

MAIN-BELT ASTEROIDS OBSERVED FROM CS3: 2020 APRIL TO JUNE

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CCD photometric observations of 18 main-belt asteroids were obtained at the Center for Solar System Studies (CS3) from 2020 April to June.

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 and are “native” magnitudes of the catalog.

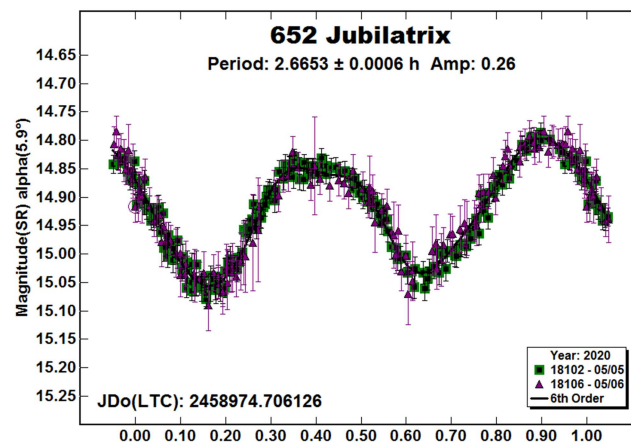
We used the ATLAS r' (SR) magnitudes. Those adjustments are mostly ≤ 0.03 mag. The occasions where larger corrections were required may have been related in part to using unfiltered observations, poor centroiding of the reference stars, and not correcting for second-order extinction terms.

The magnitudes were normalized to the comparison stars used in the earliest session and to the phase angle given in parentheses using $G = 0.15$. In other words, the data were made to seem that they were all obtained at the same time using the same comparison stars. The X-axis rotational phase ranges from -0.05 to 1.05 .

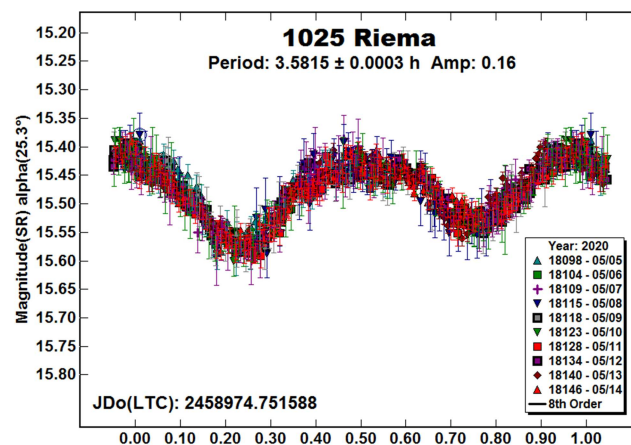
The amplitude indicated in the plots (e.g. Amp. 0.23) is the amplitude of the Fourier model curve and not necessarily the adopted amplitude of the lightcurve.

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

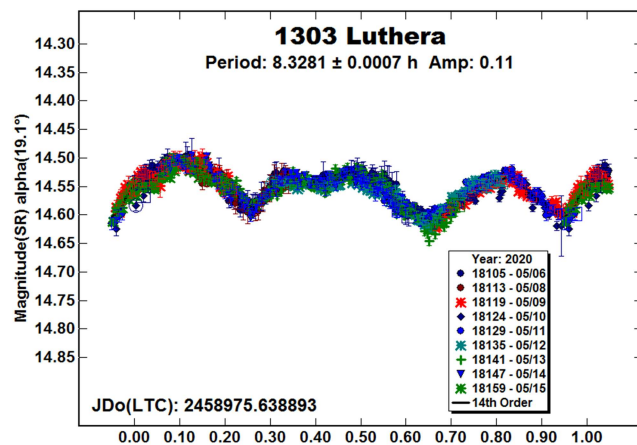
652 Jubilatrix. This member of the Eunomia group or family was undertaken as a ‘Full moon’ project to keep the telescopes observing when dimmer targets could not be observed. It was previously observed by Pilcher (2010) and Behrend (2015web, 2020web) who reported periods near 2.66 h. Kim et al. (2014) reported a spin axis model with $(\lambda, \beta) = (143^\circ, 34^\circ)$ or $(321^\circ, 27^\circ)$ and a sidereal period of 2.6626693 h.



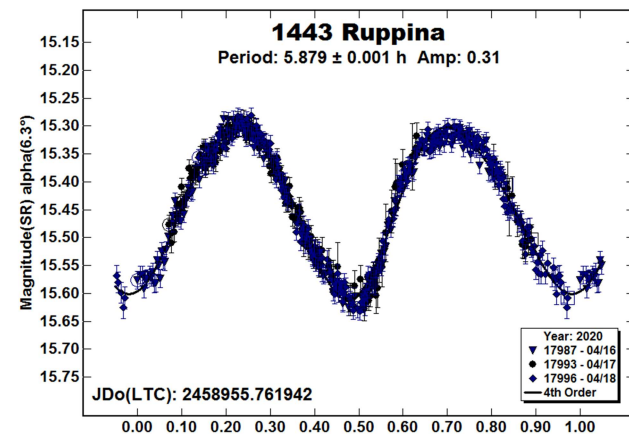
1025 Riema. We observed this Hungaria family or group member six times in the past (Warner, 2017 and references therein), each time finding a rotational period near 3.58 h. In the 2020 data we found evidence of a weak second period near 42 h. The mutual events, if real, were no more than 0.06 mag. deep. To verify the existence of a second period warrants high-quality observations by a collaboration of observers at different longitudes at future apparitions.



1303 Luthera. This outer main-belt asteroid has been observed several times in the past with a range of results. Sada (2008) found 5.878 h while Behrend (2009web, 2020web) found 7.92 h and 8.3246 h respectively. The 2020 Behrend observations were obtained five weeks prior to ours with essentially the same result.



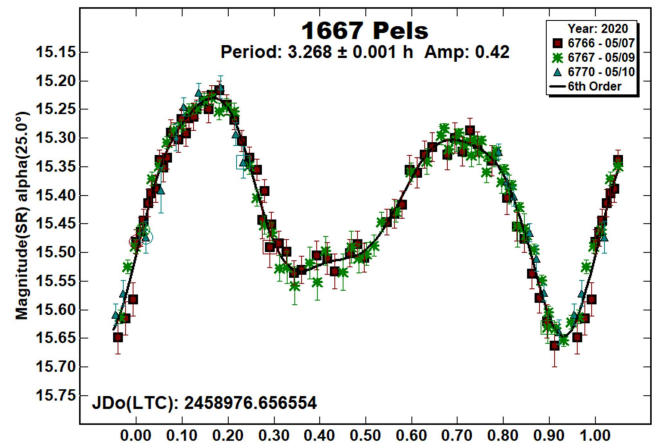
1443 Ruppina. This outer main-belt asteroid was observed many times in the past. Using sparse data from the Palomar Transient Factory Survey, Chang et al. (2015) and Wazczek et al. (2015) both found periods near 5.9 h. We found a period from our 2017 data near 5.88 h (Stephens, 2018). All of these periods are in good agreement with this year's result.



Because of the availability of the Chang and Wazczek data in the Asteroid Lightcurve Data Exchange Format database (ALCDEF, 2020), sparse data at the Asteroids – Dynamic web site (AstDyS-2, 2020), and our dense data from two apparitions, we attempted to solve for the sidereal period and pole position and create a shape model. This data was combined using *MPO LCInvert* (Bdw Publishing). This Windows-based program incorporates the algorithms developed by Kaasalainen and Torppa (2001) and Kaasalainen et al (2001) and converted by Josef Durech 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.

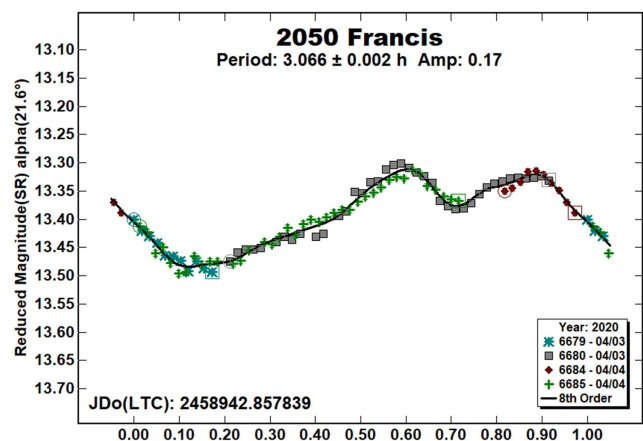
As is often the case, the pole model showed a number of possible solutions with two probable solutions 180° apart; $(\lambda, \beta, P) = (120^\circ, -15^\circ, 5.879288 \text{ h})$ and $(295^\circ, -22^\circ, 5.879290 \text{ h})$. Our preferred solution is $(120^\circ, -15^\circ)$.

1667 Pels. This inner main-belt asteroid has been observed several times in the past (Behrend, 2020web; Kryszczyńska, 2012; Stephens and Warner, 2019b) each time finding a period near 3.26 h. This year's result is in good agreement with those prior findings.



Because of the availability of sparse data and our dense data from two oppositions, we attempted a pole/shape model. A sidereal period of 3.268280 h stood out above all other possibilities. Since all of the possible pole solutions are in the southern hemisphere, the object is clearly rotating retrograde. Two probable pole positions are $(\lambda, \beta, P) = (182^\circ, -53^\circ, 3.268280 \text{ h})$ and $(16^\circ, -63^\circ, 3.268280 \text{ h})$, which are about 180° apart. Our preferred solution is $(182^\circ, -53^\circ)$.

2050 Francis. This member of the Phocaea family/group was observed by Franco et al. (2013), who found a rotational period of 3.069 h. Behrend (2020web) reported a period of 6.136 h with four extrema and twice the period reported by Franco et al. Our data in 2020, obtained a week after the Behrend data, resulted in a period which is a good fit with the Franco result.



SPIN/SHAPE MODEL FOR 1443 Ruppina

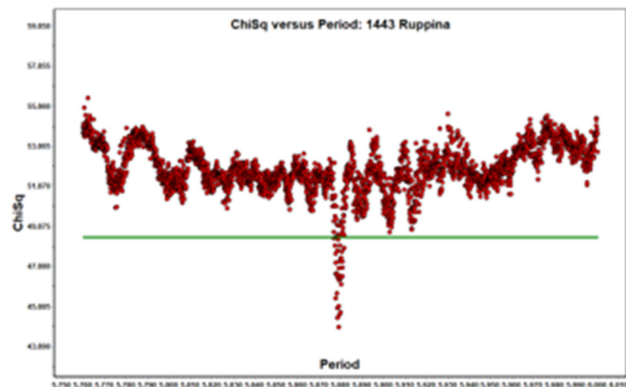


Figure 1. The initial period search results.

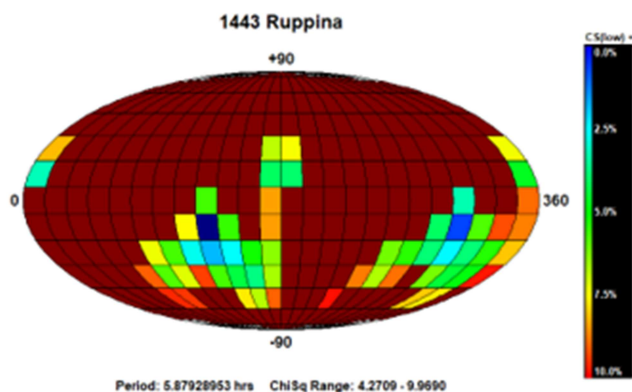


Figure 2. In this pole plot, dark red represents a solution that is more than 10% above the lowest χ^2 value. The pole search found two probable solutions.

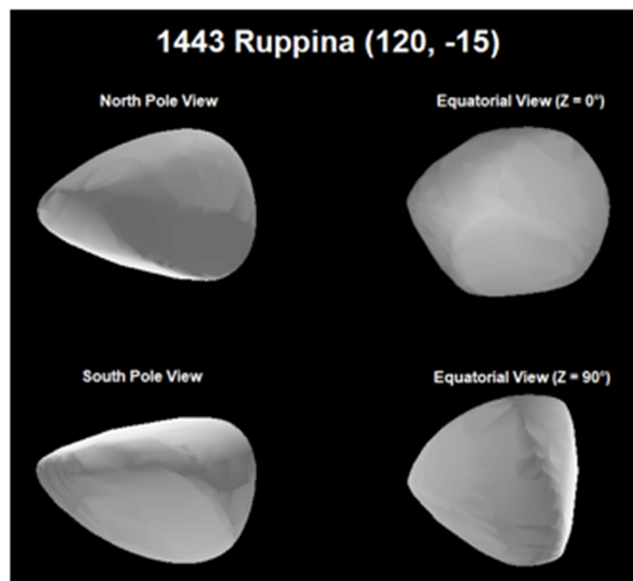


Figure 3. The shape of the asteroid based on the preferred solution.

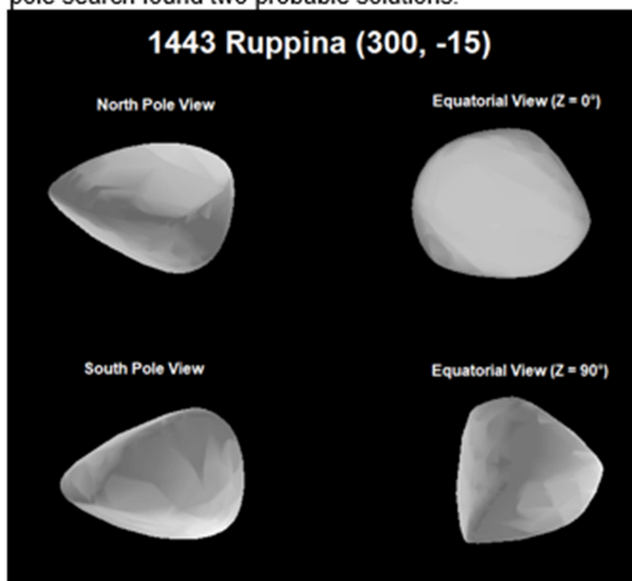


Figure 4. The shape of the asteroid based on the secondary solution.

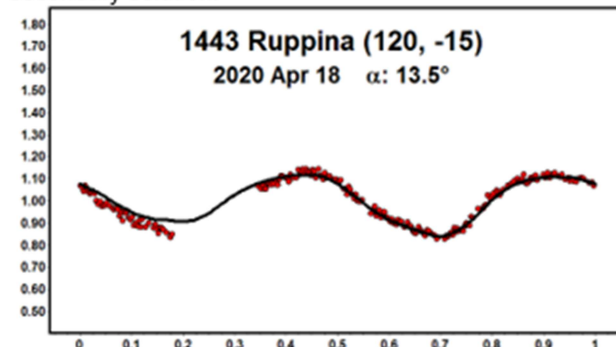
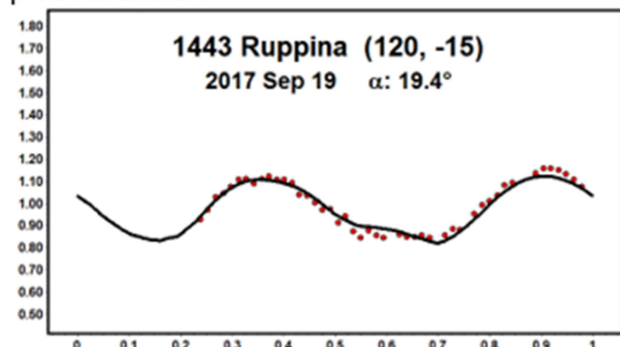


Figure 5/6. The comparison plots against the preferred pole solution for the 2017 and 2020 data. The red dots indicate the data used for modeling while the black line is the smoothed lightcurve for generated by the shape at the time of the observations. The match is very close on all occasions, which gives confidence in the shape/spin axis model.

SPIN/SHAPE MODEL FOR 1667 PELS

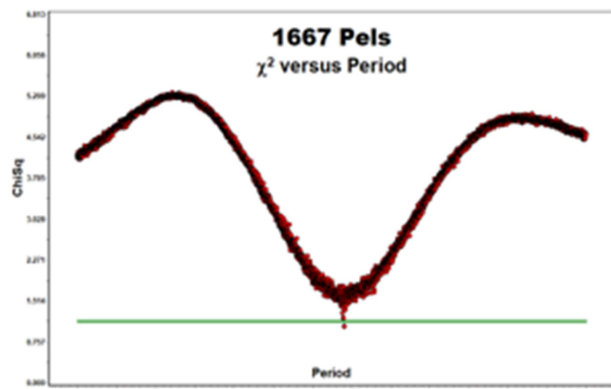


Figure 1. The initial period search results.

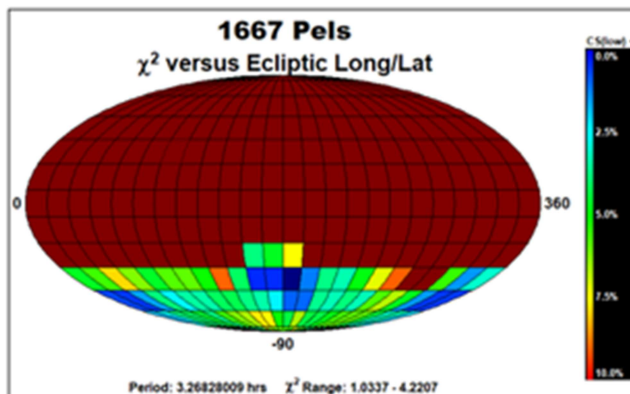


Figure 2. The pole search found two probable solutions.

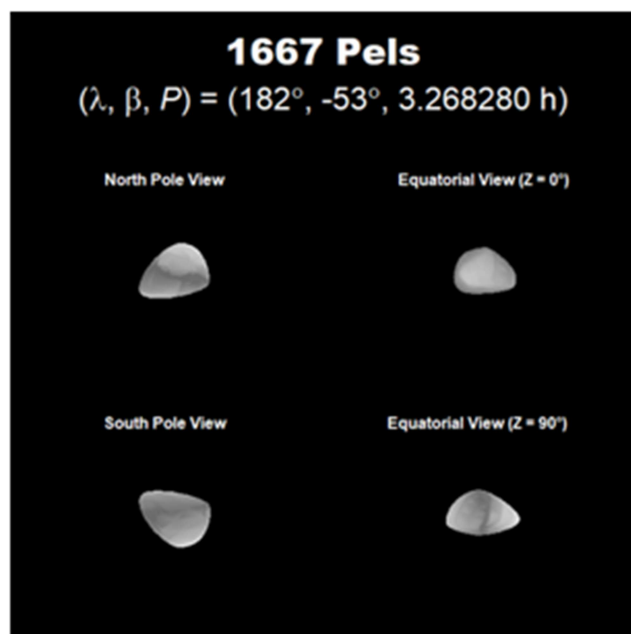


Figure 3. The shape of the asteroid based on the preferred solution.

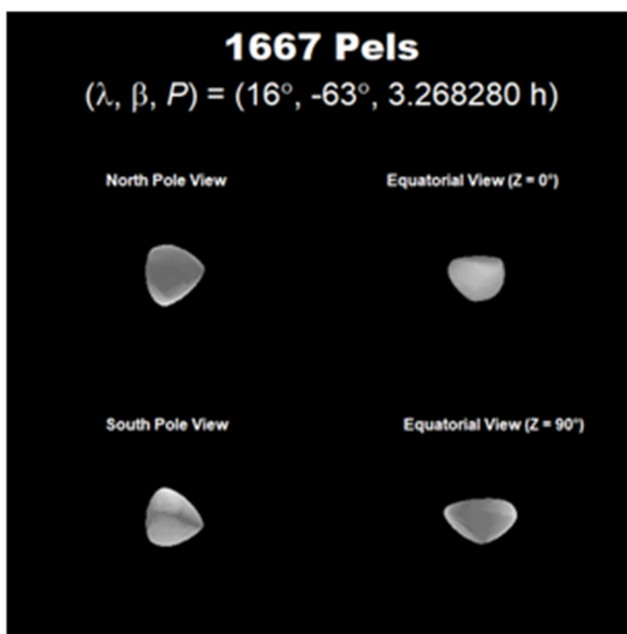


Figure 4. The shape of the asteroid based upon the secondary solution.

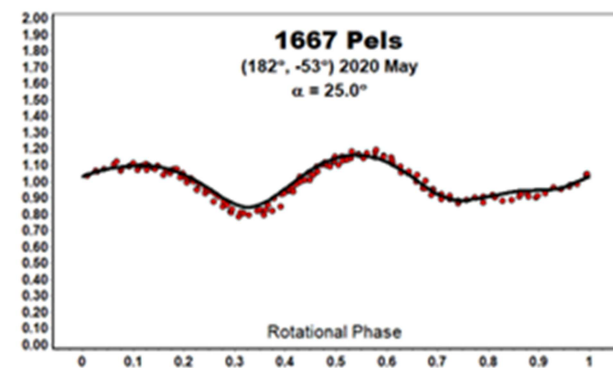
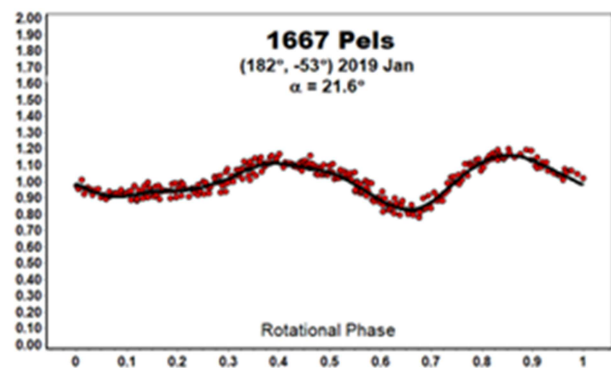
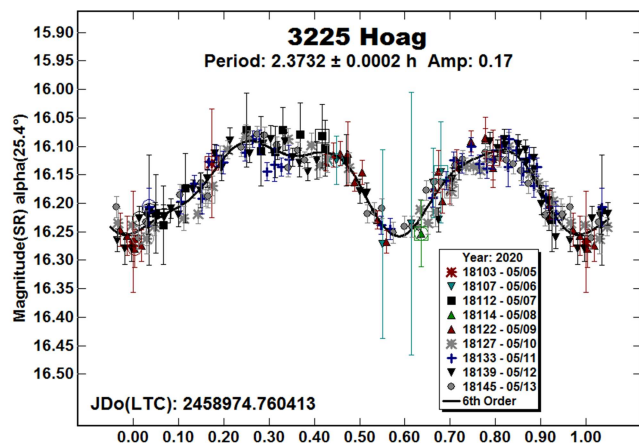
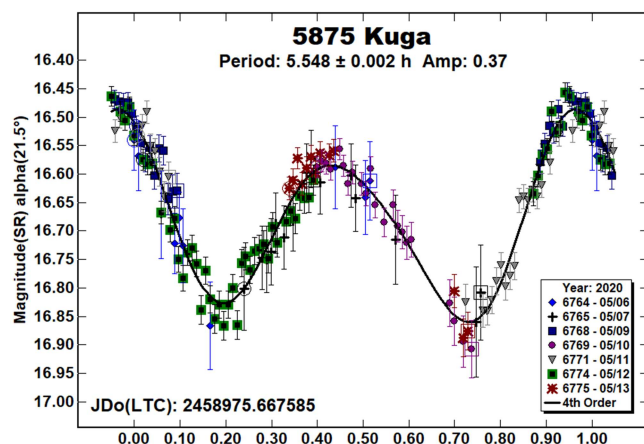


Figure 5/6. The comparison plots are against the preferred pole solution. The red dots indicate the data used for modeling while the black line is the smoothed lightcurve for generated by the shape at the time of the observations. The match is very close on both occasions, which gives confidence in the shape/spin axis model.

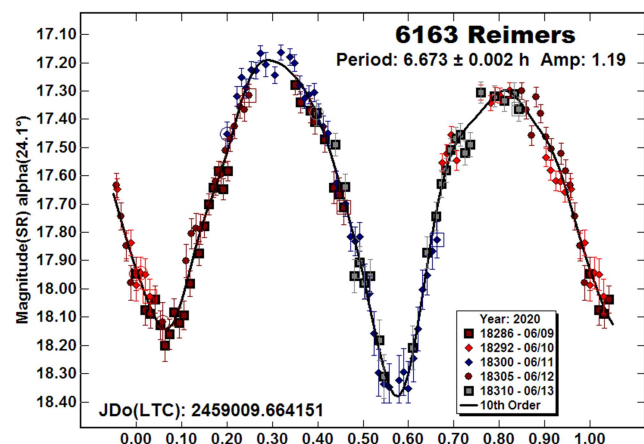
3225 Hoag. We have observed this member of the Hungaria family/group many times in the past (Stephens and Warner, 2019a and references therein), each time finding a rotational period near 2.37 h. We undertook observations this year to improve upon a preliminary pole solution.



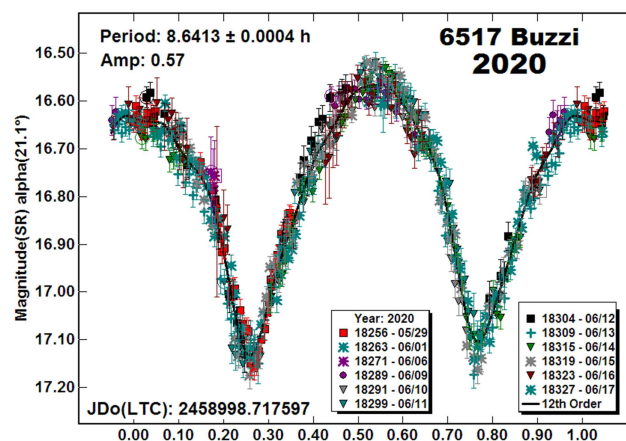
5875 Kuga. Carbo et al. (2009) observed this 9-km Vestoid finding a rotational period of 5.551 h. Using data from 2015 and 2016, Oszkiewicz et al. (2017) found rotational periods near 5.55 h. Our result from this year is in good agreement.



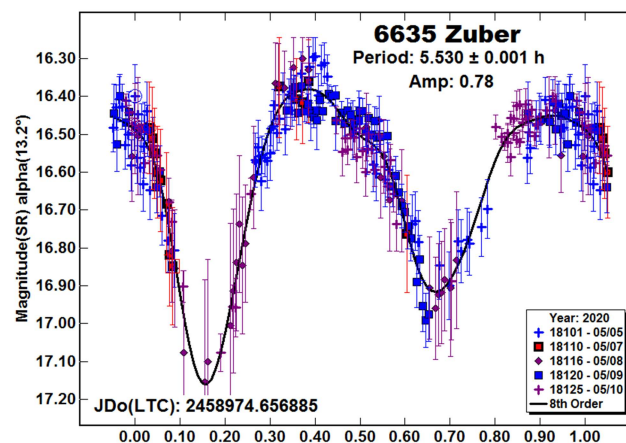
6163 Reimers. There are two reported periods in the LCDB for this member of the Hungaria family/group (Warner, 2011, 6.68 h; Waszczak et al., 2015, 6.686 h). The analysis of our data in 2020 is in good agreement with those previous results.



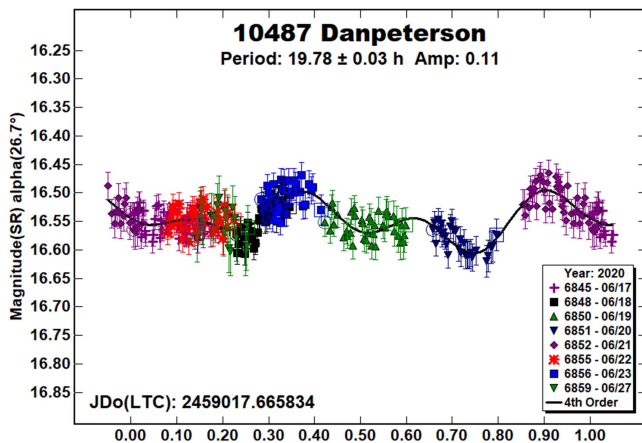
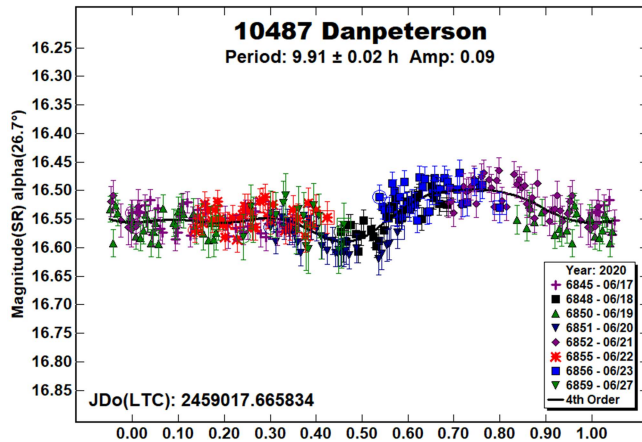
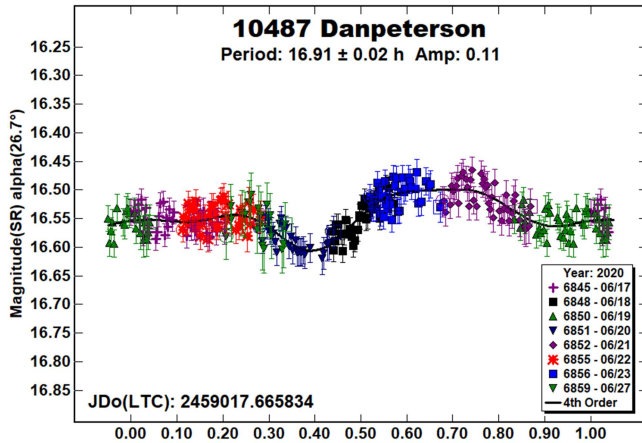
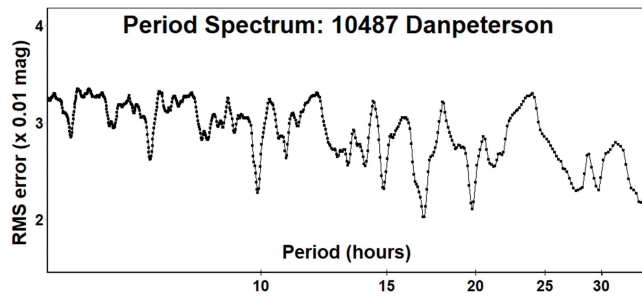
6517 Buzzi. We observed this member of the Hungaria family/group four times in the past (Warner 2014 and references therein) each time finding periods near 8.64 h. This year's result is in good agreement with those prior findings and provides additional data for a pole solution. Hanuš et al. (2016) found a pole solution $(\lambda, \beta, P) = (227^\circ, -75^\circ, 8.64468 \text{ h})$.



6635 Zuber. We have also observed this member of the Hungaria family/group four times in the past (Warner 2015 and references therein), each time finding periods near 5.53 h. Using thermal infrared data acquired by the NASA's Wide-field Infrared Survey Explorer (WISE), Hanuš et al. (2018) found a pole solution $(\lambda, \beta, P) = (262^\circ, -77^\circ, 5.53564 \text{ h})$.

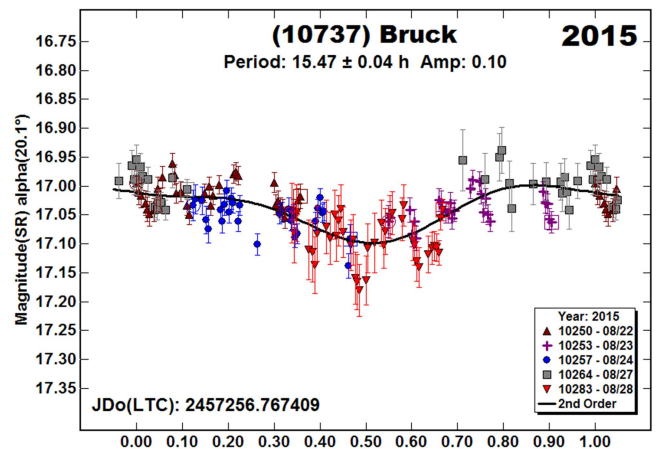
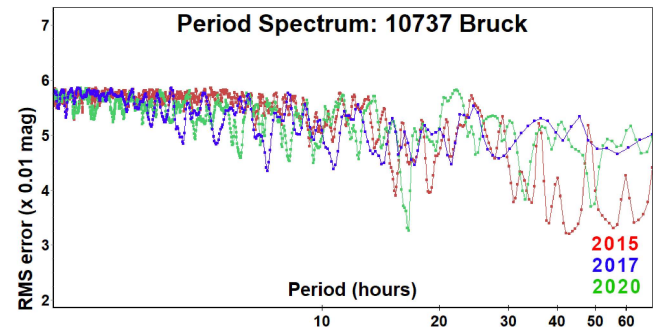
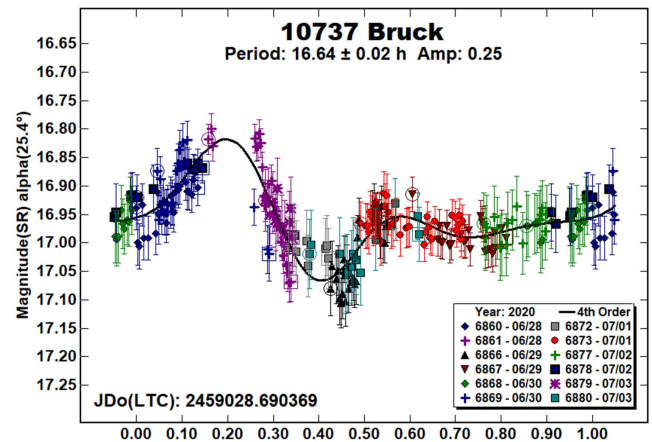


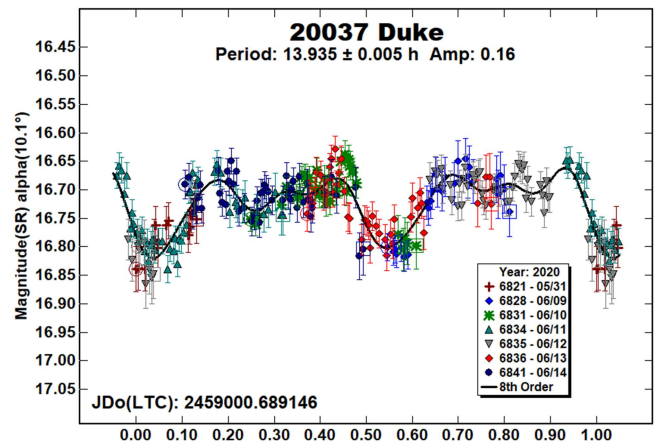
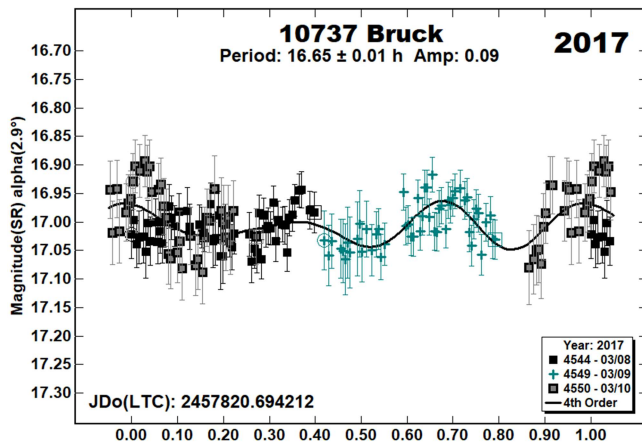
10487 Danpeterson. We found no reported lightcurves for this member of the Phocaea family/group in the LCDB. The period spectrum shows three possible solutions. Those at 16.91 h and 9.91 h are low amplitude, bimodal lightcurves and are 5:3 aliases of each other. The 19.78 h solution is a *fit by exclusion*, which is where the Fourier analysis finds a local RMS minimum by minimizing the number of overlapping data points. We have adopted the 16.91 h solution for this paper because of the slightly higher amplitude.



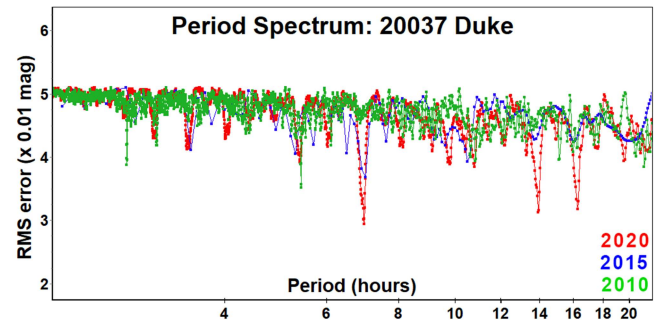
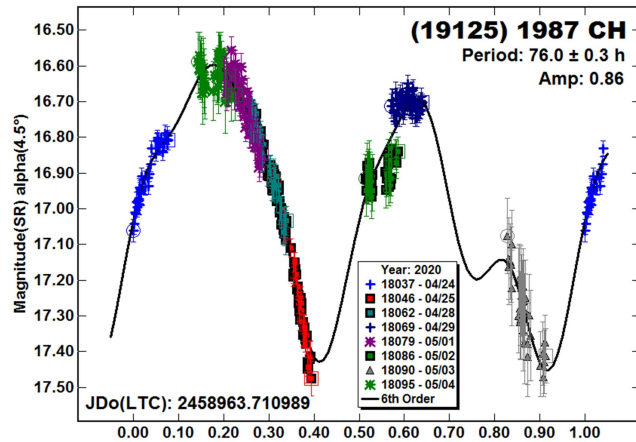
10737 Bruck. We have studied this Hungaria twice in the past (Warner 2016, 3.22 h; 2011; Stephens 2017, 7.29 h). However, the data obtained in 2020 would not fit either of those two periods. We converted the comp star magnitudes used in the 2015 and 2017 lightcurves to ATLAS SR magnitudes and reprocessed the lightcurves. The results were still not definitive. We then stacked all three period spectra on top of each other to assist in finding a dominate solution and excluding solutions not present in all three datasets.

We discounted any solutions longer than 30 h because they were all a *fit by exclusion*. The best remaining solutions were near 16.7 h, but they were not convincing. In particular, the 2015 and 2017 datasets were too sparse to be definitive for a longer period, as well as low amplitude and somewhat noisy. The next good opposition for the northern hemisphere is in 2023 October.

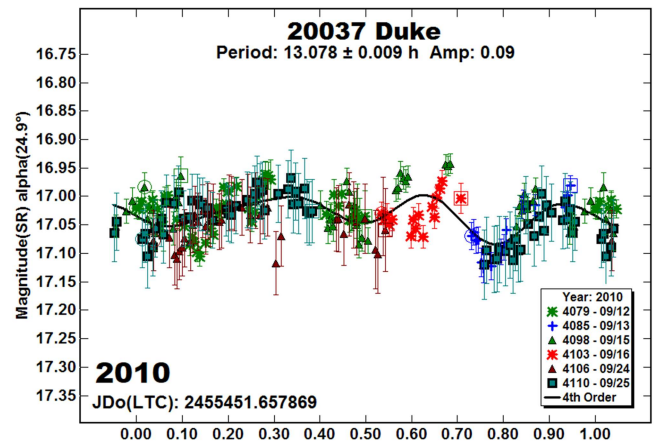




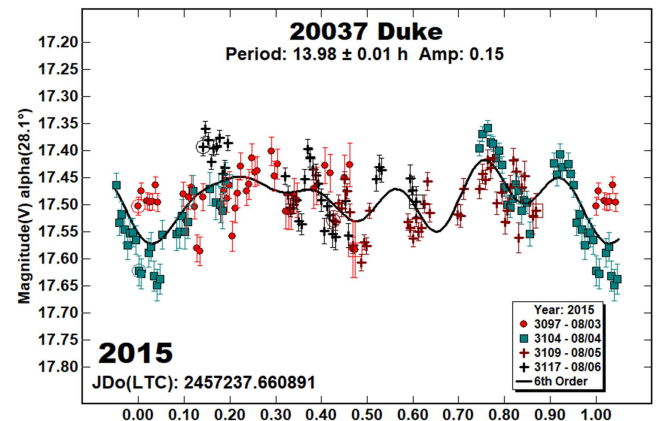
(19125) 1987 CH. Using data from the Transiting Exoplanet Survey Satellite (TESS), Pál et al. (2020) reported a rotational period of 75.8 h for this member of the Flora family/group. Our result is in good agreement.

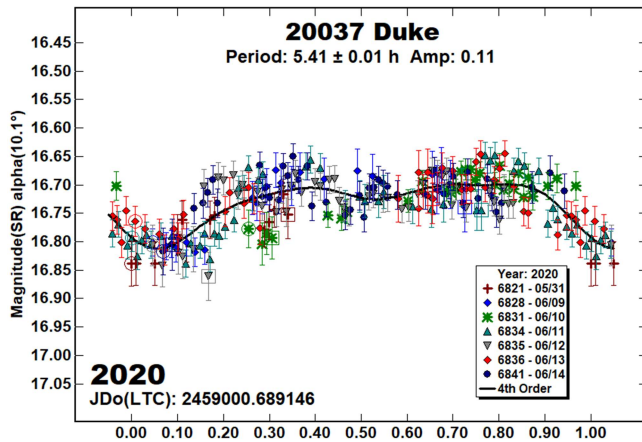
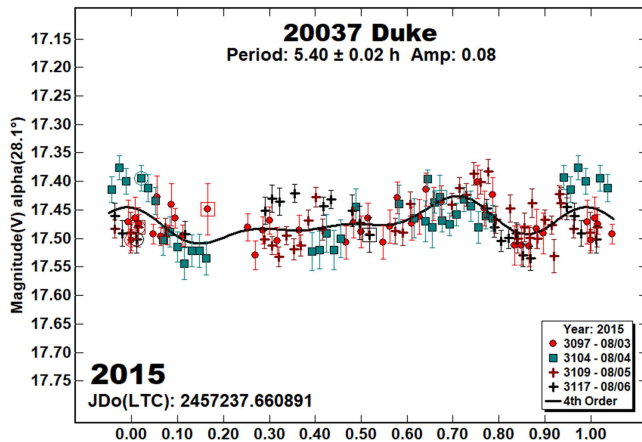
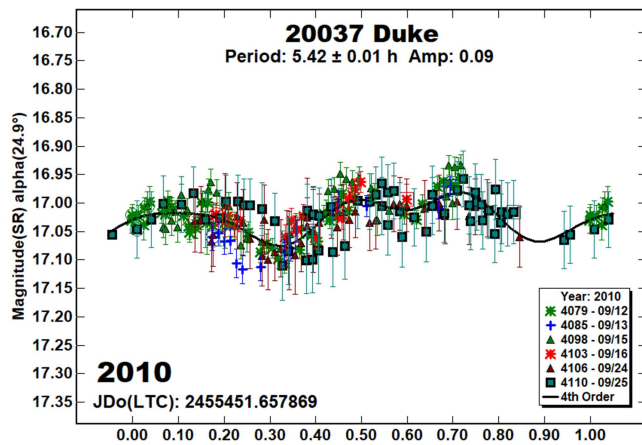


20037 Duke. Duke is another problematic low amplitude member of the Hungaria family/group. We observed this 2-km object twice in the past (Warner 2011, 5.428 h; Stephens 2016, 5.29 h). Using data from the Transiting Exoplanet Survey Satellite (TESS), Pál et al. (2020) reported a rotational period of 13.8267 h. The period spectrum showed several possible aliases; 5.4 h, 7 h, and 13.9 h.

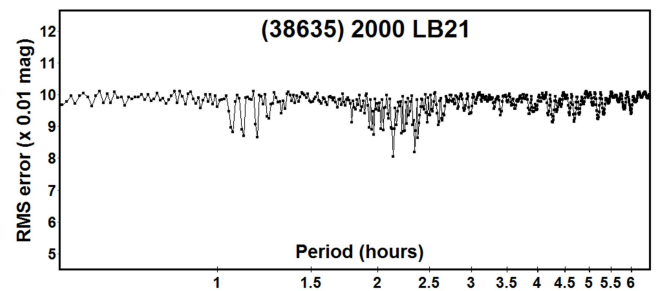
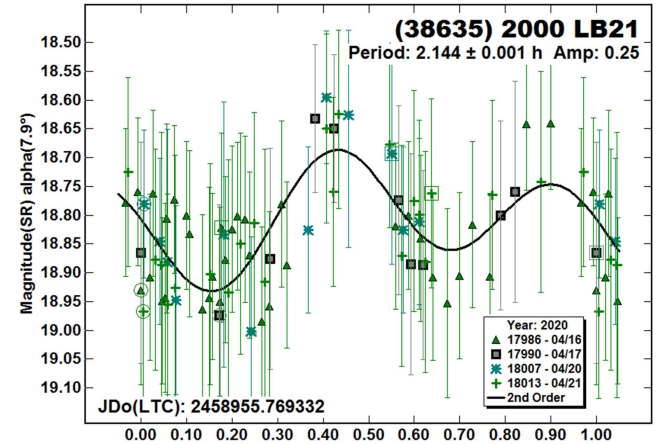


We again tried stacking the period spectra for all three datasets to look for a common period. A weak 5.4-h period was present for 2010, 2015, and 2020. The most dominant period was near 7 h, but only for 2015 and 2020. The 2020 data had a dominant 13.9-h period with a four extrema lightcurve, which matched the Pál et al. result. However, the results using the 2010 and 2015 data would not produce a good match to that period. For this paper, we are adopting the 13.935 h period with an alternate period of 5.41 h, which are a 2:5 aliases of each other.

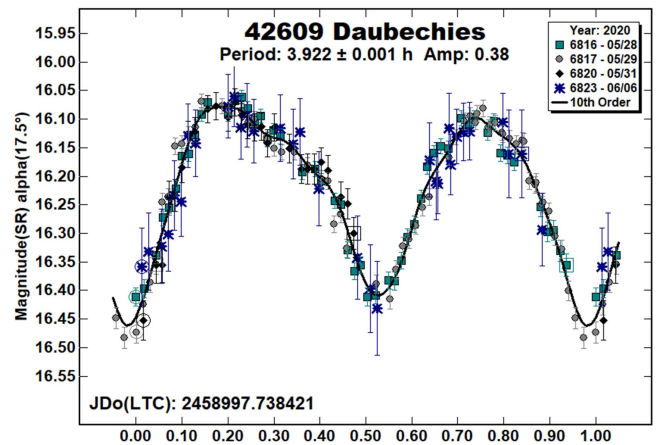




(38635) 2000 LB21. There were no previous lightcurve entries in the LCDB for this 2-km member of the Flora family/group. This was a target of opportunity using 60 second exposures on a target that was $V \sim 18.8$ mag. To be able to measure the resulting low SNR, we used the Stack/Sum - Multi processing feature in *MPO Canopus*. Images were in groups of 3 with no more than 3 minutes between any successive images in a group. There were 79 stacked-images used in the analysis.



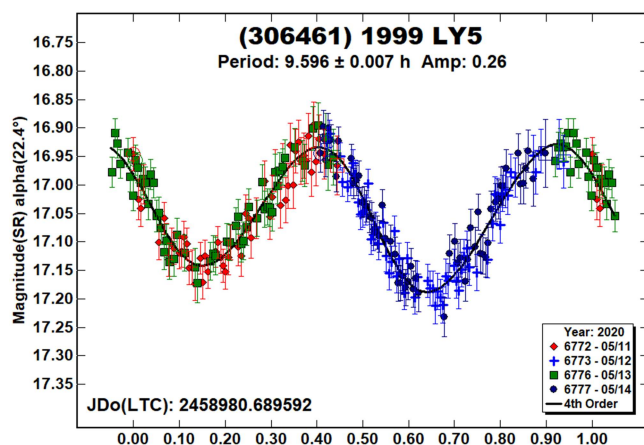
42609 Daubechies. There were no previous lightcurve entries in the LCDB for this estimated 3-km Mars-crosser.



Number	Name	2020 mm/dd	Phase	L _{PAB}	B _{PAB}	Period(h)	P.E.	Amp	A.E.	Grp
652	Jubilatrix	05/05-05/06	5.9,5.7	230	12	2.6653	0.0006	0.26	0.02	EUN
1025	Riema	05/05-05/14	25.3,24.3	253	37	3.5815	0.0003	0.16	0.01	H
1303	Luthera	05/06-05/15	19.1,19.9	169	21	8.3281	0.0007	0.11	0.01	MB-O
1443	Ruppina	04/16-04/18	6.4,5.6	223	2	5.879	0.001	0.31	0.02	MB-O
	Pole (λ , β , P)	(120°, -15°, 5.879288 h)		(295°, -22°, 5.879290 h)		a/b: 1.291	a/c: 1.210			
1667	Pels	05/07-05/10	25.0,25.7	177	5	3.268	0.001	0.42	0.02	FLOR
	Pole (λ , β , P)	(182°, -53°, 3.268280 h)		(16°, -63°, 3.268280 h)		a/b: 1.247	a/c: 1.135			
2050	Francis	04/03-04/04	21.6,21.5	201	33	3.066	0.002	0.17	0.01	PHO
3225	Hoag	05/05-05/13	25.4,27.8	183	4	2.3732	0.0002	0.17	0.02	H
5875	Kuga	05/06-05/13	21.5,22.7	177	-8	5.548	0.002	0.37	0.03	V
6163	Reimers	06/09-06/13	24.2,25.4	233	9	6.673	0.002	1.19	0.04	H
6517	Buzzi	05/29-06/17	*21.1,21.1	252	29	8.6413	0.0004	0.57	0.03	H
6635	Zuber	05/05-05/10	13.2,14.4	221	20	5.530	0.001	0.78	0.05	H
10487	Danpeterson	06/17-06/27	26.7,27.2	201	25	16.91	0.02	0.11	0.02	PHO
						^A 9.91	0.02	0.09	0.02	
10737	Bruck	06/28-07/03	25.5,25.6	274	31	16.64	0.02	0.25	0.05	H
19125	1987 CH	04/24-05/04	*4.5,6.4	216	7	76.0	0.3	0.86	0.05	FLOR
20037	Duke	05/31-06/14	10.1,17.3	246	15	13.935	0.005	0.16	0.02	H
						^A 5.41	0.01	0.11	0.02	
38635	2000 LB21	04/16-04/21	8.0,5.6	222	2	2.144	0.001	0.20	0.05	FLOR
42609	Daubechies	05/28-06/06	17.5,22.0	229	8	3.922	0.001	0.38	0.02	MC
306461	1999 LY5	05/11-05/14	22.5,23.7	201	5	9.596	0.007	0.26	0.03	MC

Table III. Observing circumstances and results. ^AThe alternate period of an ambiguous solution. 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 1443 and 1667, the second line gives the spin axis/shape modeling results. The pole solution in bold is the preferred one.

(306461) 1999 LY5. We could not find any entries in the LCDB for this Mars-crosser, estimated to be 6 km in size.



Acknowledgements

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