesta family and other nearby asteroids which escaped from the family. The amount of data is more limited in the middle and outer main belt, leading to an increase in the fraction of false positives. Earlier results from Medeiros et al. (2019) have, however, shown that a large fraction of the MOVIS candidates from the middle and outer belt include V-type objects.

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