Spin rates of V-type asteroids

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ABSTRACT

Context. Basaltic V-type asteroids play a crucial role in studies of Solar System evolution and planetesimal formation. Comprehensive studies of their physical, dynamical, and statistical properties provide insight into these processes. Thanks to wide surveys, currently there are numerous known V-type and putative V-type asteroids, allowing a detailed statistical analysis.

Aims. Our main goal is to analyze I corrected for US language conventions in this paper the currently available large sample of V-type spin rates, to find signatures of the non-gravitational Yarkovsky–O’Keefe–Radzievskii–Paddack (YORP) effect among the different V-type populations, and to estimate the spin barrier and critical density for V-type asteroids. Our intention is to increase the pool of information about the intriguing V-types.

Methods. We collected rotational periods from the literature for spectrally confirmed V-types, putative V-types, and Vesta family members. Through spectroscopic observations we confirmed their taxonomic type and verified the high confirmation rates of the putative V-types. We combined the collected periods with periods estimated in this manuscript and produced rotational frequency distributions. We determined the spin barrier in the frequency–light curve amplitude space for V-type asteroids.

Results. We analyzed rotational periods of 536 asteroids in our sample. As expected, due to the small size of the objects analyzed, the frequency distributions for the Vesta family and the V-types outside the family are inconsistent with a Maxwellian shape. The Vesta family shows an excess of slow-rotators. V-types outside the family show an excess of both slow and fast rotators. Interestingly, we found that the population of V-types outside the Vesta family shows a significant excess of fast rotators compared to the Vesta family. The estimated critical density for V-type asteroids exceeds $\rho_c = 2.0 \text{ g cm}^{-3}$, which surpasses the previous estimates.

Conclusions. We demonstrated that V-type asteroids have been influenced by the thermal radiation YORP effect and that their critical spin rate is higher than for C-type asteroids. The population of V-types outside the Vesta family shows a significant excess of fast rotators compared to the Vesta family. We hypothesize that the objects that evolved from the Vesta family through the Yarkovsky drift are also more susceptible to the YORP effect. Objects for which YORP has not yet had enough time to act and those that are more YORP resistant will be left in the family, which explains the relatively small proportion of fast rotators being left. The YORP timescale must thus be similar to the migration timescale for those objects.

Key words. minor planets, asteroids: general

1. Introduction

Basaltic V-type asteroids and their fragments, howardite-eucrite-diogenite (HED) meteorites, have been studied for about half a century. They provide important clues to the differentiation process, constrain the spatial mineralogical distribution and temperature gradient of the early Solar nebula, and even reveal some of the dynamical processes in the Solar System.

Asteroid (4) Vesta was the first object to be identified as basaltic (McCord et al. 1970; Consolmagno & Drake 1977).

A number of spectroscopically similar asteroids in the vicinity of (4) Vesta, some of which were not Vesta family members, were later identified (Binzel & Xu 1993; Florczak et al. 2002; Lazzaro et al. 2004; Alvarez-Candal et al. 2006; Burbine et al. 2001). Numerical studies showed that those outside the Vesta family borders might have escaped through a combination of the Yarkovsky effect and dynamical resonances (Carruba et al. 2005; Nesvorný et al. 2008). Furthermore, two large collisional events are believed to have produced Vestoids (Milani et al. 2014; Spoto et al. 2015); two large craters found on the surface of Vesta are thought to be evidence of this (Thomas et al. 1997; Schenk et al. 2012). The surface of these craters was mapped by the Dawn

[†] Deceased.

mission (Roatsch et al. 2012) and provided further mineralogical evidence of the Vesta–V-type asteroid–HED meteorite link (De Sanctis et al. 2013, 2012; Russell et al. 2012; McSween et al. 2013).

Some V-type asteroids are well separated from Vesta and are thus considered non-Vestoids (Lazzaro et al. 2000; Roig et al. 2008; Moskovitz et al. 2008a; Duffard & Roig 2009; Ieva et al. 2015, 2018; Migliorini et al. 2017). These asteroids show spectral properties distinct from Vestoids (Hardersen et al. 2004a; Hammergren et al. 2006; Leith et al. 2017; Ieva et al. 2015, 2018; Medeiros et al. 2019) and have a low probability ($\sim 1\%$) of having evolved from Vesta (Roig et al. 2008; Carruba et al. 2007; Michtchenko et al. 2002). Carruba et al. (2014) indicated two possible source regions for V-types in the middle main belt, and Huaman et al. (2014) three of these in the outer main belt.

There is some debate about the presence of non-Vestoids in the inner main belt (Bottke et al. 2006a; Nesvorný et al. 2008; Scott et al. 2009; Roig et al. 2008; Moskovitz et al. 2010; Wasson 2013). Particularly, the low inclination ($i \leq 6^\circ$) V-types in the inner main belt were not sufficiently reproduced in numerical simulations by Nesvorný et al. (2008) and may originate in either a distinct parent body or from an older impact on Vesta. Furthermore, some V-types in the inner main belt have rotational properties inconsistent with migration from Vesta (Oszkiewicz et al. 2015, 2017).

This complex population is spread over the entire main belt. The V-type population is predominantly composed of small objects (< 10 km in diameter), well within the range in which the Yarkovsky–O’Keefe–Radzievskii–Paddack (YORP) effect is expected to be significant. Distribution of rotational frequencies of the V-type asteroids has been so far poorly understood due to the limited number of objects studied (i.e., Hasegawa et al. 2014 examined the frequency distribution of 59 V-type asteroids). However, due to large surveys such as the SDSS and HST-VISTA, a large number of putative V-types can now be added to the spectrally known V-types and Vesta family members resulting in a large enough sample (> 500 objects) for a statistical YORP analysis.

The YORP effect (Bottke et al. 2006b) modifies the Maxwellian rotational-frequency distribution expected from a purely collisionally evolved population (Salo 1987). This effect spins up or down irregularly shaped asteroids (Rubincam 2000) creating an excess of slow and fast rotators, thereby diluting the rotation spin distributions from Maxwellian. Large asteroids (> 40 km in diameter) could retain primordial spins, whereas smaller objects are more affected by the YORP effect (Pravec et al. 2002). An excess of fast to slow rotators has been previously observed for the Flora, Hungaria, and Koronis families (Warner et al. 2009a; Kryszczyńska et al. 2012; Slivan et al. 2003, 2009) and generally for the population of small main belt (MBA) and Mars-crossing asteroids (Pravec et al. 2008). Direct detections of the YORP effect spinning up objects have been made for few asteroids so far (Lowry et al. 2007; Āurech et al. 2008; Kaasalainen & Āurech 2007; Taylor et al. 2007).

The YORP effect may also spin up objects over the spin barrier causing their disintegration and/or the formation of binary asteroids (Walsh et al. 2008). The spin barrier has been estimated at P about 2.2 h (or equivalently rotational frequency ω of around 10 d^{-1}) for the general population of small ($10 \text{ km} > D > 150 \text{ m}$) asteroids (Harris 1996). Rubble-pile asteroids with a lower bulk density are expected to have a lower spin rate limit (Pravec & Harris 2000), thus the overall spin rate of C-type asteroids should be lower than that of the V- and S-type objects. Chang et al. (2015) estimated the critical density for S- and V-type asteroids

independently as $\rho = 2.0 \text{ g cm}^{-3}$, and for C-type objects as $\rho = 1.5 \text{ g cm}^{-3}$. In that work it was also suggested that there is a need to confirm the results after supplementing the sample of objects. We are now dealing with a statistically larger sample because we supported the calculations with a significant number of new observations and putative V-types, described in the next section.

In Sect. 2, we describe the spectroscopic and photometric observations and the data reduction process. In Sect. 3, we taxonomically classify the observed asteroids and verify the high confirmation rate of putative V-types. New rotational periods are determined in Sect. 3. In Sect. 4, we perform statistical spin rate analysis for various V-type populations. The summary of our results is presented in Sect. 5.

2. Observations

2.1. Spectroscopic observations and data reduction

We obtained visible (VIS) spectra of 17 V-type and V-type candidate asteroids at three telescopes. The V-type candidates were selected out of putative V-types listed in the literature (Roig & Gil-Hutton 2006; Carvano et al. 2010; Hasselmann et al. 2012; Licandro et al. 2017; Moskovitz et al. 2008b). Most of the data were taken at the 2.5 m Nordic Optical Telescope (NOT), spectra of two asteroids were obtained at the 10 m South African Large Telescope (SALT) and the 4.3 m Lowell Discovery Telescope (LDT). The observing circumstances and optical elements used are summarized in Table A.1.

At the NOT we used the Alhambra Faint Object Spectrograph and Camera (ALFOSC) combined with grism NOT-11 or grism NOT-12 depending on the night. Both grisms are low resolution. Grism 11 covers wavelengths 3900–10 000 Å; however, fringes are noticeable starting from around 7500 Å. Grism 12 covers wavelengths 5100–11 000 Å, with fringes starting also around 7500 Å. It should be noted that grism 12 has deteriorated, and thus higher order Legendre polynomials had to be used to extract the spectra, and lamp identification was challenging. For this reason we repeated observations of some of the targeted asteroids with grism 11. For most objects we found that grism 12 is still usable; however, the reduction process was cumbersome and problematic, and the results questionable for some objects. Thus, we would recommend the decommissioning of grism 12. In Table A.1 we list the observed targets, telescope, and setup used. Slit widths are adjusted to seeing. We used non-sidereal tracking together with a five-point dither to obtain several spectra. The spectra were corrected for flat and bias. Wavelength calibration was done using He, Ne, and ThAr lamps. The collected spectra were averaged and divided by solar analog and normalized at 0.55 microns.

At the SALT we used the Robert Stobie Spectrograph (RSS) together with the low resolution grism PG0300 covering wavelengths 3700–9000 Å. Our reduction procedure followed that described in Oszkiewicz et al. (2014).

2.2. Photometric observations and data reduction

Photometric observations were conducted using several telescopes listed in Table 1. Most of the data were taken with a Cousins R_C filter, but some with Johnson V , wide-band VR, or a clear filter. The VR filter used at the Hall telescope at Lowell Observatory has a passband similar to Sloan r' . The half maximum wavelengths are close to 5200 and 7000 Å, compared to the Sloan r' limits of about 5600 and 6950 Å. Thus, it is only

Table 1. Telescopes and instruments used for the photometric observations.

Telescope	Observatory	Instrument	Aperture	IAU code	Bands	No. of nights
Perkins	Lowell Observatory	Prism	1.83 m	688	<i>R</i>	2
Hall	Lowell Observatory	Nasa42	1.07 m	688	<i>R</i> , <i>VR</i>	20
31 inch	Lowell Observatory	Nasa31	0.79 m	688	<i>R</i>	6
UH88	Mauna Kea-UH	Tektronix 2048 ² CCD	2.24 m	T12	<i>r'</i>	12
JKT	La Palma	Andor CCD	1.0 m	950	<i>R</i> , <i>V</i>	13
RBT	Winer Observatory	Andor iXon 888	0.7 m	648	<i>R</i> , <i>L</i>	6
Zeiss	Modra Observatory	Apogee Ap8p	0.6 m	118	<i>R</i>	144
OMT-800	Odessa-Mayaki	FLI 9000	0.8 m	583	<i>V</i>	5
AZT-3	Odessa-Mayaki	UAI CCD	0.48 m	583	<i>R</i>	5
Total						213

slightly wider on the blue side of the nominal r' passband. The L filter used at the RBT telescope at Winer Observatory is an interferometric luminosity filter with a transmission window from 3700 to 7000 Å. Altogether we obtained data on 213 nights, mostly at Modra Observatory and Lowell Observatory. We performed standard photometric reduction with bias and flat-field correction followed by ordinary aperture photometry. We used the commercial software Canopus (version 10.7.12.7) for data from the Lowell Observatory, Mauna Kea Observatories, and Odessa-Mayaki Observatory, making use of its built-in photometric catalog and *Gaia* DR2 catalog to obtain approximate R_C or Sloan r' nightly zero points. At Modra Observatory a clear filter was used, and for the data processing MaxIm DL and their own software. Linkages to nearly the same magnitude level (within 0.05 mag) were done using the Carlsberg Meridian Catalogue stars with the help of Astrometrica (method described in Dymock & Miles 2009). This resulted in magnitudes close to the Cousins R filter. We also used the Starlink package (version NAMAKA) for data from the Roque de los Muchachos Observatory, Kitt Peak Observatory, and Winer Observatory. We generally used three (in Starlink) to five (in Canopus) comparison stars in each field, usually of much higher signal-to-noise ratio than the target, and selected to have near-asteroidal colors if possible (i.e., roughly $0.5 < B - V < 0.95$ or $0.35 < g - r < 0.85$). For asteroids near their stationary points, we could use the same comparison star sets on multiple nights. The measuring apertures were generally 8–12 arcsec in diameter, depending on the image quality. The typical mean nightly root mean square scatter of the ensemble of comparison stars was 0.006–0.01 mag.

3. Results

3.1. Spectral classification

We report spectra of 17 asteroids, for 11 of which optical spectra were obtained for the first time. Out of these 7 asteroids had not been observed at either near-infrared (NIR) or visible and infrared (VIR) wavelengths previously, thus those constitute new classifications. Asteroids (1914) Hartbeespoortdam, (2704) Julian Loewe, (4434) Nikulin, (5037) Habing, 5525 (1991 TS4), and (7558) Yurlov were observed for comparison with the literature (Alvarez-Candal et al. 2006; Spahr et al. 1997; Burbine & Binzel 2002; Bus & Binzel 2002; Solontoi et al. 2012; Wisniewski 1991; Moskovitz et al. 2008b). In Fig. 1, we present all the obtained optical spectra, and in Fig. 2, the spectra

concatenated with available NIR spectra from the literature. The obtained spectra closely match those reported in the literature.

We classified the observed spectra using the M4AST online tool and the standard error method of Popescu et al. (2012). In Table 2 we report two closest classes for each spectrum, along with the distance to the class templates and reliability as defined by Popescu et al. (2012, 2011). Reliability is a function of wavelength range covered and number of discrete data points used in the classification. The mathematical formulation of this parameter can be found in Popescu et al. (2012, 2011). Most of our targets (with the exception of 3302 Schliemann and 9652 1996 AF2) are consistent with the V- or R-type templates (DeMeo et al. 2009). The computed distance between the data and the V- and R- templates is very similar. This is due to the fact that the two classes are very similar in VIS wavelengths and differ more in the NIR wavelengths. Since R-types are very rare we consider the 15 observed objects V-types. This results in an 88% rate of success for confirmation on V-types.

High confirmation rates were also found by other authors i.e., 90% in Moskovitz et al. (2008b) or 78% in Solontoi et al. (2012). This very high confirmation rate leads us to assume that most of the asteroids that have their SDSS colors consistent with the V-type template are indeed V-types, and thus may be used in further analysis.

In Table 3 we derived the reflectivity gradient in the 5000–7500 Å and 8000–9200 Å range (slope A and slope B, respectively) and 1.0 μ m band depth (as in Ieva et al. 2015) for the observed asteroids. As noted by Ieva et al. (2015) a steeper slope A could be indicative of weathered surfaces (Fulvio et al. 2012, 2016), while a deeper apparent depth could be indicative of bigger grain size or fresh unweathered pyroxene (Hiroi et al. 1995; Cloutis et al. 2013). The derived parameters are consistent with typical Vestoidal values. We do not list parameters for objects observed with grism 12 because the mechanical damage of the grism the wavelength calibration required fitting a high order polynomial and may be imprecise. Some spectra covered the 1.0 μ m band well, which allowed us to determine band minima (BI) by fitting a third-degree polynomial. The resulting values are listed in Table 3.

For asteroid 8645 we obtained both VIS and NIR spectra for the first time. For asteroids (5235) Jean-Loup and (5560) Amytis the obtained spectra are complementary to the NIR data in the literature. The minima of the 1.0 μ m band that we obtained are consistent, within the uncertainties, with those derived by Hardersen et al. (2014b) based on NIR spectra. We note that the variability of methods used for band characterization between

Fig. 1. Visible spectra obtained in this project. Spectral templates are denoted as follows: V (orange stars), R (green diamonds), Sr (red pentagons), Sv (blue triangles).

different authors does not allow a direct comparison of the spectral parameters. For example, [Moskovitz et al. \(2010\)](#) used polynomial fits and continuum removal for the 1.0 μm band, but not for the 2.0 μm band; [Leith et al. \(2017\)](#) used a modified Gaussian model ([Sunshine et al. 1990](#)); and [Birlan et al. \(2016\)](#) followed the method of [Cloutis et al. \(1986\)](#), which uses polynomial fitting in selected regions for finding band minima

and removing of double sloped linear continuum for the band centers.

3.2. Rotational periods outside the Vesta family asteroids

We determined new rotational periods for 18 V-type asteroids outside the dynamical Vesta family. We list them in Table 4 along

Fig. 1. continued.

Fig. 2. Spectra obtained in this project for asteroids having both VIS and NIR spectra (NIR data obtained by us or from the literature). The orange line with stars represents the V-type template from [DeMeo et al. \(2009\)](#).

with diameters, geometric albedos, and the observed light curve amplitudes. For asteroids with unknown albedo we list the average value for the Vesta family of $p_v = 0.361 \pm 0.111$ ([Masiero et al. 2013](#)). A similar value is given by [Thomas et al. \(2011\)](#) for main belt V-types. [Usui et al. \(2012\)](#) gives lower average value of $p_v = 0.297 \pm 0.131$, but this estimate is based on only four objects.

Composite light curves for these objects are shown in [Fig. A.1](#). The combined distribution of rotational properties of V-types in the inner main belt is derived in [Sect. 4](#). All composite light curves were obtained using Fourier analysis, as in [Kwiatkowski et al. \(2010\)](#). For most of the observed asteroids the rotation periods were computed based on data spanning long time intervals, resulting in a synodic period averaged over

Table 2. Taxonomic classification using the standard error method.

Ast. num.	Tax. type	Dist.	Reliab.	Obs. night
1914 Hartbeespoortdam	V-type	0.020	29.2%	2019-04-22
	R-type	0.046		
2704 Julian Loewe	V-type	0.020	24.3%	2018-04-03
	R-type	0.058		
2798 Vergilius	R-type	0.050	29.2%	2018-04-22
	V-type	0.057		
2823 Van der Laan	V-type	0.076	97.5%	2019-06-09
	Sv-type	0.161		
3302 Schliemann	Sv-type	0.074	29.2%	2019-06-09
	Sr-type	0.079		
3331 Kvitasberg	V-type	0.035	29.2%	2019-04-22
	R-type	0.060		
4434 Nikulin	V-type	0.075	95.1%	2018-04-03
	R-type	0.120		
5037 Habing	V-type	0.057	29.2%	16-09-2016
	R-type	0.075		
5235 Jean-Loup	V-type	0.036	100%	16-09-2016
	Sv-type	0.157		
5525 (1991 TS4)	R-type	0.041	26.8%	16-09-2016
	V-type	0.056		
5560 Amytis	V-type	0.076	100%	2018-09-16
	R-type	0.185		
5754 (1992 FR2)	V-type	0.04	100%	2018-04-22
	Sv-type	0.135		
6819 McGarvey	V-type	0.030	26.8%	2018-09-16
	R-type	0.084		
7558 Yurlov	R-type	0.048	24.3%	2018-04-03
	V-type	0.067		
8645 (1988 TN)	V-type	0.068	92.6%	2018-09-16
	Sv-type	0.189		
9652 (1996 AF2)	R-type	0.046	29.2%	2020-01-08
	Sr-type	0.047		
17057 (1999 GS4)	R-type	0.099	29.2%	2018-09-16
	V-type	0.109		

Notes. Columns are asteroid number, taxonomic type distance from the template, and reliability of the classification. For each spectrum we list the two best matches. When possible we supplemented the spectra with the NIR counterpart from the literature.

Table 3. Spectral parameters: Slope A, Slope B, and apparent depth, as in [Ieva et al. \(2015\)](#), and without phase correction, center of the $1.0 \mu\text{m}$ (BI) band.

Asteroid	Slope A (%/10 ³ Å)	Slope B (%/10 ³ Å)	Depth –	BI (μm)
1914	14.04	–27.49	1.53	0.93
2798	10.99	–25.87	1.45	0.92
2823	17.10	–30.50	1.45	0.92
3331	15.58	–27.88	1.61	0.92
5037	19.13	–23.57	1.45	0.94
5235	14.25	–29.01	1.68	0.94
5525	15.92	–28.58	1.42	0.96
5560	18.03	–25.71	1.53	0.93
5754	12.56	–25.85	1.46	0.93
6819	14.37	–28.82	1.73	0.94
9652	15.16	–24.55	1.30	0.93
17057	19.40	–28.40	1.59	0.94

that interval. Corresponding uncertainties are thus small and do not fully reflect the changes in synodic period. Therefore, we round the computed uncertainties to the first significant digit and provide the determined synodic periods to the same accuracy.

Asteroids (2247) Hiroshima, (2823) van der Laan, (5235) Jean-Loup, 7558 Yurlov, (8761) Crane, (9481) Menchu, and (9531) Jean-Luc are spectroscopically confirmed V-types ([Wisniewski 1991](#); [Moskovitz et al. 2008b, 2010](#); [Sanctis et al. 2011](#); [Solontoi et al. 2012](#); [Hicks et al. 2014](#); [Hardersen et al. 2014b, 2018](#)). For (3331) Kvistaberg and (6819) McGarvey, we confirmed their V-type classification. Objects (7798) 1996 CL, (22113) 2000 RH9, and (27192) Senegali are putative V-types ([Roig & Gil-Hutton 2006](#); [Carvano et al. 2010](#); [Hasselmann et al. 2012](#); [Licandro et al. 2017](#)). Asteroid (5037) Habing was indicated by [Carvano et al. \(2010\)](#) and [Hasselmann et al. \(2012\)](#) as a QV_p type. In our work and that of [Solontoi et al. \(2012\)](#), its spectrum shows a deep $0.9 \mu\text{m}$ absorption band, typical of V-types.

4. Statistical analysis of rotational periods of V-type and V-type candidate asteroids

We supplement the rotational periods estimated in Sect. 3 with those known from the literature for spectroscopically confirmed V-types (V), V-type candidates (V_c), and dynamical Vesta family members (assumed to be V-types) to perform statistical analysis. Since the V-type candidates have high confirmation rates, as shown in Sect. 3, we consider this to be a reasonable approach that does not skew our statistics substantially.

Our sample contains 536 asteroids (Tables A.2–A.7), including 428 Vesta family members ([Nesvorný 2015](#)), and 108 outside the Vesta family. In total, there are 155 spectroscopically confirmed V-types and 131 V-type candidates. The remaining objects are dynamical Vesta family members assumed to be V-types ([Moskovitz et al. 2008b](#) estimate that ~20% of the Vesta family are interlopers). We list them in Tables A.2–A.7 together with their synodic period, diameter, proper (or osculating for near-Earth asteroids, hereafter NEAs) orbital elements, and classification. Around 15% of NEAs are considered binary ([Pravec et al. 1999](#); [Pravec & Harris 2007](#); [Bottke & Melosh 1996](#)). A similar fraction is expected among small MBAs ($d < 10 \text{ km}$). Since most V-types are smaller than 10 km in diameter, we expect around 15% binaries in our sample. However only 12 objects (3703, 3782, 5474, 5481, 18527 (Vesta family) 809, 2486, 5037, 32008 (Vesta fugitives) 854, 4383 (inner other group) 164121 (near-Earth)) are confirmed binaries. Thus, our sample may contain a larger number of undiscovered binaries.

Asteroids of known spectral type other than V-type were excluded from our analysis (e.g., those in the Vesta family were assumed to be interlopers). Spectral candidates are taken from [Carvano et al. \(2010\)](#), [Hasselmann et al. \(2012\)](#), [Solontoi et al. \(2012\)](#), [Moskovitz et al. \(2008b\)](#), and [Licandro et al. \(2017\)](#).

We subdivide our sample into several dynamically important groups, similarly to [Ieva et al. \(2018\)](#):

- Vesta family: Vesta family members, as defined by [Nesvorný \(2015\)](#) using the hierarchical clustering method (having orbital elements within ranges $2.26 \text{ au} < a < 2.48 \text{ au}$, $0.03 < e < 0.16$, $5^\circ < i < 8.3^\circ$). This sample contains 27 spectrally confirmed, 89 candidate, and 312 assumed V-types.
- Vesta fugitives: asteroids that escaped the Vesta family borders and are no longer identifiable as Vesta family members using the traditional clustering methods. Following the definition of [Nesvorný et al. \(2008\)](#), a Vesta family fugitive is a

Table 4. Asteroid synodic periods and amplitudes found within this project.

Asteroid no. and name	Diameter (km)	Geometric albedo	Amplitude (this work) (mag)	Period (this work) (h)
(1914) Hartbeespoortdam	9.56 ± 0.19	0.21 ± 0.03	0.04	6.3406 ± 0.0002
(2247) Hiroshima	4.37 ± 0.10	0.47 ± 0.10	0.14	4.4972 ± 0.0002
(2442) Corbett	8.33 ± 0.38	0.26 ± 0.04	0.19	11.456 ± 0.001
(2486) Metsahovi	7.88 ± 0.06	0.27 ± 0.03	0.13	4.4499 ± 0.0002
(2823) van der Laan	5.36 ± 0.06	0.32 ± 0.05	0.07	2.6262 ± 0.0001
(3331) Kvistaberg	4.62 ± 0.93	<i>0.36 ± 0.11</i>	0.16	7.5888 ± 0.0001
(4188) Kitezh	6.59 ± 0.16	0.34 ± 0.04	0.23	2.5820 ± 0.0001
(5037) Habing ^(*)	5.68 ± 0.08	0.32 ± 0.07	0.29	2.8290 ± 0.0001
(5235) Jean-Loup	6.71 ± 0.11	0.36 ± 0.06	0.10	2.4524 ± 0.0001
(6819) McGarvey	4.68 ± 0.22	0.24 ± 0.06	0.31	2.7247 ± 0.0001
(7558) Yurlov	4.62 ± 0.93	<i>0.36 ± 0.11</i>	0.15	4.1157 ± 0.0001
(7798) 1996 CL	4.96 ± 0.73	0.29 ± 0.11	0.60	3.8724 ± 0.0001
(8645) 1988 TN	5.08 ± 0.33	0.30 ± 0.07	0.48	7.6250 ± 0.0001
(8761) Crane	3.84 ± 0.78	<i>0.36 ± 0.11</i>	0.23	2.6379 ± 0.0001
(9481) Menchu	4.67 ± 0.04	0.20 ± 0.05	0.15	3.0519 ± 0.0001
(9531) Jean-Luc	4.18 ± 0.23	0.28 ± 0.05	0.08	2.4999 ± 0.0001
(22113) 2000 RH9	3.05 ± 0.62	<i>0.36 ± 0.11</i>	0.23	6.7425 ± 0.0004
(27192) Senegali	3.35 ± 0.68	<i>0.36 ± 0.11</i>	0.09	5.5741 ± 0.0001

Notes. Albedos and diameters are from the astorb database (<https://asteroid.lowell.edu/astinfo/>). For asteroids with unknown albedo an average value of $p_v = 0.361 \pm 0.11$ (Masiero et al. 2013) was assumed and the diameter was computed based on the assumed albedo and absolute magnitude from JPL (<https://ssd.jpl.nasa.gov/sbdb.cgi>); these objects are highlighted in italics. ^(*)We reported (5037) Habing as a binary in CBET 4730 based on 2020 opposition data.

V-type asteroid with $a < 2.3$ au and a comparable e and i to the Vesta family. This sample contains 19 confirmed and 16 putative V-types.

- Low- i : Low inclination V-types with a comparable semi-major axis to the Vesta family and smaller inclinations ($i < 6^\circ$ and $2.3 \text{ au} < a < 2.5 \text{ au}$, as defined by Nesvorný et al. 2008). There are 15 confirmed and 12 putative V-types in this group.
- Inner Other (IO): the remaining V-type asteroids in the inner main belt were identified as IOs ($a < 2.5 \text{ au}$). There are 10 confirmed and 12 putative V-types.
- V-type NEAs: a V-type asteroid in the near-Earth region (with a perihelion $q < 1.3 \text{ au}$). This sample contains 20 confirmed and 1 putative V-type.
- Middle outer V-type (MOV): an asteroid located in the middle and outer main belt ($2.5 \text{ au} < a < 5.0 \text{ au}$). There is only one spectrally confirmed MOV.

This division reflects interesting regions that may show various YORP signatures.

4.1. Signatures of the YORP effect

In Fig. A.1, we present the frequency distributions for the different subgroups. It should be noted that there are known observational biases working against small-amplitude and long-period asteroids (Marciniak et al. 2015, 2018) that are challenging to take into account. However, longer periods contribute to the low frequency bins amplifying the conclusions on YORP affecting the distribution. Small-amplitude objects may contribute to all bins. Rotations of the primaries of the binary systems were added into the frequency distributions. They mostly contribute to the fast-rotating bins and to the area near the spin barrier limit in Fig. 4, thus helping to constrain it.

The rotational frequency distribution for the Vesta family varies from that of the general inner main belt population (Lupishko et al. 2019). A significantly smaller excess of slow rotators and almost no fast rotators are observed for the Vesta family. The number of slowest rotating asteroids ($\omega \sim 0\text{--}1 \text{ d}^{-1}$) in the general inner main belt population (Lupishko et al. 2019) is about the same as in the peak bin ($\omega \sim 4\text{--}5 \text{ d}^{-1}$, which coincides with the rotation of (4) Vesta), whereas for the Vesta family we observe around $\sim 50\%$ fewer asteroids among the slowest rotators than in the peak bin. Fast rotators from the last three bins constitute around 30% of the peak bin in the general population and around 20% of the peak bin in the Vesta family. However, we note that the size distribution varies between objects in this study (0.7–10 km) and that of Lupishko et al. (2019) (3–15 km), and therefore differences are expected.

Similarly the frequency distribution for V-types outside the Vesta family varies from that of the general inner main belt population (Lupishko et al. 2019). Slow rotators constitute around 50% of the peak bin and fast rotators around 50% of the peak bin. Therefore, there is a smaller excess of slow rotators among V-types outside the Vesta family than in the general inner main belt population and larger excess of fast rotators.

The population of V-types outside the Vesta family (and its sub-populations: fugitives and low- i) shows a surplus of slow and fast rotating objects compared to a Maxwellian distribution. The fraction of fast rotators is also larger than that in the Vesta family. However, the fugitives and low- i constitute a small sample, thus valid conclusions can only be made for the collective population of V-types outside the Vesta family.

Interestingly, fewer fast rotators are observed in the Vesta family than in the population outside the family. This is likely due to the YORP effect spinning up small irregular asteroids,

Fig. 3. Number vs. rotation frequency (in cycles per day) for different V-type populations. Rotation periods from LCDB (Warner et al. 2009b) and this work.

which are also more likely to migrate (via the Yarkovsky drift and resonances) outside the Vesta family, leaving more YORP-modification resistant objects (i.e., larger or more regularly shaped) in the core of the family. Farinella et al. (1998) showed that the Yarkovsky drift for basaltic objects is optimized for objects with diameters of ~ 10 km. The diameters of the V-types outside the Vesta family vary from less than 1 km to around 10 km, which is reasonably close in the range to the optimal diameter. We show the histograms for NEAs and IO in Fig. 3. Due to the low number of known periods in these populations no compelling conclusions can be made.

To verify the influence of adding candidates to the samples, we plotted the distributions exclusively for spectrally confirmed V-types. Due to the small number of spectrally confirmed V-types in the Vesta family we cannot judge the influence of the candidates on the final sample. For asteroids outside the Vesta family we still have a substantial excess of fast rotators and a small excess of slow rotators, thus the conclusions remain unchanged.

4.2. Spin barrier

In Fig. 4, we present the location of the spectroscopically confirmed and candidate V-type asteroids in the size–frequency space. The spectroscopically confirmed V-types offset to the left of the plot (toward smaller sizes) are NEAs. The visible lack of spectroscopically confirmed objects with intermediate sizes is likely due to their low apparent brightness, making them difficult targets for spectroscopy. Generally, the rotational properties of our sample resemble those of the general asteroid population. This means that most V-types and V-type candidates have rotation periods that are greater than about 2.2 h, with the majority being between 2.4 and 21 h.

We determined the spin barrier in frequency–light curve amplitude space. Light curve amplitudes for each asteroid (with quality code U-code ≥ 2) were taken from the online service by Warner et al. (2009b) and this work. The frequency plot is shown

Fig. 4. Size–frequency distribution for dynamical Vesta family, V-types, and V-type candidates asteroids (top) and the same for the diameter range between 0.5 and 10 km (bottom).

Fig. 5. Observed light curve amplitude vs. spin rate of V-type asteroids. The dashed curves are approximate upper limits of spin rates of bodies held together by self-gravitation only, with bulk densities plausible for asteroids.

in Fig. 5. The theoretical lines expected for various bulk densities according to [Pravec & Harris \(2000\)](#) are indicated. The critical period corresponds to the period of a body with an ideal balance of the acceleration of gravity at the surface with the centrifugal acceleration at the equator ([Pravec & Harris 2000](#)). The critical period depends on object elongation (and thus light curve amplitude) and density (both of which correlate with tensile strength). The derivation of the critical period can be found in [Pravec & Harris \(2000\)](#).

The critical bulk density, estimated as $P_{\text{critical}} = \sqrt{3\pi/G\rho} \approx 3.3/\sqrt{\rho}$, exceeds the 2.0 g cm^{-3} estimated by [Chang et al. \(2015\)](#); one object is located at around 2.52 g cm^{-3} . For comparison, the bulk density of the HED meteorites is around 3.17 g cm^{-3} ([McSween et al. 2011](#)).

5. Summary

We confirmed the taxonomic type of 17 objects (11 observed spectroscopically in the visible wavelengths for the first time) outside the Vesta family. We found that their spectral parameters are well within Vestoidal values.

We found synodic periods for 18 asteroids. We supplemented them with rotation periods from the literature and determined the distribution of rotational frequencies for V-types in the Vesta family and those outside the family. This sort of juxtaposition is presented for the first time for V-types in the literature.

The V-types outside the Vesta family show a significant surplus of fast rotators compared to the Vesta family. These might be objects evolved from the Vesta family that are more susceptible to both YORP and Yarkovsky effect. Thus, the YORP timescale must be comparable to the migration timescale for those objects.

We show for the first time that the spin barrier for the V-type asteroids exceeds the critical density of 2.0 g cm^{-3} .

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4.3 m Lowell Discovery Telescope, 0.7 m *Roman Baranowski* telescope at Winer Observatory, 0.6 m Zeiss telescope at Modra Observatory, 0.8 m Odessa Multifunctional Telescope and 0.48 m AZT-3 telescope at Odessa-Mayaki Observatory. Some of the observations reported in this paper were obtained with the Southern African Large Telescope (SALT). Polish participation in SALT is funded by grant No. MNiSW DIR/WK/2016/07.

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Appendix A: Additional tables and figures

Table A.1. Observing setup and circumstances for VIS spectra.

Asteroid	Telescope	Grism	Slit width (arcsec)	Observing night	Phase angle (deg)	Air mass	Solar Analog	Airm mass	Ref. VIS	Ref. NIR
1914 Hartbeespoortdam	NOT	11	1.3	2019-04-22	14.3	1.32	SA 110-361	1.34	(1)	(2)
2704 Julian Loewe	NOT	11	1.3	2019-06-09	6.7	1.60	HD 133011	1.47	(3)	
2798 Vergilius	NOT	11	1.3	2019-04-22	5.0	1.67	SA102-1081	1.66		
2823 Van der Laan	NOT	11	1.3	2019-06-09	6.2	1.59	HD 140990	1.60		(4)
3302 Schliemann	NOT	11	1.3	2019-06-09	26.1	1.49	HD 203311	1.50		
3331 Kvitaseberg	NOT	11	1.3	2019-04-22	17.3	1.06	HD 77730	1.08		
4434 Nikulin	NOT	12	1.3	2018-04-03	9.0	1.26	Land 107-998	1.24	(3)	(5)
5037 Habing	NOT	11	1.3	2018-09-16	14.7	1.41	HD 210078	1.36	(6)	
5235 Jean-Loup	NOT	11	1.3	2018-09-16	19.2	1.06	51 Peg	1.13		(7)
5525 (1991 TS4)	NOT	11	1.3	2018-09-16	25.4	1.35	Hyades 64	1.21	(6)	
5560 Amytis	NOT	11	1.3	2018-09-16	7.4	1.51	HIP 11915	1.41	(6)	(7)
5754 (1992 FR2)	SALT	PG0300	3.0	2017-11-27	17.5	1.22	HD 11532	1.2		(8)
6819 McGarvey	NOT	11	1.3	2018-09-16	17.9	1.58	51 Peg	1.34		
7558 Yurlov	NOT	12	1.3	2018-04-03	27.2	1.32	Land 102-1081	1.18	(9)	
8645 (1988 TN)	LDT	150 1/mm	3	2020-01-08	7.1	1.01	SA 102-1081	1.43		
	LDT	PRISM	1.34	2020-01-08	7.1	1.05	SA 102-1081	1.4		
9652 (1996 AF2)	NOT	11	1.3	2019-04-22	9.3	1.43	HD 117860	1.44		
17057 (1999 GS4)	NOT	11	1.3	2018-09-16	15.5	1.32	HD 209847	1.36		

Notes. Columns are: asteroid designation, telescope, grisms, slit width, observing night, asteroid phase angle, asteroid air mass at the start of exposures, solar analogs used, air masses of the solar analogs at the start of exposures. References are given for the first publication of each asteroid spectrum.

References. (1) Alvarez-Candal et al. (2006), (2) Fulvio et al. (2016), (3) Bus & Binzel (2002), (4) Moskovitz et al. (2010), (5) Duffard et al. (2004), (6) Solontoi et al. (2012), (7) Hardersen et al. (2014b), (8) Hardersen et al. (2018), (9) Moskovitz et al. (2008b).

Table A.2. Spectral V-types and V-type candidates (V_c) in the Vesta family population, their physical and orbital parameters.

Asteroid No.	Synodic period (LCDB) (h)	U-code (LCDB)	Diameter (km)	Class, references	a (au)	e	$\sin(i)$
(4) Vesta	5.34212766	3	525.4	$V^{(1,14,15,16,17,18,19)}$	2.362	0.099	0.1113
1929	2.9887	3	7.8	$V^{(1,10,17,18,19)}$	2.363	0.114	0.1232
1933	3.671	3	4.5	$V^{(1,9,10)}$	2.353	0.094	0.1188
1959	7.726	3	6.9	$V_c^{(12,21)}$	2.316	0.095	0.1193
1979	7.5209	3	4.8	$V^{(5,12,21)}, QV^{(2,13)}$	2.374	0.102	0.1136
2011	8.209	3	5.2	$V^{(2,6,8,9,12,13,21)}, J^{(1,10)}$	2.387	0.111	0.1110
2045	82.4	2	9.7	$V^{(1,17,18,19)}$	2.380	0.090	0.1164
2468	5.122	3	6.2	$V^{(1,17)}$	2.327	0.115	0.1122
2508	17.7	2–	4.9	$V^{(1,9,11,12,17,21)}$	2.368	0.094	0.1124
2511	4.144	3	7.9	$V^{(1,17,19)}$	2.299	0.095	0.1271
2590	15.59	3	7.9	$V^{(1,3,10)}$	2.343	0.097	0.1177
2974	856.0	2+	5.9	–	2.312	0.094	0.1236
3155	8.31	3	7.0	$V^{(1,17,18,19)}, J^{(10,22)}$	2.343	0.098	0.1165
3263	3.193	2+	4.9	–	2.414	0.085	0.1198
3268	17.0	2	6.0	$V^{(1,20)}$	2.347	0.100	0.1223
3281	6.7295	3	5.5	–	2.350	0.122	0.1074
3376	7.916	3–	7.9	$V^{(2,11,13)}, Sq^{(1,17)}$	2.349	0.096	0.1232
3703	3.235	3	3.7	$V^{(3,19)}$	2.332	0.091	0.1183

Notes. Proper elements are from Novakovic et al. (2017): a – proper semi-major axis, e – proper eccentricity, $\sin(i)$ – sine of proper inclination.

References. Taxonomic classification/candidacy is from: ⁽¹⁾Neese (2010), ⁽²⁾Hasselmann et al. (2012), ⁽³⁾Wisniewski (1991), ⁽⁴⁾Solontoi et al. (2012), ⁽⁵⁾Oszkiewicz et al. (2014), ⁽⁶⁾Sanctis et al. (2011), ⁽⁷⁾Hardersen et al. (2018), ⁽⁸⁾Hardersen et al. (2015), ⁽⁹⁾Hasegawa et al. (2014), ⁽¹⁰⁾Xu et al. (1995), ⁽¹¹⁾Spahr et al. (1997), ⁽¹²⁾Licandro et al. (2017), ⁽¹³⁾Carvano et al. (2010), ⁽¹⁴⁾Binzel et al. (1989), ⁽¹⁵⁾Barucci et al. (1987), ⁽¹⁶⁾Howell et al. (1994), ⁽¹⁷⁾Bus & Binzel (2002), ⁽¹⁸⁾DeMeo et al. (2009), ⁽¹⁹⁾Moskovitz et al. (2010), ⁽²⁰⁾Hicks et al. (2014), ⁽²¹⁾Popescu et al. (2018), ⁽²²⁾Binzel & Xu (1993), ⁽²³⁾Lazzaro et al. (2004), ⁽²⁴⁾Chang et al. (2019), ⁽²⁵⁾Erasmus et al. (2018), ⁽²⁶⁾Erasmus et al. (2019).

Table A.2. continued.

Asteroid No.	Synodic period (LCDB) (h)	U-code (LCDB)	Diameter (km)	Class, references	a (au)	e	$\sin(i)$
3720	4.79	2+	4.3	—	2.320	0.093	0.1139
3782	3.84	3	5.9	$V^{(1,2,7,13,17,19)}$	2.416	0.108	0.1063
3936	6.6322	3	4.6	—	2.428	0.123	0.1112
3944	5.565	2	5.9	$V^{(1,10)}$	2.369	0.109	0.1177
4215	12.6	2	6.6	$V^{(1,17,19)}, J^{(10,22)}$	2.418	0.098	0.1152
4524	1069.0	2	12.1	—	2.321	0.087	0.1291
4228	2.772	2	3.5	$V_c^{(12,21)}$	2.304	0.090	0.1047
4684	12.169	3–	5.3	—	2.398	0.107	0.1025
4852	9.715	2	4.0	—	2.304	0.095	0.1087
5111	2.839	3	6.5	$V^{(1,2,13,18,19)}, J^{(17)}$	2.354	0.083	0.1168
5240	5.673	3	7.0	$V^{(1,17)}$	2.383	0.105	0.1108
5307	5.343	3	5.7	$V_c^{(12,21)}$	2.415	0.122	0.1081
5474	3.6242	3	5.1	—	2.383	0.105	0.1214
5481	3.6196	3	3.9	$V^{(1,2,13,17,19,23)}$	2.340	0.093	0.1101
5858	7.553	3	5.6	—	2.315	0.090	0.1135
6003	104.406	2	5.7	—	2.344	0.094	0.1116
6085	5.556	3	5.0	$V_c^{(12,21)}$	2.307	0.092	0.1243
6131	6.77	2	4.6	$V_c^{(2,13)}$	2.423	0.125	0.1031
6159	10.639	3	5.3	—	2.291	0.089	0.1105
6331	9.333	2+	5.3	$V^{(2,9,13)}$	2.358	0.096	0.1230
6418	6.377	3	6.4	—	2.260	0.108	0.1171
6659	12.985	2	5.5	—	2.372	0.106	0.1045
6877	4.1745	3	4.7	$V_c^{(2,12,13,21)}$	2.323	0.088	0.1224
6944	2.9128	3	3.4	$V^{(2,4,13)}$	2.316	0.108	0.1210
6956	4.463	2	4.3	$V_c^{(2,13)}$	2.443	0.111	0.1100
7012	8.938	2	4.7	$V_c^{(12)}$	2.312	0.095	0.1189
7334	4.0659	3	4.1	$V_c^{(2,13)}$	2.413	0.109	0.1070
7510	5.38	2	3.4	—	2.267	0.110	0.1129
7767	85.658	2	3.9	—	2.372	0.099	0.1051
7933	3.26	2+	3.0	—	2.328	0.091	0.1188
7946	51.343	2	4.4	$V_c^{(2,13)}$	2.370	0.097	0.1115
8108	28.5696	2	4.5	$V^{(2,4,13)}$	2.369	0.089	0.1252
8359	2.89111	3	8.2	—	2.350	0.107	0.1206
8692	4.698	2	3.8	—	2.354	0.094	0.1045
9136	5.75	2	3.7	—	2.436	0.116	0.1105
9199	5.322	2+	7.1	—	2.401	0.094	0.1246
9204	80.483	2	5.2	$V_c^{(2,12,13,21)}$	2.332	0.099	0.1195
9220	6.04	2	4.1	$V_c^{(21)}$	2.406	0.102	0.1078
9295	5.13	2–	3.5	$V_c^{(2,13)}$	2.390	0.106	0.1089
9325	4.607	2	4.7	—	2.429	0.102	0.1127
9392	5.524	2	4.0	—	2.444	0.097	0.1064
9616	5.018	2	3.5	$V_c^{(12,21)}$	2.422	0.109	0.1091
9753	4.356	2	4.3	—	2.429	0.117	0.1019
9872	11.598	2	3.0	—	2.369	0.109	0.1130
10001	213.368	2	4.1	—	2.377	0.115	0.1166
10022	4.564	2	4.1	—	2.369	0.111	0.1072
10320	5.92	2	2.8	$V^{(2,9,13)}$	2.288	0.089	0.1154
10484	5.508	3	4.6	$V^{(2,5,13)}$	2.321	0.100	0.1122
10868	80.145	2	2.8	$V_c^{(2,13)}$	2.313	0.093	0.1124
11697	2.805	2+	2.7	—	2.343	0.097	0.1219
11917	89.317	2	3.7	—	2.340	0.091	0.1190
12088	3.342	2	3.7	$V_c^{(2,13)}$	2.355	0.106	0.1209
12405	13.218	2	2.4	$V_c^{(2,13)}$	2.373	0.085	0.1046
12578	6.008	2	2.3	—	2.301	0.091	0.1301
12584	7.071	2	3.0	—	2.372	0.094	0.1180

Table A.2. continued.

Asteroid No.	Synodic period (LCDB) [h]	U-code (LCDB)	Diameter [km]	Class, references	a [au]	e	$\sin(i)$
12619	5.847	2	2.9	—	2.455	0.109	0.1090
12982	601.869	2	2.4	—	2.388	0.121	0.1018
13058	4.299	2	24.1	—	2.358	0.109	0.1133
13164	3.334	2	2.9	$V_c^{(12,21)}$	2.300	0.095	0.1215
13243	88.4	2	4.5	—	2.288	0.098	0.1209
13258	4.59	2	4.0	—	2.372	0.097	0.1165
13262	8.35	2	3.7	$V_c^{(2,13)}$	2.377	0.100	0.0991
13607	4.133	2	3.8	—	2.332	0.090	0.1085
13855	3.023	2	3.0	$V_c^{(12,21)}$	2.462	0.124	0.1115
13894	5.478	2	3.9	—	2.359	0.093	0.1130
14044	9.25874	2	4.2	—	2.431	0.106	0.1057
14218	6.245	2	3.2	$V_c^{(2,13)}$	2.392	0.109	0.1024
14383	8.713	2	3.2	$V_c^{(2,13)}$	2.372	0.098	0.1105
14385	3.78	2	3.1	—	2.360	0.097	0.1159
14527	6.012	3—	2.4	$V_c^{(2,13)}$	2.282	0.083	0.1223
14568	3.523	2	3.4	$V_c^{(2,13)}$	2.393	0.089	0.1196
14686	4.3283	3	4.6	—	2.334	0.090	0.1059
14832	8.07	2+	4.4	—	2.293	0.096	0.1086
15032	4.405511	2	3.6	$V_c^{(2,12,13,21)}$	2.372	0.111	0.1096
15411	4.389	2	3.4	—	2.360	0.107	0.1129
15634	3.002	2	4.5	$V_c^{(2,13)}$	2.348	0.086	0.1183
16021	13.	2	2.6	—	2.335	0.102	0.1115
16214	6.272	2	4.1	—	2.333	0.119	0.1136
16382	4.9	2	2.0	—	2.328	0.090	0.1233
16462	62.366	2	4.4	—	2.465	0.117	0.1134
16950	3.028	2	3.3	—	2.321	0.102	0.1270
16977	50.07	2	4.1	—	2.385	0.106	0.1240
17035	2.899	2	4.8	$V_c^{(2,4,7,13)}$	2.444	0.112	0.1086
17079	4.18	2+	2.8	$V_c^{(2,13)}$	2.443	0.120	0.1081
17409	3.849	2	2.5	$V_c^{(2,13)}$	2.306	0.090	0.1150
17469	17.172	2	6.0	$V_c^{(2,4,13)}$	2.371	0.123	0.1163
17821	5.934	2	2.1	$V_c^{(2,13)}$	2.314	0.084	0.1153
18527	3.3529	3	3.4	—	2.399	0.105	0.1114
19298	78.54	2	2.8	—	2.392	0.114	0.1111
19662	5.93	3	3.2	—	2.292	0.093	0.1193
19979	7.568	2+	5.3	$V_c^{(2,4,13)}$	2.459	0.109	0.1053
20073	3.49	3	2.4	—	2.300	0.096	0.1228
20300	2.62	3—	2.7	$V_c^{(2,13)}$	2.334	0.117	0.1190
20308	6.863	2	3.6	—	2.289	0.101	0.1294
20537	15.626	2	2.8	—	2.311	0.100	0.1273
20570	4.132	2	3.6	—	2.309	0.090	0.1148
21126	5.8397	3	6.2	—	2.407	0.125	0.1079
21321	13.92	2	3.4	—	2.314	0.091	0.1150
21341	3.502	2	3.9	—	2.391	0.096	0.1063
21397	5.836	2	2.1	—	2.304	0.105	0.1172
21406	9.185	2	2.9	—	2.340	0.087	0.1100
21485	12.26	2	2.2	—	2.352	0.084	0.1155
22411	5.262	2	3.8	—	2.380	0.088	0.1074
22515	6.558	2	2.4	—	2.311	0.110	0.1143
22666	5.218	2	3.5	—	2.477	0.120	0.1112
22776	3.407	3—	3.2	—	2.317	0.087	0.1140
22908	16.375	2	3.6	—	2.312	0.104	0.1222
23002	6.62	2	2.3	—	2.404	0.081	0.1067
23228	67.582	2	2.4	—	2.326	0.098	0.1186
23521	14.464	2	2.9	—	2.285	0.091	0.1231

Table A.2. continued.

Asteroid No.	Synodic period (LCDB) [h]	U-code (LCDB)	Diameter [km]	Class, references	a [au]	e	$\sin(i)$
23588	7.197	2	2.6	—	2.408	0.097	0.1090
23705	82.636	2	3.8	—	2.451	0.127	0.1121
23750	10.278	2	2.4	$V_c^{(2,13)}$	2.379	0.084	0.1148
23758	3.12	2	2.8	$V_c^{(2,13)}$	2.337	0.094	0.1029
23766	2.721	3	4.5	—	2.469	0.118	0.1138
23804	532.24	2	2.7	$V_c^{(2,13)}$	2.367	0.109	0.1082
24115	2.635	2	3.2	$V_c^{(12,21)}$	2.402	0.112	0.1110
24147	5.938	2	2.0	—	2.371	0.105	0.1099
24201	12.774	2	2.2	—	2.351	0.085	0.1292
24304	6.139	2	2.3	—	2.328	0.091	0.1162
25220	8.65	2	2.7	$V_c^{(12,21)}$	2.349	0.099	0.1231
25468	5.573	2	4.3	—	2.351	0.093	0.1177
25469	8.57	2	3.7	—	2.323	0.098	0.1215
25907	6.936	2	2.7	—	2.288	0.101	0.1258
26084	121.957	2	2.8	$V_c^{(2,13)}$	2.466	0.112	0.1076
26230	7.318	2	3.1	$V_c^{(2,13)}$	2.456	0.120	0.1129
26284	7.501	2	2.9	$V_c^{(2,13)}$	2.411	0.087	0.1211
26736	12.343	2	2.0	$V_c^{(2,13)}$	2.383	0.090	0.1152
27018	5.733	2	2.4	—	2.354	0.097	0.1039
27060	5.798	2	3.5	$V_c^{(2,13,24)}, S^{(25,26)}$	2.348	0.097	0.1302
27377	6.182	2	1.9	$V_c^{(2,13)}$	2.328	0.093	0.1171
27529	4.129	2	2.8	$V_c^{(2,13)}$	2.362	0.095	0.1154
27834	4.25	2	3.0	—	2.335	0.098	0.1196
27880	4.998	2	2.2	$V_c^{(2,13)}$	2.378	0.118	0.1059
28396	12.548	2	1.9	—	2.342	0.100	0.1168
28735	5.19	2	3.5	$V_c^{(2,13)}$	2.349	0.096	0.1178
29140	2.99	2	2.4	—	2.380	0.105	0.1177
29194	6.02	2	2.7	—	2.407	0.093	0.1041
29762	13.106	2	3.2	—	2.282	0.108	0.1154
30329	28.4	2+	2.9	$V_c^{(12,21)}$	2.406	0.088	0.1028
30570	4.587	2	3.0	—	2.460	0.124	0.1133
31108	13.237	2	2.3	—	2.309	0.085	0.1121
31429	36.9	2	2.5	—	2.311	0.100	0.1247
31737	6.93	2	3.6	—	2.376	0.093	0.1126
31888	5.13	2	2.2	$V_c^{(2,13)}$	2.353	0.106	0.1243
32232	5.68	2+	4.7	$V_c^{(2,13)}$	2.404	0.094	0.1162
32522	3.62	2	3.6	—	2.376	0.089	0.1148
32626	6.23	3—	3.4	—	2.340	0.101	0.1228
32678	6.985	2	3.4	—	2.366	0.116	0.1093
32953	4.329	2	2.4	—	2.342	0.096	0.1180
33539	9.135	2	2.2	$V_c^{(2,13)}$	2.336	0.096	0.1265
35821	4.931	2	3.3	$V_c^{(2,13)}$	2.482	0.109	0.1081
35886	3.19	2	4.0	—	2.315	0.087	0.1261
35965	6.76072	2	3.2	$V_c^{(2,13,20)}$	2.319	0.114	0.1114
37088	3.359	2	2.6	—	2.363	0.108	0.1137
37637	5.366	2	1.8	$V_c^{(2,13)}$	2.293	0.080	0.0917
37776	42.409	2	1.6	—	2.387	0.096	0.1189
38140	14.476	2	1.8	—	2.276	0.093	0.1157
38707	6.1509	3—	2.3	—	2.278	0.093	0.1123
38879	5.537	2	2.7	$V_c^{(12,21)}$	2.405	0.092	0.1151
39051	6.4	2	2.1	—	2.309	0.098	0.1231
39088	5.373	2	2.4	—	2.306	0.109	0.1138
39218	54.444	2	3.5	$V_c^{(2,13)}$	2.318	0.106	0.1171
39494	7.353	2	1.8	$V_c^{(2,13)}$	2.300	0.106	0.1118
39829	5.331	2	1.6	—	2.275	0.092	0.1123

Table A.2. continued.

Asteroid No.	Synodic period [LCDB] [h]	U-code (LCDB)	Diameter [km]	Class, references	a [au]	e	$\sin(i)$
39863	9.0488	2	3.5	—	2.304	0.112	0.1185
40279	6.656	2	2.1	—	2.302	0.097	0.1176
40370	7.38	3—	1.6	—	2.292	0.079	0.1127
40408	9.217	2	2.0	—	2.341	0.093	0.1259
40453	17.442	2	2.5	—	2.323	0.085	0.1141
40574	5.346	2	1.7	—	2.336	0.099	0.1068
41789	8.932	2	3.5	—	2.296	0.111	0.1194
42644	16.0	2—	3.9	$V_c^{(12,21)}$	2.367	0.103	0.1161
42653	5.495	2	2.2	—	2.299	0.104	0.1169
42655	5.168	2	2.8	—	2.329	0.105	0.1092
42866	42.227	2	2.7	—	2.354	0.104	0.1201
42915	5.504	2	2.1	—	2.286	0.081	0.1102
42953	2.67	2	2.3	—	2.318	0.115	0.1104
43463	9.697	2	1.6	—	2.320	0.099	0.1168
43464	101.649	2	2.0	—	2.297	0.093	0.1171
43492	5.08	2+	1.6	—	2.313	0.089	0.1266
43941	5.374	2	2.7	—	2.303	0.092	0.1167
44569	5.514	2	2.0	$V_c^{(21)}$	2.275	0.095	0.1271
44681	17.337	2	1.7	$V_c^{(2,13)}$	2.282	0.106	0.1164
44864	9.121	2	1.9	$V_c^{(2,13)}$	2.368	0.082	0.1034
44872	5.068	2	2.3	—	2.324	0.096	0.1116
45041	4.66	3	2.1	—	2.342	0.101	0.1213
45052	2.721	2	1.9	—	2.330	0.105	0.1154
45073	3.16	3—	3.0	$V_c^{(2,13)}$	2.334	0.123	0.1151
45160	4.104	2	2.0	—	2.311	0.111	0.1177
45270	7.851	2	2.8	—	2.393	0.089	0.1184
45986	5.85	2—	2.1	—	2.340	0.095	0.1158
46784	19.	2—	2.0	—	2.252	0.104	0.1174
47229	47.168	2	2.0	—	2.305	0.089	0.1206
47271	6.902	2	3.0	—	2.379	0.117	0.1189
47332	3.992	2	2.4	—	2.370	0.103	0.1078
47369	2.55	2	4.3	—	2.390	0.119	0.1075
47406	5.838	2	1.8	—	2.392	0.094	0.1016
47528	6.44	2+	2.3	—	2.416	0.091	0.1011
48094	11.613	2	1.9	—	2.318	0.092	0.1210
48120	78.226	2	2.1	—	2.391	0.101	0.1159
48134	5.778	2	2.3	—	2.360	0.106	0.1191
48190	2.4	2	1.9	—	2.275	0.082	0.1053
48376	534.962	2	2.7	—	2.345	0.107	0.1017
48507	6.9	2	3.0	—	2.344	0.096	0.1191
48644	8.28	2—	2.6	$V_c^{(12,21)}$	2.436	0.099	0.1076
48734	6.446	2	2.2	$V_c^{(12,21)}$	2.281	0.080	0.1136
48748	7.018	2	2.1	—	2.293	0.110	0.1196
48907	13.896	2	1.9	—	2.347	0.096	0.1056
48935	5.363	2	2.4	$V_c^{(2,13)}$	2.297	0.093	0.1200
48966	9.203	2	2.6	—	2.392	0.092	0.1260
48981	6.979	2	3.7	—	2.338	0.107	0.1114
48997	6.55436	2	3.5	—	2.305	0.112	0.1183
48999	7.044	2	2.5	—	2.346	0.095	0.1145
49039	72.	2	3.1	—	2.349	0.097	0.1185
50025	11.003	2	2.3	$V_c^{(2,13)}$	2.365	0.103	0.1088
50138	11.38	2	2.0	—	2.379	0.113	0.1114
50179	6.066	2	1.6	—	2.350	0.092	0.1061
50196	10.166	2	2.9	$V_c^{(2,13)}$	2.310	0.097	0.1240
50329	7.06	2	2.5	—	2.340	0.092	0.1188
51609	6.767	3	2.0	—	2.309	0.107	0.1118
52852	5.432	3—	2.5	—	2.263	0.097	0.1211

Table A.2. continued.

Asteroid No.	Synodic period (LCDB) (h)	U-code (LCDB)	Diameter (km)	Class, references	a (au)	e	$\sin(i)$
53515	8.652	2	2.8	$V_c^{(2,13)}$	2.327	0.120	0.1176
53632	9.055	2	1.9	$V_c^{(2,13)}$	2.393	0.099	0.1107
53734	5.05	2	2.7	$V_c^{(2,12,13,21)}$	2.335	0.120	0.1161
53930	10.593	2	1.7	–	2.448	0.096	0.1050
54076	4.95	2	2.0	–	2.377	0.097	0.1095
55293	4.62	2	1.6	–	2.350	0.103	0.1147
55459	11.308	2	2.0	–	2.447	0.114	0.1118
56394	9.32	2+	1.9	–	2.452	0.097	0.1075
57478	5.887	3–	2.5	–	2.342	0.096	0.1220
58049	5.376	2	1.2	–	2.343	0.086	0.1178
58658	4.95	2	2.1	–	2.436	0.098	0.1125
59291	2.8868	3–	3.1	–	2.286	0.095	0.1293
59345	6.19	2	3.1	–	2.428	0.103	0.1083
59489	5.455	2	3.4	–	2.398	0.116	0.1132
60326	18.993	2	1.8	–	2.328	0.097	0.1139
60507	9.411	2	2.2	–	2.355	0.092	0.1042
61036	6.617	2	1.7	–	2.353	0.094	0.1042
63264	7.74	2–	1.6	–	2.323	0.095	0.1276
63702	4.66	2	2.8	–	2.473	0.106	0.1096
64599	9.89378	2	2.3	–	2.329	0.100	0.1203
65068	8.763	2	1.8	$V_c^{(2,12,13,21)}$	2.290	0.107	0.1242
65242	5.168	2	2.2	–	2.389	0.079	0.1212
65345	14.148	2	1.8	–	2.417	0.094	0.1094
65719	7.18	2	2.0	$V_c^{(2,13)}$	2.308	0.092	0.1181
66189	7.88	3	1.7	–	2.314	0.116	0.1101
67847	2.473	2	1.5	–	2.265	0.111	0.1084
67909	13.567	2	2.8	–	2.287	0.091	0.1265
69076	4.829	2	1.8	$V_c^{(2,13)}$	2.332	0.091	0.1268
69253	10.967	2	1.2	–	2.286	0.100	0.1259
69267	6.44372	2	3.4	–	2.359	0.104	0.1088
69595	6.67	3–	1.7	–	2.297	0.096	0.1226
69596	7.02	2	2.2	$V_c^{(2,13)}$	2.314	0.089	0.1201
70085	4.95	2	2.0	–	2.273	0.088	0.1146
70301	9.561	2	2.2	–	2.360	0.097	0.1204
70478	12.125	2	2.3	–	2.336	0.084	0.1190
74219	5.7	2–	5.4	–	2.464	0.118	0.1144
74639	5.08	2	1.5	–	2.303	0.090	0.0999
74885	20.87	2	1.1	–	2.314	0.094	0.1182
75011	2.8	2	2.5	$V_c^{(2,13)}$	2.324	0.096	0.1162
75403	7.139	2	1.9	–	2.436	0.113	0.1108
75423	2.552	2	2.2	–	2.386	0.085	0.1084
75426	7.45	2	2.7	–	2.392	0.093	0.1175
75605	4.68	2	2.0	–	2.410	0.115	0.1100
76898	14.138	2	2.1	–	2.322	0.100	0.1213
77186	32.112	2	2.0	$V_c^{(2,13)}$	2.356	0.093	0.1172
77357	2.6	2–	2.4	–	2.366	0.086	0.1059
77590	5.892	2	2.1	$V_c^{(2,12,13,21)}$	2.402	0.106	0.1062
79559	62.854	2	2.9	–	2.415	0.116	0.1095
79621	3.512	2	2.1	–	2.398	0.105	0.1162
79639	6.026	2	3.3	–	2.320	0.098	0.1269
79704	6.4	2+	2.0	–	2.393	0.100	0.1106
79738	7.28	2	2.0	–	2.408	0.105	0.1276
80180	5.71	2	1.6	–	2.309	0.104	0.1097
80186	41.094	2	1.1	–	2.314	0.120	0.1091
80234	4.32	2+	1.4	–	2.294	0.096	0.1230
80371	5.128	2	1.6	–	2.317	0.092	0.1059

Table A.2. continued.

Asteroid No.	Synodic period (LCDB) (h)	U-code (LCDB)	Diameter (km)	Class, references	a (au)	e	$\sin(i)$
80438	4.682	2	1.4	—	2.344	0.086	0.1161
80623	5.057	2+	1.6	—	2.324	0.121	0.1139
80678	5.066	2	2.1	—	2.379	0.104	0.1055
80704	10.535	2	1.7	—	2.256	0.095	0.1103
80775	5.362	2	1.6	—	2.394	0.099	0.1076
81263	6.3	3—	2.0	$V_c^{(2,13)}$	2.406	0.110	0.1091
82660	5.631	2	2.0	—	2.461	0.128	0.1105
84042	8.07	2	1.3	—	2.273	0.098	0.1210
84668	6.67	2+	2.2	—	2.461	0.121	0.1063
85959	89.669	2	2.1	—	2.268	0.090	0.1169
86492	5.466	2	1.5	$V_c^{(2,13)}$	2.325	0.107	0.1193
88352	7.01	2—	2.3	—	2.385	0.099	0.1124
88367	3.962	2	2.1	—	2.389	0.087	0.1134
88531	2.9	2	1.4	—	2.370	0.093	0.1106
88622	4.524	2	2.2	—	2.381	0.105	0.1038
89410	10.895	2	2.4	—	2.443	0.104	0.1163
89413	7.876	2	1.8	—	2.433	0.090	0.1177
89736	10.699	2	2.6	—	2.462	0.123	0.1119
96817	5.631	2	2.3	—	2.462	0.115	0.1111
97674	8.161	2	2.1	—	2.478	0.103	0.1074
98384	67.293	2	1.5	—	2.353	0.101	0.1208
98603	8.052	2	1.7	—	2.295	0.112	0.1159
99656	5.339	2	1.8	—	2.404	0.085	0.1161
99742	4.663	2	1.3	—	2.272	0.100	0.1240
101924	4.231	2	1.5	—	2.280	0.113	0.1097
102112	63.867	2	1.4	—	2.271	0.105	0.1076
102380	63.867	2	1.4	—	2.300	0.110	0.1112
103071	7.399	2	1.1	—	2.393	0.097	0.1273
103132	2.51	2+	2.2	$V_c^{(12,21)}$	2.453	0.118	0.1122
104182	195.786	2	1.6	—	2.409	0.105	0.1110
107026	2.789	2	1.3	—	2.295	0.089	0.1198
107587	4.165	2	1.5	—	2.319	0.096	0.1183
107750	5.605	2	1.4	—	2.338	0.080	0.1131
108438	17.466	2	1.4	—	2.281	0.086	0.1216
109187	19.737	2	1.4	—	2.324	0.089	0.1257
114146	7.626	2	1.5	—	2.405	0.095	0.1164
115358	4.85	2—	1.5	—	2.376	0.091	0.1248
115758	42.577	2	1.5	—	2.298	0.093	0.1205
116588	5.61	2	1.2	—	2.259	0.095	0.1177
117247	50.985	2	1.6	—	2.291	0.101	0.1244
118293	16.235	2	1.3	$V_c^{(2,13)}$	2.325	0.104	0.1074
120019	6.266	2	1.7	—	2.334	0.106	0.1117
124297	5.78	2	1.6	$V_c^{(2,13)}$	2.383	0.093	0.1036
124548	6.498	2	1.7	$V_c^{(2,13)}$	2.359	0.091	0.1273
125091	4.45	2+	2.0	—	2.314	0.097	0.1254
125390	9.14	2	1.5	$V_c^{(21)}$	2.377	0.090	0.1159
129334	5.16	2	0.9	—	2.323	0.097	0.1212
130682	5.046	2	2.5	—	2.393	0.097	0.1194
130753	53.595	2	1.7	—	2.404	0.093	0.1074
130820	12.98	2	1.4	—	2.394	0.100	0.1019
134702	9.007	2	0.9	—	2.395	0.109	0.1097
136785	37.614	2	1.3	—	2.287	0.098	0.1259
137280	62.323	2	1.1	—	2.279	0.083	0.1168
137366	5.522	2	1.3	—	2.300	0.107	0.1264
137736	67.796	2	1.4	—	2.398	0.112	0.1047
139201	7.719	2	1.3	—	2.343	0.099	0.1296
139312	4.003	2	1.3	—	2.384	0.100	0.1172

Table A.2. continued.

Asteroid No.	Synodic period (LCDB) (h)	U-code (LCDB)	Diameter (km)	Class, references	a (au)	e	$\sin(i)$
142061	62.558	2	1.1	—	2.324	0.108	0.1171
143946	7.695	2	1.2	$V_c^{(2,13)}$	2.302	0.096	0.1102
143950	17.105	2	1.3	—	2.387	0.108	0.1137
144033	4.368	2	1.4	$V_c^{(2,13)}$	2.418	0.098	0.1114
144067	5.49	2	1.4	—	2.478	0.102	0.1074
144564	138.112	2	1.8	—	2.333	0.114	0.1052
144974	246.672	2	0.9	—	2.274	0.083	0.1190
145092	20.051	2	1.2	—	2.310	0.096	0.1219
147037	4.234	2	1.6	—	2.354	0.094	0.1188
147887	4.6566	3	1.6	—	2.351	0.086	0.1205
149379	8.449	2	1.2	—	2.400	0.103	0.1018
149385	3.316	2	1.6	—	2.354	0.084	0.1170
150080	4.728	2	1.0	—	2.334	0.086	0.1160
150789	5.242	2	1.2	—	2.330	0.098	0.1249
152212	7.27	2	1.2	—	2.336	0.104	0.1122
153672	28.24	2	1.5	—	2.432	0.103	0.1129
161772	7.194	2	1.1	$V_c^{(2,13)}$	2.368	0.084	0.1283
162577	6.085	2	1.2	—	2.343	0.090	0.1064
167138	4.206	2	1.3	—	2.298	0.109	0.1164
171400	4.852	2	1.8	—	2.411	0.125	0.1122
172473	5.360	2	1.0	—	2.288	0.106	0.1033
172601	39.971	2	1.0	—	2.320	0.086	0.1030
173255	4.638	2	1.4	—	2.287	0.098	0.1218
174606	5.666	2	1.3	—	2.270	0.098	0.1227
174655	4.638	2	1.4	—	2.304	0.095	0.1166
174830	42.158	2	1.6	—	2.403	0.126	0.1122
174837	42.97	2	1.4	—	2.386	0.097	0.1176
175809	202.127	2	1.0	—	2.291	0.107	0.1203
175856	4.96	2	1.3	—	2.321	0.096	0.1172
176111	6.29	2	1.2	—	2.332	0.097	0.1144
176139	5.13	2	0.9	$V_c^{(2,13)}$	2.313	0.105	0.1096
176829	14.596	2	1.3	—	2.453	0.103	0.1196
177302	7.735	2	1.3	—	2.399	0.105	0.1271
179604	31.426	2	0.9	—	2.344	0.115	0.1099
180511	13.288	2	1.5	—	2.450	0.113	0.1155
183303	6.006	2	1.4	—	2.390	0.120	0.1054
183708	6.519	2	1.0	—	2.294	0.087	0.1125
184483	6.998	2	1.4	—	2.422	0.097	0.1066
186652	5.22	2	0.9	—	2.279	0.084	0.1033
189740	9.32	2	1.3	—	2.436	0.116	0.1136
194458	6.52	2	1.2	—	2.344	0.090	0.1086
194912	12.68	2	1.9	—	2.381	0.095	0.1120
209060	4.14	3—	1.7	—	2.390	0.086	0.1155
220143	3.502	2+	1.3	—	2.324	0.088	0.1110
220205	9.835	2	1.1	—	2.404	0.089	0.1100
221153	5.422	2	1.0	—	2.480	0.124	0.1164
223121	6.003	2	1.1	$V_c^{(2,13)}$	2.305	0.085	0.1192
226642	4.962	2	1.4	$V_c^{(2,13)}$	2.342	0.097	0.1185
230162	5.78	2	1.2	—	2.378	0.093	0.1082
253531	10.158	2	1.2	—	2.299	0.096	0.1333
253725	6.497	2	1.0	—	2.344	0.094	0.1142
253734	6.182	2	0.9	—	2.330	0.104	0.1115
255623	59.226	2	1.1	—	2.406	0.106	0.1096
257325	4.62	2+	1.0	—	2.439	0.101	0.1175
257631	13.17	2	0.7	—	2.301	0.119	0.1094
259709	9.859	2	1.2	$V_c^{(2,13)}$	2.293	0.101	0.1244

Table A.2. continued.

Asteroid No.	Synodic period (LCDB) (h)	U-code (LCDB)	Diameter (km)	Class, references	a (au)	e	$\sin(i)$
262418	5.887	2	1.1	–	2.334	0.100	0.1246
264331	5.85	2	1.0	–	2.420	0.114	0.1128
270739	5.462	2	0.9	–	2.340	0.097	0.1184
272214	20.278	2	1.1	$V_c^{(2,13)}$	2.299	0.105	0.1218
273498	9.1	2	1.4	–	2.448	0.101	0.1117
279536	9.189	2	1.3	–	2.406	0.091	0.1114
283252	8.28	2	1.2	–	2.425	0.100	0.1159
294796	8.833	2	1.0	–	2.334	0.094	0.1238
308335	5.89	2	1.1	–	2.283	0.085	0.1151
316495	5.186	2	0.8	–	2.261	0.097	0.1252
323324	4.389	2	0.9	–	2.323	0.109	0.1104
332477	13.52	2–	1.0	–	2.376	0.117	0.1191
333887	3.914	2	1.0	$V_c^{(2,13)}$	2.307	0.086	0.1192
334150	5.294	2	1.1	–	2.377	0.095	0.1195
337824	2.548	2	1.0	–	2.420	0.089	0.1094
339771	4.95	2	0.9	–	2.280	0.097	0.1180
339899	8.47	2	1.5	–	2.327	0.108	0.1039
349755	8.47	2–	1.5	–	2.452	0.111	0.1091
387135	4.059	2	1.3	–	2.445	0.101	0.1075
390500	3.23	2	0.8	–	2.281	0.103	0.1092

Table A.3. As in Table A.2, but for the fugitive population.

Asteroid No.	Synodic period (LCDB) (h)	U-code (LCDB)	Diameter (km)	Class, references	a (au)	e	$\sin(i)$
809	15.4142	3	9.5	$V^{(1,4,15,17,19)}$	2.283	0.145	0.1179
956	16.492	3	10.5	$V^{(1,4,15,17,19)}$	2.298	0.158	0.1119
2049	8.91	2	2.5	$V_c^{(2,14)}$	1.949	0.074	0.4109
2486	4.4518	3	7.9	$V^{(8,10,13,18)}$	2.268	0.122	0.1410
2579	3.63599	3	4.6	$V^{(1,5,15,16,17)}$	2.210	0.082	0.1054
2912	5.71076	3	6.5	$V^{(1,15,16,17)}$	2.289	0.118	0.1186
3307	4.902	3–	3.6	$V^{(1,15)}$	2.259	0.100	0.1212
3850	2.4289	3	4.2	$V^{(1,15)}$	2.235	0.105	0.0814
4692	2.736	2+	4.9	$V_c^{(2,14)}$	2.256	0.122	0.0505
5037	2.8290	–	5.7	$QV_p^{(2,14)}, V_c^{(20)}$	2.273	0.143	0.1282
5235	2.4524	–	6.7	$V^{(2,12,14)}$	2.297	0.120	0.0961
5525	14.088	3–	5.3	$V^{(2,7,14)}$	2.221	0.081	0.1279
5560	7.732	3–	4.7	$V^{(2,7,14)}$	2.286	0.118	0.0852
5754	8.9021	3	6.3	$V_c^{(2,11,14)}$	2.267	0.091	0.0843
5952	4.512546	3	4.9	$V^{(2,11,13,14,18)}$	2.270	0.141	0.0796
6406	6.819	3	4.1	$V^{(8,9,13,18)}$	2.276	0.124	0.1336
6819	2.7249	–	4.7	$V_c^{(2,14)}$	2.294	0.102	0.0975
7558	4.1121	–	4.4	$V^{(2,3,6,14)}$	2.290	0.110	0.0904
8761	2.6386	–	3.7	$V^{(2,9,14)}$	2.242	0.096	0.0639
9481	3.0519	–	4.7	$V^{(2,14,17)}$	2.287	0.139	0.036
9531	2.5003	–	4.2	$V^{(2,7,17,14)}$	2.235	0.136	0.0957
10666	3.4947	3–	4.0	$V^{(2,11,14)}$	2.222	0.110	0.0934

Notes. In bold, we flag asteroids for which we determined or confirmed periods in this article.

References. ⁽¹⁾Neese (2010), ⁽²⁾Hasselmann et al. (2012), ⁽³⁾Wisniewski (1991), ⁽⁴⁾Florczak et al. (2002), ⁽⁵⁾Oszkiewicz et al. (2019), ⁽⁶⁾Moskovitz et al. (2008b), ⁽⁷⁾Solontoi et al. (2012), ⁽⁸⁾Alvarez-Candal et al. (2006), ⁽⁹⁾Sanctis et al. (2011), ⁽¹⁰⁾Fulvio et al. (2016), ⁽¹¹⁾Hardersen et al. (2018), ⁽¹²⁾Hardersen et al. (2014b), ⁽¹³⁾Licandro et al. (2017), ⁽¹⁴⁾Carvano et al. (2010), ⁽¹⁵⁾Bus & Binzel (2002), ⁽¹⁶⁾DeMeo et al. (2009), ⁽¹⁷⁾Moskovitz et al. (2010), ⁽¹⁸⁾Popescu et al. (2018), ⁽¹⁹⁾Lazzaro et al. (2004), ⁽²⁰⁾Solontoi et al. (2012).

Table A.3. continued.

Asteroid No.	Synodic period (LCDB) (h)	U-code (LCDB)	Diameter (km)	Class, references	a (au)	e	$\sin(i)$
14322	7.462	3	3.5	$V^{(2,7,14)}$	2.234	0.106	0.1283
15882	5.05	2	3.8	$V_c^{(2,14)}$	2.297	0.175	0.0419
16416	36.506	2	3.4	$V^{(2,14,17)}$	2.196	0.107	0.1079
17028	12.80411	2	2.0	$V_c^{(2,14)}$	2.226	0.152	0.0758
22113	6.7426	—	2.9	$V_c^{(2,14)}$	2.239	0.121	0.0958
23615	368.	2	3.5	$V_c^{(2,14)}$	1.961	0.114	0.3890
26433	7.933	2	2.6	$V_c^{(2,14,18)}$	2.264	0.110	0.1252
32008	3.0171	3	3.1	$V_c^{(2,14)}$	2.192	0.144	0.1221
37142	47.068	2	1.5	$V_c^{(2,14)}$	2.229	0.122	0.1147
48635	28.106	2	2.4	$V_c^{(2,14)}$	2.266	0.107	0.1034
70069	6.252	2	1.7	$V_c^{(2,14)}$	2.231	0.105	0.1073
84975	22.711	2	1.4	$V_c^{(2,14)}$	2.293	0.126	0.1149
187060	8.125	2	1.0	$V_c^{(2,14)}$	2.241	0.097	0.1318

Table A.4. As in Table A.2, but for the low inclination population.

Asteroid No.	Synodic period (LCDB) (h)	U-code (LCDB)	Diameter (km)	Class, references	a (au)	e	$\sin(i)$
1914	6.331	2	9.6	$V^{(2,5,12)}$	2.406	0.139	0.0848
2247	4.4974	—	4.4	$V^{(2,12,16)}$	2.449	0.090	0.1017
2442	11.453	2	8.3	$V^{(1,2,12,14)}, J^{(8,18)}$	2.388	0.097	0.0944
2566	4.451	3	7.8	$V^{(1,13,14,15)}$	2.450	0.104	0.0771
2653	5.5228	3	9.9	$V^{(1,13,15)}$	2.444	0.114	0.0888
2704	2.6382	3	5.2	$V^{(1,2,12,13)}$	2.385	0.117	0.0889
2763	7.8	3	7.5	$V^{(1,3,9,11,13,15,17)}, S^{(19)}$	2.404	0.179	0.0756
2823	2.6262	—	5.4	$V^{(2,4,12,15)}$	2.326	0.175	0.0726
3331	7.5888	—	4.4	$V_c^{(2,10,11,12)}$	2.418	0.112	0.0624
3849	2.778	2	5.8	$V^{(1,2,6,12,13)}$	2.474	0.065	0.0940
3867	28.035	2	5.4	$V_c^{(2,12)}$	2.351	0.136	0.0954
4188	2.58	3—	6.6	$V^{(1,2,12,13,14,15)}$	2.335	0.111	0.0986
4796	3.5086	3	5.7	$V^{(1,2,7,12,13,15)}$	2.355	0.141	0.0538
7798	3.8724	—	5.0	$V_c^{(2,12)}$	2.479	0.131	0.0800
7899	85.658	2	3.9	$V_c^{(2,12)}$	2.343	0.114	0.0937
8645	7.616	3—	5.1	$V^{(2,7,12)}$	2.431	0.041	0.0885
9223	3.758	2	4.5	$V^{(2,6,12)}$	2.301	0.080	0.0699
11149	12.85	3—	3.5	$V_c^{(2,12)}$	2.442	0.079	0.1035
15481	5.01	2	4.7	$V_c^{(2,12)}$	2.383	0.107	0.0784
15630	8.064	2	3.6	$V^{(2,6,12,17)}$	2.326	0.146	0.0818
27192	5.5741	—	3.2	$V_c^{(2,12)}$	2.323	0.119	0.097
29337	4.5096	3	4.2	$V_c^{(2,12)}$	2.468	0.189	0.1025
47417	11.71	2—	4.6	$V_c^{(2,12)}$	2.400	0.090	0.0990
56570	3.22	2	2.4	$V^{(2,11,12)}$	2.378	0.096	0.0721
82125	2.554	2	1.8	$V_c^{(2,12)}$	2.414	0.092	0.0976
118567	6.741	2	1.3	$V_c^{(2,12)}$	2.318	0.093	0.1026
151036	4.974	2	1.9	$V_c^{(2,12)}$	2.448	0.124	0.0957

Notes. In bold we flag asteroids for which we determined or confirmed periods in this article.

References. ⁽¹⁾Neese (2010), ⁽²⁾Hasselmann et al. (2012), ⁽³⁾Duffard et al. (2004), ⁽⁴⁾Moskovitz et al. (2008b), ⁽⁵⁾Alvarez-Candal et al. (2006), ⁽⁶⁾Hardersen et al. (2018), ⁽⁷⁾Hasegawa et al. (2014), ⁽⁸⁾Xu et al. (1995), ⁽⁹⁾Spahr et al. (1997), ⁽¹⁰⁾Roig & Gil-Hutton (2006), ⁽¹¹⁾Licandro et al. (2017), ⁽¹²⁾Carvano et al. (2010), ⁽¹³⁾Bus & Binzel (2002), ⁽¹⁴⁾DeMeo et al. (2009), ⁽¹⁵⁾Moskovitz et al. (2010), ⁽¹⁶⁾Hicks et al. (2014), ⁽¹⁷⁾Popescu et al. (2018), ⁽¹⁸⁾Binzel & Xu (1993), ⁽¹⁹⁾Erasmus et al. (2019).

Table A.5. As in Table A.2, but for the inner other population.

Asteroid No.	Synodic period (LCDB) (h)	U-code (LCDB)	Diameter (km)	Class, references	a (au)	e	$\sin(i)$
854	37.56	3	7.8	$V^{(2,3,12)}$	2.368	0.164	0.1124
2432	3.206	3–	7.4	$V_c^{(2,12)}$	2.352	0.129	0.1158
2851	5.414	3–	8.8	$V^{(1,13,14,15)}$	2.478	0.123	0.1348
3536	5.79	3	3.2	$V^{(1,22,26,31,35)}$	2.343	0.077	0.1156
3900	5.324	3	5.0	$V^{(1,7,10,11,13,17)}$	2.371	0.113	0.1224
4383	3.4069	3	6.5	$V^{(2,7,9,12)}$	2.425	0.055	0.1095
5150	5.1953	3	5.4	$V_c^{(2,11,12,17)}$	2.477	0.138	0.1076
5524	8.416	3	19.9	$V_c^{(2,11,12,17)}$	2.366	0.059	0.1194
5599	3.6195	3	6.4	$V^{(2,12,16)}$	2.419	0.155	0.1264
5875	5.551	3	7.5	$V^{(2,6,11,12,17)}$	2.379	0.067	0.1246
6680	6.722	3	4.5	$V_c^{(2,12)}$	2.322	0.095	0.1408
6976	4.025	3	5.5	$V_c^{(2,12)}$	2.333	0.119	0.1303
7484	6.237	2	4.0	$V_c^{(2,12)}$	2.405	0.071	0.1114
9368	2.9183	3	4.3	$V^{(2,5,12)}$	2.310	0.163	0.1289
9652	4.385	2	6.0	$V_c^{(2,12)}$	2.418	0.197	0.1196
18641	5.2461	3	3.7	$V_c^{(2,12)}$	2.357	0.097	0.1344
25327	6.716	3	4.4	$V^{(4)}$	2.434	0.186	0.2187
25542	10.55227	2	2.7	$V_c^{(2,12)}$	2.443	0.116	0.1224
35062	19.08	2	3.2	$V^{(2,4,11,12,17)}$	2.370	0.285	0.1755
42979	3.498	2	2.0	$V_c^{(2,12)}$	2.400	0.110	0.1198
53533	5.674	2	2.4	$V_c^{(2,12)}$	2.419	0.137	0.1082
54584	2.92	3–	3.2	$V_c^{(2,12)}$	2.342	0.123	0.1431

References. ⁽¹⁾Neese (2010), ⁽²⁾Hasselmann et al. (2012), ⁽³⁾Birlan et al. (2011), ⁽⁴⁾Solontoi et al. (2012), ⁽⁵⁾Hardersen et al. (2018), ⁽⁶⁾Hardersen et al. (2015), ⁽⁷⁾Hasegawa et al. (2014), ⁽⁸⁾Xu et al. (1995), ⁽⁹⁾Pajuelo et al. (2018), ⁽¹⁰⁾Spahr et al. (1997), ⁽¹¹⁾Licandro et al. (2017), ⁽¹²⁾Carvano et al. (2010), ⁽¹³⁾Bus & Binzel (2002), ⁽¹⁴⁾DeMeo et al. (2009), ⁽¹⁵⁾Moskovitz et al. (2010), ⁽¹⁶⁾Hicks et al. (2014), ⁽¹⁷⁾Popescu et al. (2018).

Table A.6. As in Table A.2, but for the NEA population.

Asteroid No.	Synodic period (LCDB) (h)	U-code (LCDB)	Diameter (km)	Class, references	a (au)	e	$\sin(i)$
1981	5.22	3	3.4	V ⁽⁶⁾	0.650	1.777	0.6400
3361	3.532	3	0.3	V ^(3,17)	0.323	1.210	0.0470
3551	4.93	2	0.9	V ^(1,11)	0.487	2.093	0.1650
3908	4.42601	3	1.0	V ^(1,7,15)	0.459	1.927	0.0380
4055	7.475	3	2.5	V ^(1,2,5,7,8,10,11,13,14,16,18,19)	0.326	1.820	0.3950
5604	5.3375	3	0.6	V ^(1,5,7,13)	0.405	0.927	0.0840
6611	2.5568	3	0.8	V ^(1,12)	0.485	1.696	0.1500
7889	2.741	3	1.7	V ^(4,7) , R ⁽²⁰⁾	1.261	0.346	0.6000
52750	26.43	2+	1.1	V ^(4,5)	0.525	1.427	0.1940
55532	46.08	2	1.3	V ⁽¹⁸⁾ , Sk ⁽⁷⁾	1.794	0.696	0.623
137052	9.007	3–	0.9	V ^(1,12)	0.810	1.248	0.2570
137199	2.767	3	1.2	V ⁽²¹⁾ , Q ⁽¹⁸⁾	1.457	0.293	0.285
137924	10.57	3–	1.0	V ⁽⁵⁾	0.895	0.876	0.4340
152756	2.845	3	0.5	V ⁽¹⁸⁾ , S ⁽⁶⁾	1.451	0.415	0.263
163249	3.7663	3	0.6	V ⁽¹⁸⁾	1.344	0.335	0.121
164121	2.343	3	1.7	V ^(5,19)	1.11	0.292	0.695
297418	6.314	3	0.4	V ⁽⁵⁾	0.467	0.811	0.1800
389694	5.24	2–	0.5	V ⁽¹⁸⁾	1.545	0.492	0.327
477762	15.04	2–	0.3	QV _c ⁽¹⁸⁾	2.06	0.495	0.205
1996 JA1	5.227	3	0.2	V ⁽⁹⁾	0.701	2.567	0.3680
1997 GL3	7.572	2	0.3	V ^(1,12)	0.782	2.276	0.1160

References. ⁽¹⁾Neese (2010), ⁽²⁾Hasselmann et al. (2012), ⁽³⁾Wisniewski (1991), ⁽⁴⁾Duffard et al. (2004), ⁽⁵⁾Thomas et al. (2014), ⁽⁶⁾Binzel et al. (2001), ⁽⁷⁾Binzel et al. (2004), ⁽⁸⁾Hardersen et al. (2018), ⁽⁹⁾Spahr et al. (1997), ⁽¹⁰⁾Carvano et al. (2010), ⁽¹¹⁾Binzel et al. (1989), ⁽¹²⁾Bus & Binzel (2002), ⁽¹³⁾DeMeo et al. (2009), ⁽¹⁴⁾Hicks et al. (2014), ⁽¹⁵⁾Popescu et al. (2018), ⁽¹⁶⁾Lazzaro et al. (2004), ⁽¹⁷⁾Hasegawa et al. (2018), ⁽¹⁸⁾Lin et al. (2018), ⁽¹⁹⁾Sanchez et al. (2013), ⁽²⁰⁾Dandy et al. (2003), ⁽²¹⁾Carry et al. (2016).

Table A.7. As in Table A.2, but for the Middle/Outer Main Belt population.

Asteroid No.	Synodic period (LCDB) (h)	U-code (LCDB)	Diameter (km)	Class, references	a (au)	e	$\sin(i)$
1459	4.678	3	29.2	V ^(3,5,8) , Vw ^(1,7)	3.150	0.213	0.2681

References. ⁽¹⁾Neese (2010), ⁽³⁾Solontoi et al. (2012), ⁽⁵⁾Lazzaro et al. (2000), ⁽⁷⁾DeMeo et al. (2009), ⁽⁸⁾Lazzaro et al. (2004).

Fig. A.1. Composite light curves of the observed V-type asteroids (as in Table 4).

Fig. A.1. continued.

Fig. A.1. continued.