MAIN-BELT ASTEROIDS OBSERVED FROM CS3: 2019 OCTOBER TO DECEMBER

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CCD photometric observations of 21 main-belt asteroids were obtained at the Center for Solar System Studies (CS3) from 2019 October to December.

The Center for Solar System Studies (CS3) has seven telescopes which are normally used in program asteroid family studies. The focus is on near-Earth asteroids, but when suitable targets are not available, Jovian Trojans and Hildas are observed. When a nearly full moon is too close to the family targets being studied, targets of opportunity amongst the main-belt families were selected.

Table I lists the telescopes and CCD cameras that were used to make the observations. Images were unbinned with no filter and had master flats and darks applied. The exposures depended upon various factors including magnitude of the target, sky motion, and Moon illumination.

Telescope	Camera
0.30-m f/6.3 Schmidt-Cass	FLI Microline 1001E
0.35-m f/9.1 Schmidt-Cass	FLI Microline 1001E
0.35-m f/9.1 Schmidt-Cass	FLI Microline 1001E
0.35-m f/9.1 Schmidt-Cass	FLI Microline 1001E
0.35-m f/11 Schmidt-Cass	FLI Microline 1001E
0.40-m f/10 Schmidt-Cass	FLI Proline 1001E
0.50-m F8.1 R-C	FLI Proline 1001E

Table I: List of CS3 telescope/CCD camera combinations.

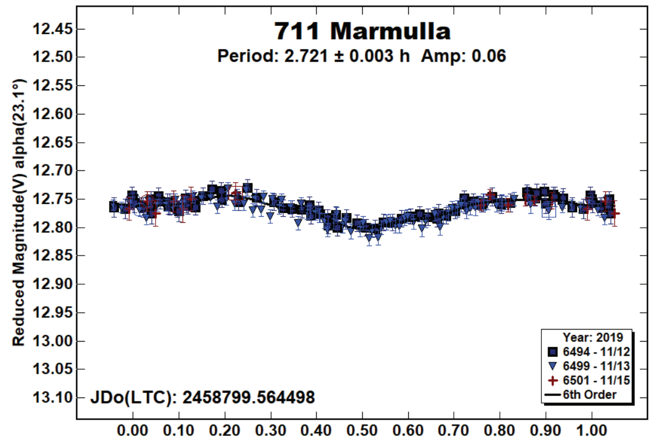
Image processing, measurement, and period analysis were done using *MPO Canopus* (Bdw Publishing), which incorporates the Fourier analysis algorithm (FALC) developed by Harris (Harris et al., 1989). The Comp Star Selector feature in *MPO Canopus* was used to limit the comparison stars to near solar color. Night-to-night calibration was done using field stars from the ATLAS catalog (Tonry et al., 2018), which has Sloan *griz* magnitudes that were derived from the GAIA and Pan-STARR catalogs, among others. The authors state that systematic errors are generally no larger than 0.005 mag, although they can reach 0.02 mag in small areas near the Galactic plane. BVRI magnitudes were derived by Warner using formulae from Kostov and Bonev (2017). The overall errors for the BVRI magnitudes, when combining those in the ATLAS catalog and the conversion formulae, are on the order of 0.04-0.05 mag.

In the lightcurve plots, the Y-axis may be labeled "Reduced Magnitude" or "Magnitude." Unless otherwise indicated, the values are Johnson V. The latter are sky (catalog-derived) magnitudes while "Reduced Magnitude" indicates that sky magnitudes were corrected to unity distances by applying –5*log (rΔ) to the measured sky magnitudes, with r and Δ being, respectively, the Sun-asteroid and the Earth-asteroid distances in AU. The magnitudes were normalized to the phase angle given in parentheses using $G = 0.15$. The X-axis rotational phase ranges from –0.05 to 1.05.

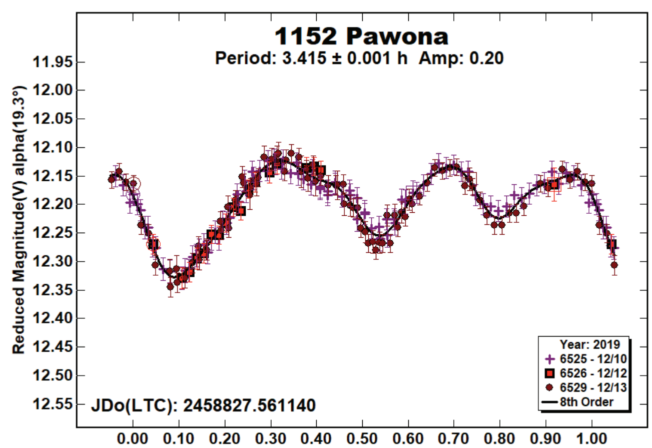
The amplitude indicated in the plots (e.g. Amp. 0.23) is the amplitude of the Fourier model curve and not necessarily the adopted amplitude of the lightcurve.

For brevity, only some of the previously reported rotational periods may be referenced. A complete list is available at the lightcurve database (LCDB; Warner et al., 2009).

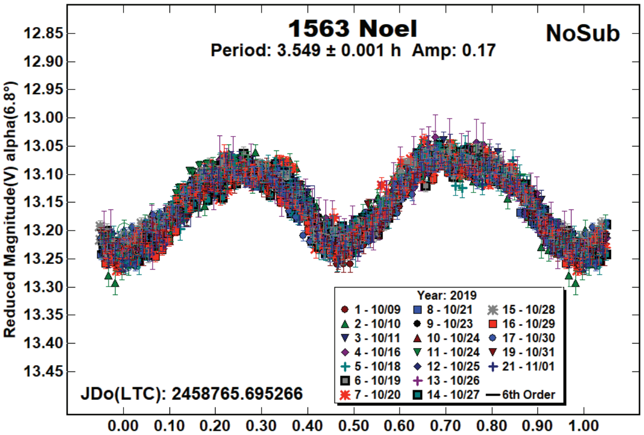
711 Marmulla. This member of the Flora family has had two reported rotational periods in the past. Kryszczyńska et al. (2012) reported a period of 2.88 h and Skiff et al. (2019) reported a period of 2.7216 h. Our result agrees with the Skiff period.

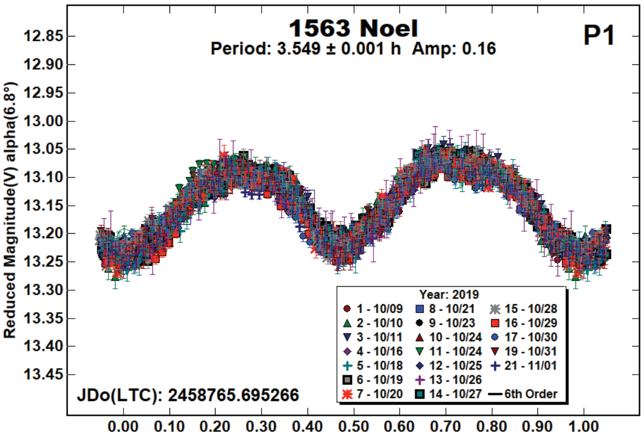


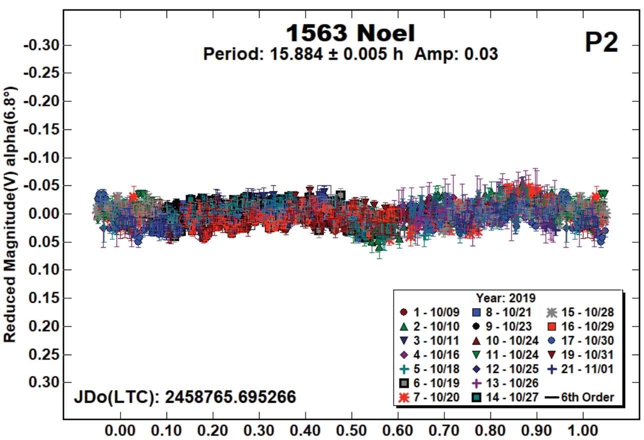
1152 Pawona. This Vestoid has been observed several times in the past. Koff and Clark (2002), Behrend (2019), Schmidt (2017), and Klinglesmith et al. (2017) all reported periods near 3.42 h. Our period agrees with those prior results.



1563 Noel. This member of the Flora family has been observed in 2008, 2013 and 2015 by the Photometric Survey for Asynchronous Binary Asteroids (Pravec 2019) as being a 'Prime Suspect' of being a binary asteroid. At each opposition the survey and individual members (Oey et al. 2017, Apostolovska et al. 2017) found rotational periods near 3.549 h. At the 2019 opposition, sings of a weak secondary period signal was detected (NoSub). Several values for that period, all commensurate with an Earth day, were found. The solution of 15.9 h best fit the data. With such a small amplitude, observations at stations at different longitudes have the best chance of confirming this suspected binary.

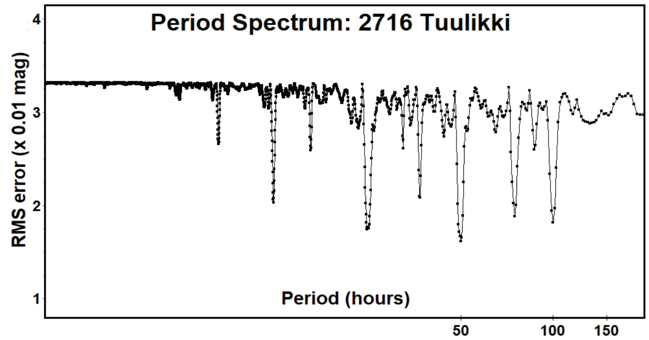


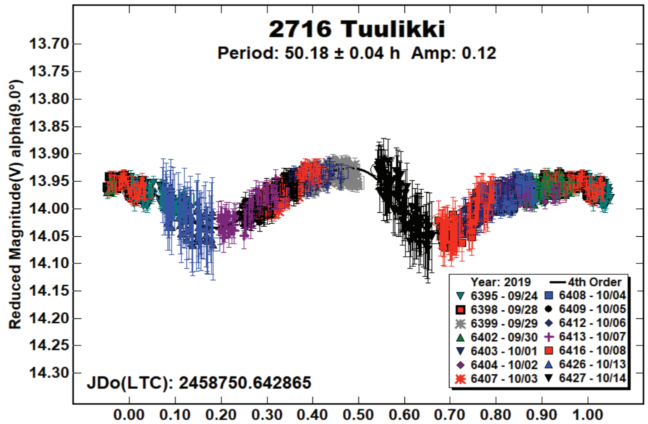




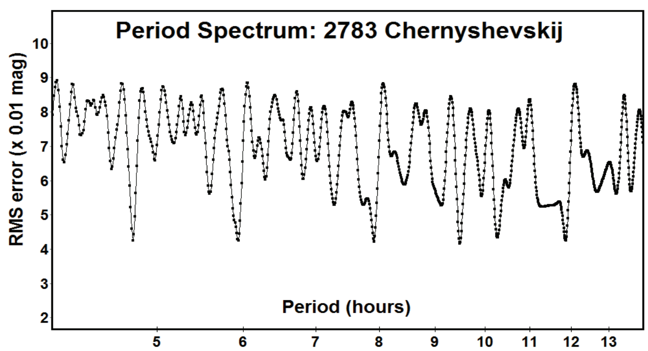
2716 Tuulikki. This appears to be the first reported lightcurve period for Tuulikki, which is a Vestoid member with an estimated diameter of 5.2 km. Per the period spectrum, the period with the best fit is nearly commensurate with two Earth days. This requires an extended observing campaign to construct a complete lightcurve.

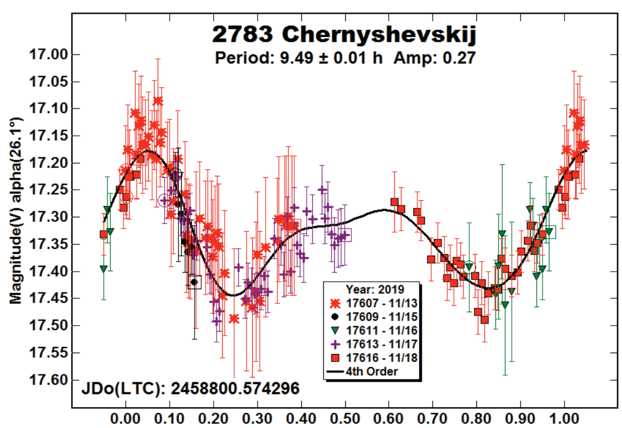
Other solutions created monomodal or trimodal lightcurves, which are possible due to the low amplitude (Harris et al., 2014), and cannot be formally excluded.



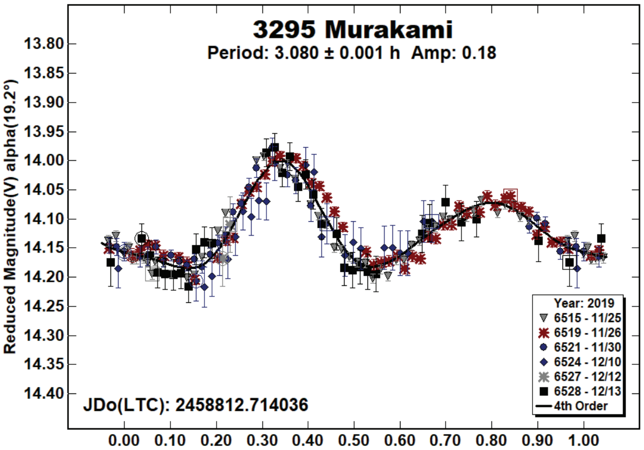


2783 Chernyshevskij. From observations obtained in 2011, Behrend (2019) reported a period of 9.455 h. Our data at the 2019 opposition was incomplete and noisy. They showed several possible periods of equal probability, including one near 12 h that is a 4:5 alias of the Behrend result. Given the high quality Behrend lightcurve, we have adopted the 9.49 h period is the probable correct period.

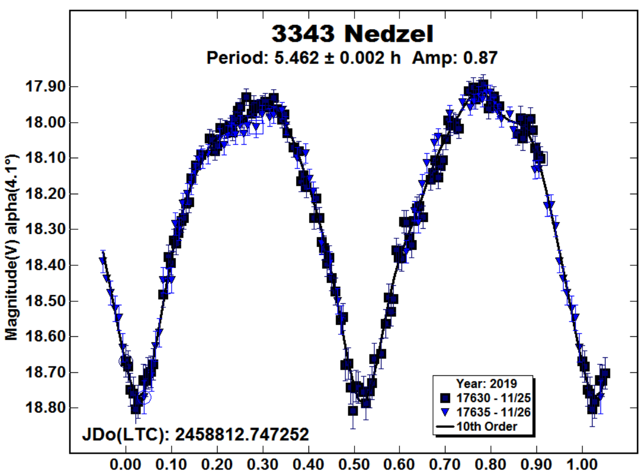




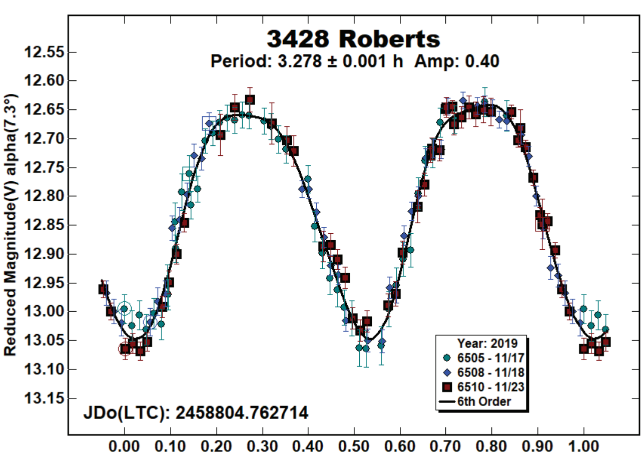
3295 Murakami. This is the first reported lightcurve period in the LCDB for this middle main-belt asteroid.



3343 Nedzel. We worked this Mars crosser twice in the past (Stephens 2018 and Warner 2018b), finding periods of 5.46 h. In addition, Folberth et al. (2012) found a period of 5.462 h. Using sparse data from the Lowell Observatory Database, Ďurech et al. (2018) found a sidereal period of 5.463570 h. Our solution is in good agreement.

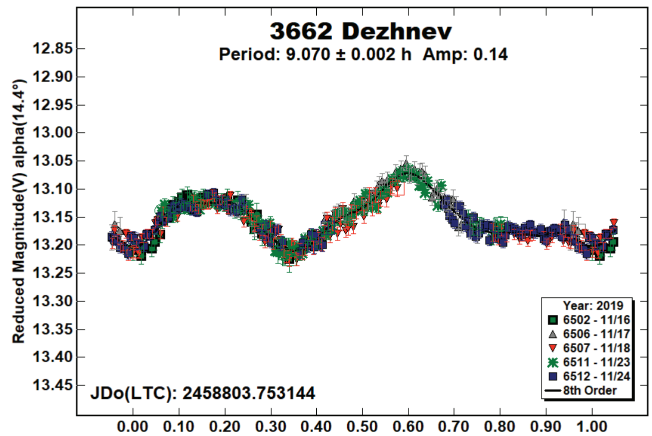


3428 Roberts. Oliver et al. (2008) observed this main-belt object and found a synodic rotational period of 3.278 h. Our period is in good agreement with those results.

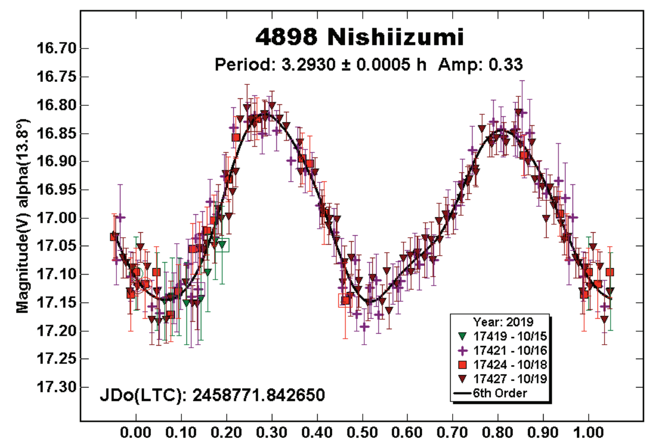


Hanuš et al. (2016), using only sparse data, found a pole solution with ecliptic coordinates of (λ, β) = (63°, +49°) and a sidereal period of 3.27835 h. They also found an alternate pole solution of (231°, +49°). Our observations were done to provide a dense data set to help improve the pole in future modeling.

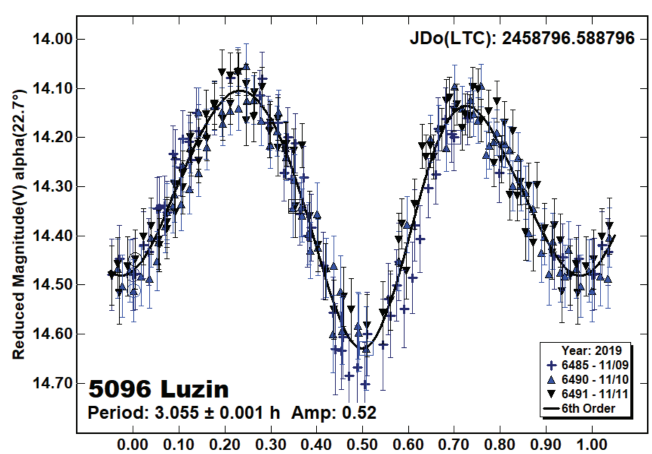
3662 Dezhnev. There were no previous entries in the LCDB for this 9.4 km member of the Eunomia group/family.



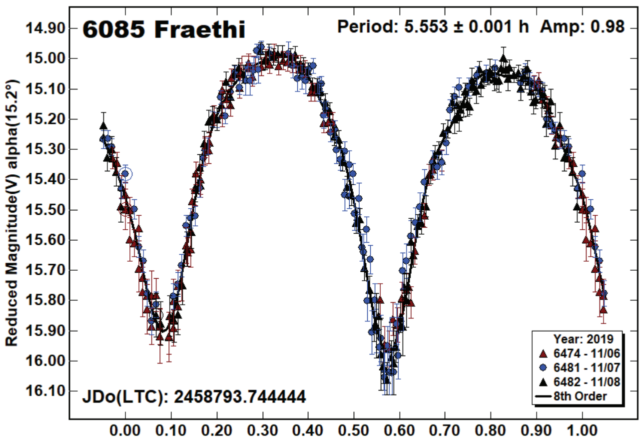
4898 Nishiizumi. Previous results for this 2 km Hungaria (Warner 2007; 2012; 2015; 2018a) were close to our result of 3.2930 h.



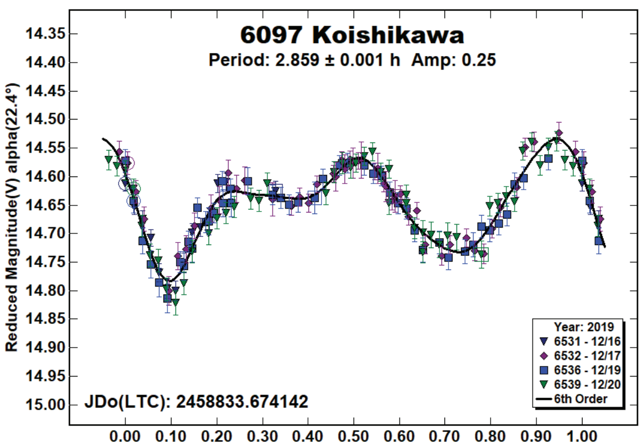
5096 Luzin. Klinglesmith et al. (2013) observed this Vestoid in 2012 and determined the rotational period to be 3.054 h. Our result is in good agreement with their period.



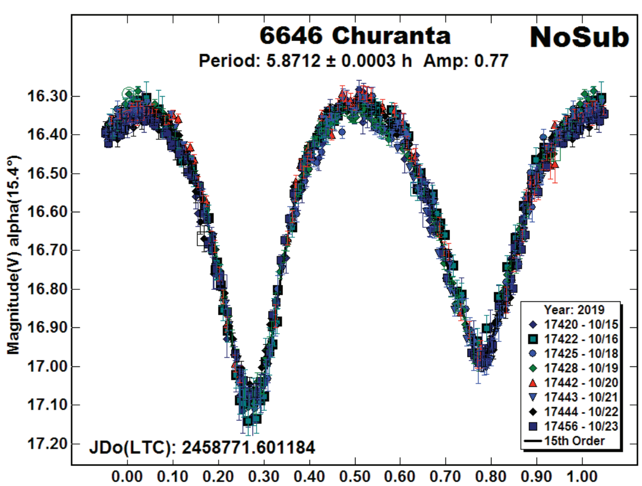
6085 Fraethi. We found a period of 5.556 h in 2015 (Stephens 2016). The 2019 result agrees with that prior result.

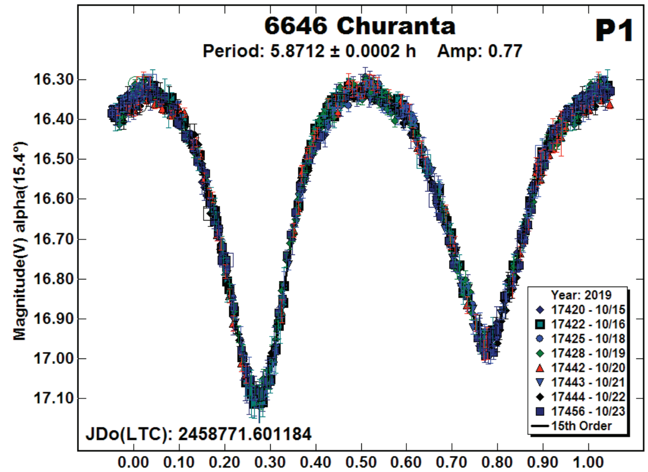


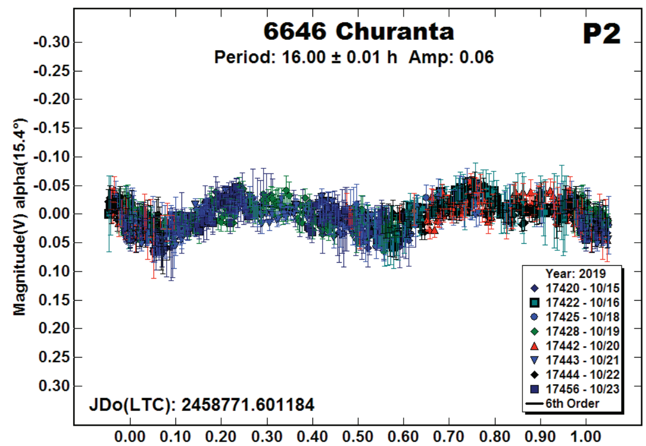
6097 Koishikawa. This member of the Flora group/family was observed in 2010 and 2017 by the Photometric Survey for Asynchronous Binary Asteroids (Pravec, 2019; Oey and Groom 2019). Both groups reported P = 2.8598 h. Our result is in good agreement.



6646 Churanta. We worked this Hungaria three times in the past (Warner 2007, 2012, 2015), each time finding a rotational period of 5.87 h. Since the amplitude at all four oppositions is consistent, the spin axis must be close to one of the ecliptic poles. During the 2019 apparition, slight deviations in the lightcurve suggested a secondary period (NoSub).

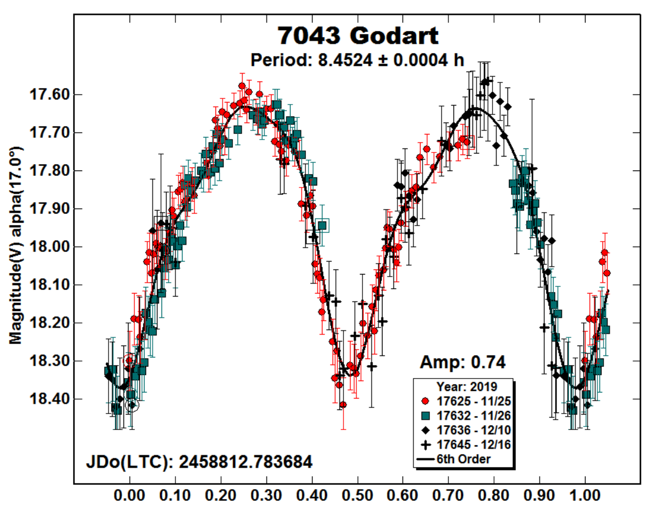






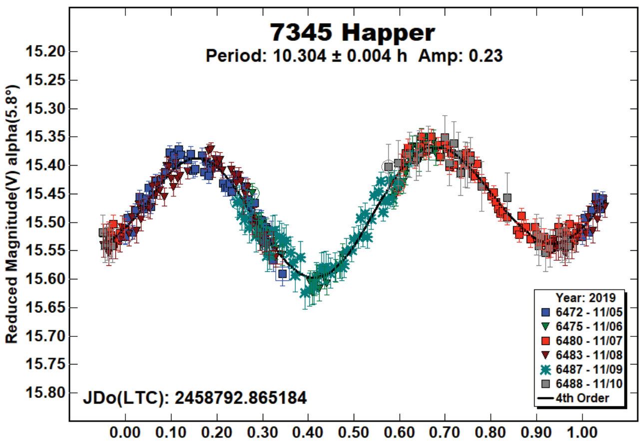
We did a dual-period search and found a secondary period of 16.00 h with no mutual events (P2). We are concerned that the P2 is exactly 2/3 day, so that the two nearly symmetrical halves alternate each night, but there is *almost* enough asymmetry in the P2 curve to overcome these doubts. The next opportunity for northern observers is 2023 February.

7043 Godart. This member of the Flora group/family has been well studied in the past as part of the Photometric Survey for Asynchronous Binary Asteroids (Pravec et al. 2019) and by Waszczak et al. (2005).

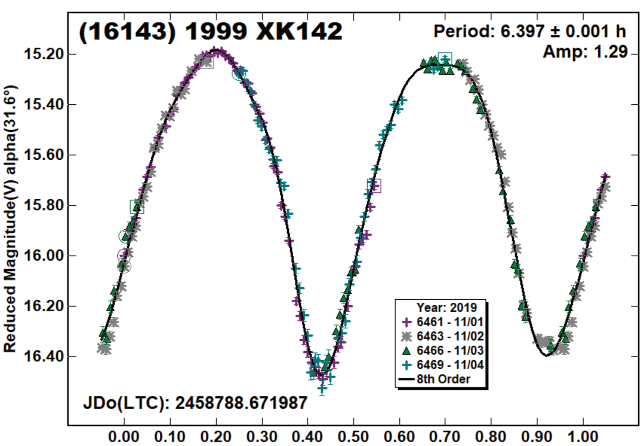


Both groups reported periods near 8.45 h. Our solution is in good agreement. Hanuš et al. (2013) reported ecliptic coordinates (λ,β,$P_{SIDERAL}$) = (73°, +62°, 8.4518 h) and a weaker, competing solution of (235°, 80°, 8.4518 h).

7345 Happer. No records were found in the LCDB for this Mars crosser, so this is another new discovery of an asteroid rotational period.



(16143) 1999 XK142. Per the LCDB, this Mars crosser has been observed twice by the Palomar Transient Factor survey (Waszczak et al. 2015; Chang et al. 2015). We also observed it in 2016 (Stephens 2016). Each time, a period near 6.4 h was found. Our result is in agreement with the periods in those prior works.



The Waszczak data were available on the ALCDEF asteroid photometry database (*http://www.alcdef.org/*), so we attempted a pole and shape model.

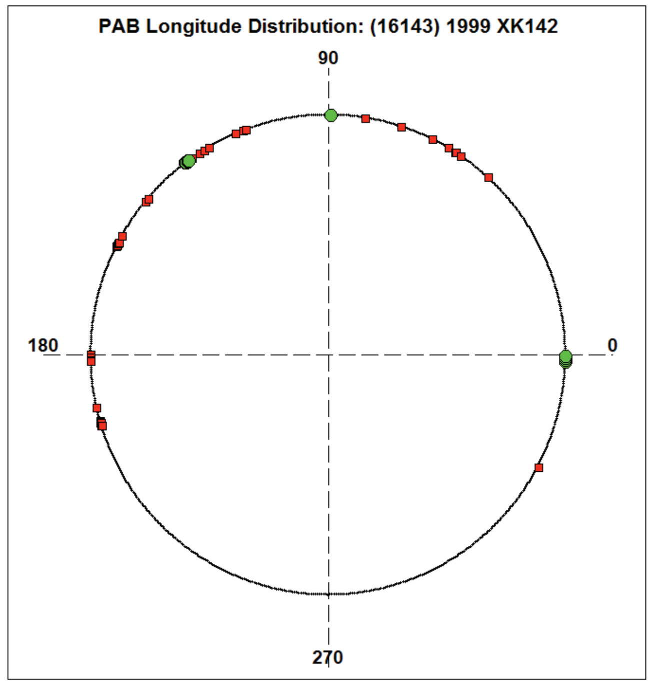
Sparse data observations were obtained from the Catalina Sky Survey and USNO-Flagstaff survey using the AstDyS-3 site (*https://newton.spacedys.com/astdys/*). These sparse data were combined with our dense data using *MPO LCInvert*, (Bdw Publishing). This Windows-based program incorporates the algorithms developed by Kassalainen et al. (2001a, 2001b) and converted by Josef Ďurech from the original FORTRAN to C. A period search was made over a sufficiently wide range to assure finding a global minimum in χ^2 values.

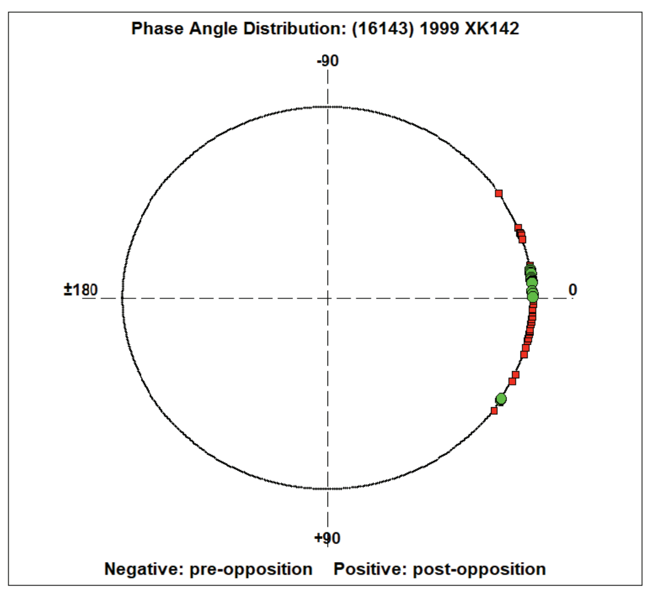
The modeling processing using lightcurve inversion has been detailed previously (e.g., Warner 2017, and references therein). The idea is to find a shape and its orientation such that its modeled lightcurves closely match the original data. Main-belt asteroids usually require data from at least three oppositions at different phase angle bisector longitudes before a reliable model can be developed.

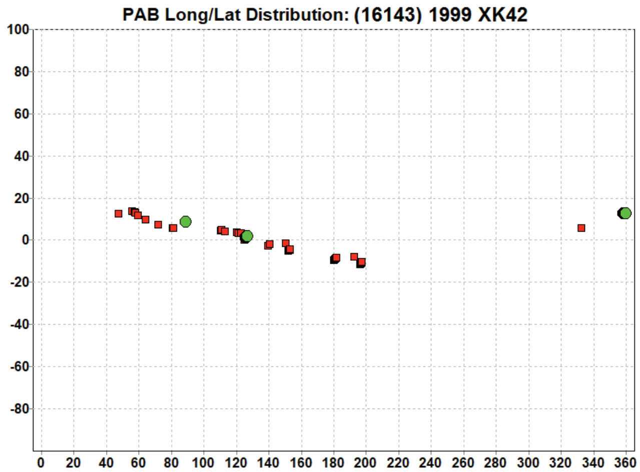
In the PAB longitude plot, green circles represent dense lightcurves while red squares represent sparse data from one or more of the surveys. The green line in the period plot lies 10% above the lowest χ^2 value. This was an ideal solution since it has a well-defined shape with only one data point below the line.

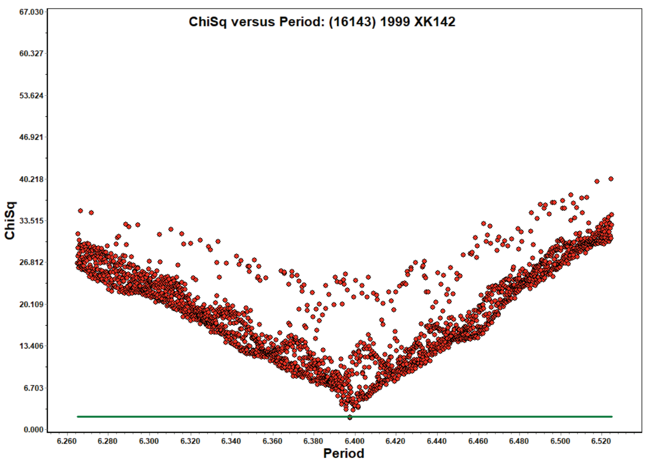
855 Newcombia	Eclipitic Long/Lat	Sidereal Period (hours)
Preferred	(197°, -91°)	6.397446 ± 0.000001
Alternate	(17°, -89°)	

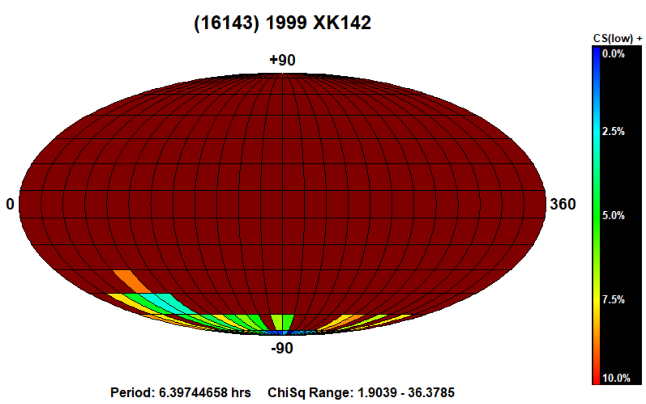
Table II. The two pole solutions for (1643) 1999 XK142. It is common in lightcurve inversion to get two solutions that differ by about 180° in longitude.







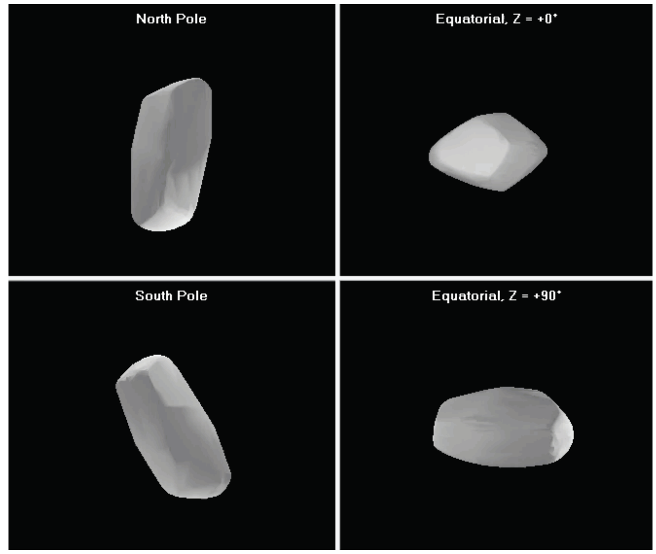


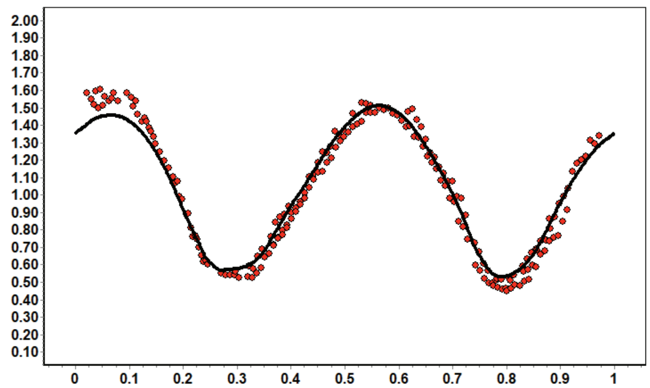


In the pole plot, dark red represents a solution that is more than 10% above the lowest χ^2 value. A "perfect" solution is when there is only one dark blue region and all the others are dark red. The result of our search was (λ, β, P) = (17°, –89°, 6.397446 h), which indicates that the asteroid is in retrograde rotation. The estimated error in the pole position is a circle with radius of 10° and 1-2 units in the last decimal place of the period.

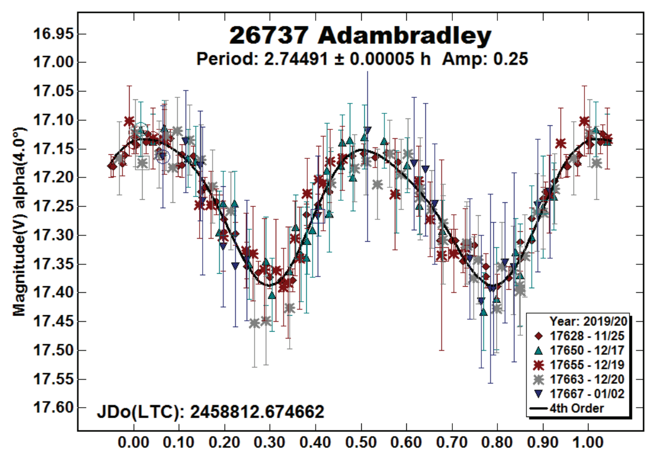
When the spin axis pole is |β| ~ 90°, the longitude becomes almost meaningless since even a small shift in the pole direction can put the longitude 0° ≤ λ < 360°.

To check the quality of the solution, the original data (red dots) are plotted against the model (black line) for a given date. This particular comparison shows that the model is close but needs further refinement, i.e., more data!





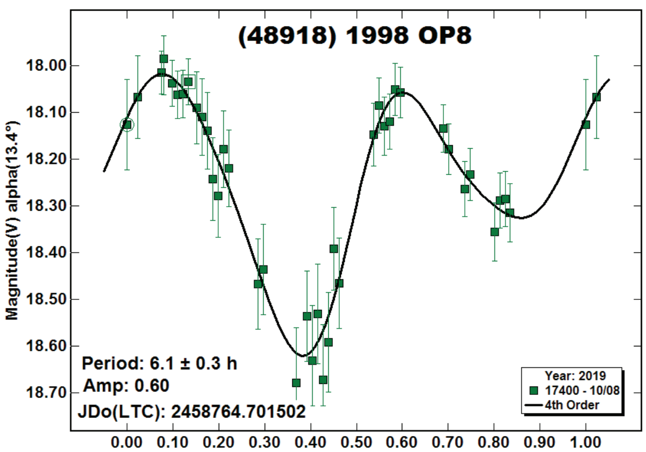
26737 Adambradley, (48918) 1998 OP8. There was no rotation period posted in the LCDB for either of these two presumptive members of the Baptistina family.



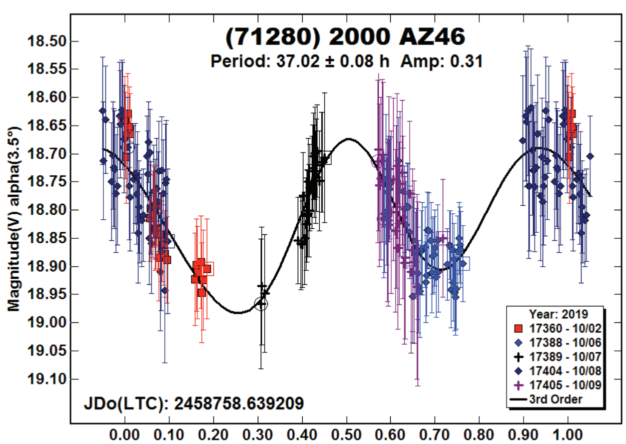
Mainzer et al. (2016) used WISE data to find a diameter and albedo for both asteroids. For 26737, they used H = 14.50 to derive D = 3.643 ± 0.363 km and p_V = 0.211 ± 0.037. The values for 48918 when using H = 14.70 were D = 2.674 ± 0.126 km and p_V = 0.326 ± 0.043. Generally, Baptistina members have an albedo around p_V = 0.057 (Warner et al., 2009), making these two asteroids somewhat on the bright side. Spectroscopic observations or detailed orbital analysis will be needed to confirm Baptistina family membership.

Number	Name	2019 mm/dd	Phase	L_{PAB}	B_{PAB}	Period(h)	P.E.	Amp	A.E.	Grp
711	Marmulla	11/12-11/15	23.1,23.8	6	3	2.721	0.003	0.06	0.01	FLOR
1152	Pawona	12/10-12/13	19.3,20.0	30	6	3.415	0.001	0.20	0.02	V
1563	Noel	10/09-11/01	*6.8,6.0	28	-4	3.549	0.001	0.16	0.01	FLOR
						15.884	0.005	0.03	0.01	
2716	Tuulikki	09/24-10/14	9.0,17.8	348	6	50.18	0.04	0.12	0.02	V
2783	Chernyshevskij	11/13-11/24	26.1,27.1	352	0	9.49	0.01	0.27	0.03	MB-I
3295	Murakami	11/25-12/13	19.2,24.4	33	-10	3.080	0.001	0.18	0.02	MB-M
3343	Nedzel	11/25-11/26	4.1,4.3	60	10	5.462	0.002	0.87	0.03	MC
3428	Roberts	11/17-11/23	7.3,9.5	36	2	3.278	0.001	0.40	0.02	MB-M
3662	Dezhnev	11/16-11/24	14.4,16.9	26	12	9.070	0.002	0.14	0.01	MB-M
4898	Nishiizumi	10/15-10/19	13.8,15.8	359	1	3.2930	0.0005	0.33	0.02	H
5096	Luzin	12/31-12/31	*13.8,15.8	0	0	3.055	0.001	0.52	0.03	V
6085	Fraethi	11/06-11/08	15.2,14.3	71	-6	5.553	0.001	0.98	0.02	FLOR
6097	Koishikawa	12/16-12/20	22.4,23.5	41	-4	2.859	0.001	0.25	0.02	V
6646	Churanta	10/15-10/23	*15.4,15.4	29	21	5.8712	0.0002	0.77	0.01	H
						16.00	0.01	0.06	0.01	
7043	Godart	12/31-12/31	*15.4,15.4	0	0	8.4524	0.0004	0.74	0.05	FLOR
7345	Happer	11/05-11/10	5.9,2.7	50	-2	10.304	0.004	0.23	0.02	MC
16143	1999 XK142	11/01-11/04	31.6,32.1	359	13	6.397	0.001	1.29	0.01	MC
26737	Adambradley	11/25-01/02	4.0,20.6	58	1	2.74491	0.00005	0.25	0.03	BAP
48918	1998 OP8	12/31-12/31	*31.6,32.1	0	0	6.1	0.3	0.60	0.05	BAP
71280	2000 AZ46	10/02-10/09	*3.5,3.4	13	8	37.02	0.08	0.31	0.04	MB-O
100935	1998 MA42	10/02-10/26	*8.1,13.9	14	8	411	1	0.85	0.10	MC

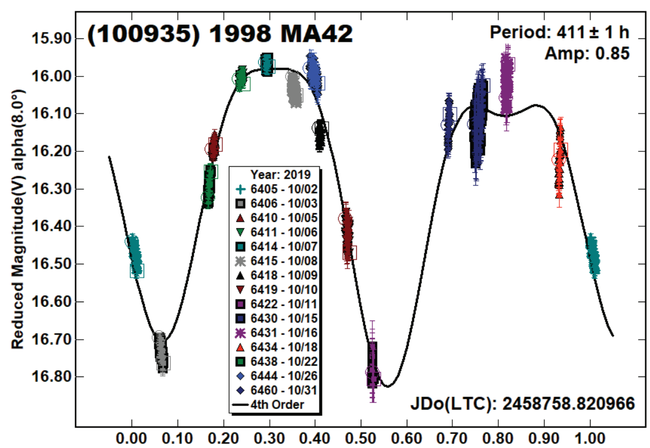
Table III. Observing circumstances and results. The phase angle is given for the first and last date. If preceded by an asterisk, the phase angle reached an extrema during the period. L_{PAB} and B_{PAB} are the approximate phase angle bisector longitude/latitude at mid-date range (see Harris et al., 1984). Grp is the asteroid family/group (Warner et al., 2009). For a binary, the first line gives the rotation period of the primary and the second line gives the orbital period of the satellite.



(71280) 2000 AZ46. There were no previously reported periods in the LCDB for this outer main-belt member to guide the analysis of the 2019 data. Despite the noise in the data, the amplitude of 0.31 mag, the repeating coverage on four nights, and covering a minima and maxima gives some confidence to the solution.



(100935) 1998 MA42. Given the long rotational period, it is not surprising that there are no previously reported lightcurves in the LCDB for this Mars crosser. After nearly a month of observations, there was sufficient double coverage of the lightcurve to have confidence in the primary rotational period, which is longer than the period where tumbling would be more likely than not (Pravec et al., 2005). This seems to be confirmed by several nights showing obvious signs of not matching the Fourier curve.



Acknowledgements

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LIGHTCURVES AND ROTATION PERIODS OF 10 HYGIEA, 47 AGLAJA, 455 BRUCHSALIA, 463 LOLA, AND 576 EMANUELA

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Synodic rotation periods and amplitudes are found for 10 Hygiea 13.828 ± 0.001 h, 0.23 ± 0.01 magnitudes with one maximum and minimum per rotational cycle; 47 Aglaja 13.173 ± 0.001 h, 0.21 ± 0.02 magnitudes; 455 Bruchsalia 11.839 ± 0.001 h, 0.50 ± 0.03 magnitudes; 463 Lola 6.2071 ± 0.0001 h, maximum amplitude 0.50 ± 0.03 magnitudes; 576 Emanuela 20.372 ± 0.001 h, 0.12 ± 0.01 magnitudes.

Observations to produce the results reported in this paper were made at the Organ Mesa Observatory with a Meade 35 cm LX200 GPS Schmidt-Cassegrain, SBIG STL-1001E CCD, unguided. For the bright targets 10 Hygiea and 47 Aglaja exposure times were 30 seconds with R filter for 10 Hygiea and clear filter for 47 Aglaja. For all other targets reported here images were obtained with 60 second exposure times, clear filter. To reduce the number of data points on the lightcurves and make them easier to read, data points have been binned in sets of 3 with maximum time difference 5 minutes.

10 Hygiea. The Lightcurve Data Base (Warner et al. 2009, updated 2019 August) lists 8 previously published rotation periods with supporting lightcurves for 10 Hygiea. Five of the periods are near 27.630 hours, with amplitudes between 0.09 and 0.33 magnitudes, based on lightcurves showing the usual two maxima and minima per rotational cycle. This value was considered reliable for many years. Vernazza et al. (2019) obtained disk resolved images of 10 Hygiea in 2017 and 2018 with the SPHERE (Spectro-Polarimetric High contrast Exoplanet Research) instrument on the 8 meter VLT at the European Southern Observatory. These images reveal Hygiea to be very nearly spherical with hemispheric albedo variegation. There is only one maximum and minimum per rotational cycle, and a sidereal period of 13.82559 hours is included in the publication. New photometric observations on 6 nights 2019 Nov. 26 – Dec. 17 provide a good fit to a lightcurve with synodic period 13.828 ± 0.001 hours, amplitude 0.23 magnitudes, with one maximum and minimum per rotational cycle. This is compatible with the period by Vernazza et al. The split halves plot to the double period of 27.652 hours shows that the two halves are almost identical and confirms by a different observational technique the shorter period.

Number	Name	yyyy/mm/dd	Phase	LPAB	BPAB	Period(h)	P.E	Amp	A.E.
10	Hygiea	2019/11/26-2019/12/17	1.0, 6.9	63	3	13.828	0.001	0.23	0.01
47	Aglaja	2019/11/17-2019/12/02	6.0, 2.3	68	5	13.173	0.001	0.21	0.02
455	Bruchsalia	2019/12/11-2020/01/08	17.2, 14.3	156	12	11.839	0.001	0.50	0.03
463	Lola	2019/10/08-2019/11/24	24.1, 5.3	58	5	6.2071	0.0001	0.50	0.03
576	Emanuela	2019/09/25-2019/11/06	16.5, 5.5	42	13	20.372	0.001	0.12	0.01

Table I. Observing circumstances and results. Pts is the number of data points. The phase angle is given for the first and last date, unless a minimum (second value) was reached. LPAB and BPAB are the approximate phase angle bisector longitude and latitude at mid-date range (see Harris *et al.*, 1984).