

MAIN-BELT ASTEROIDS OBSERVED FROM CS3: 2020 JULY TO SEPTEMBER

Robert D. Stephens

Center for Solar System Studies (CS3) / MoreData!
11355 Mount Johnson Ct., Rancho Cucamonga, CA 91737 USA
rstephens@foxandstephens.com

Brian D. Warner

Center for Solar System Studies (CS3) / MoreData!
Eaton, CO

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CCD photometric observations of 25 main-belt asteroids were obtained at the Center for Solar System Studies (CS3) from 2020 July to September. In addition, updated periods were found for 1582 Martir, (14923) 1994 TU3, and (23482) 1991 LV.

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.

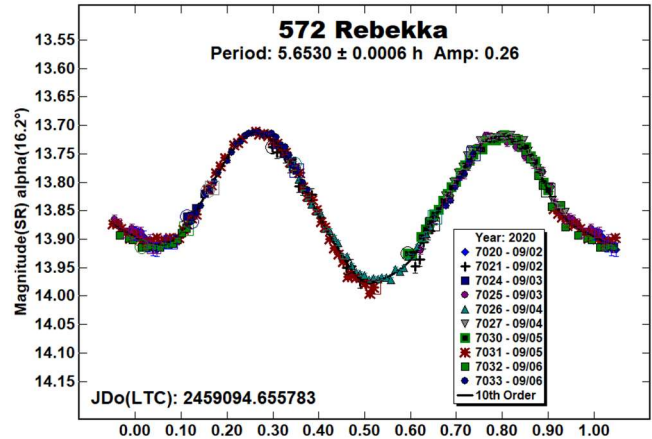
We used the ATLAS r' (SR) magnitudes. Zero-point adjustments are mostly ≤ 0.03 mag. The occasions where larger corrections were required may have been related in part to using unfiltered observations, poor centroiding of the reference stars, and not correcting for second-order extinction terms.

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 .

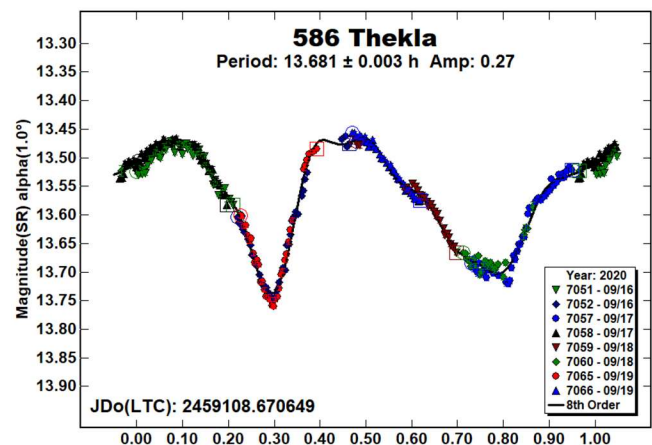
The amplitude indicated in the plots (e.g. Amp. 0.23) is the amplitude of the Fourier model curve and not necessarily the adopted amplitude of the lightcurve.

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).

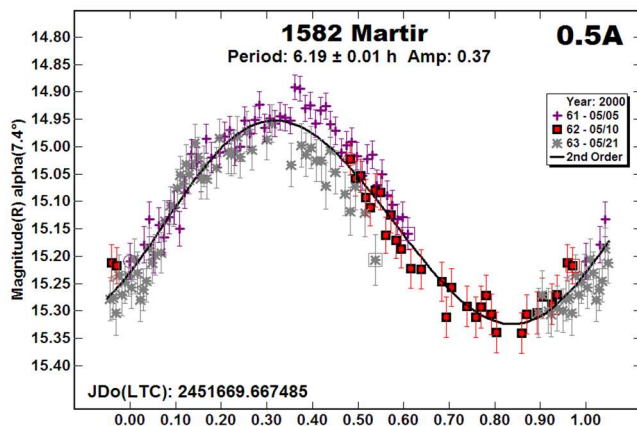
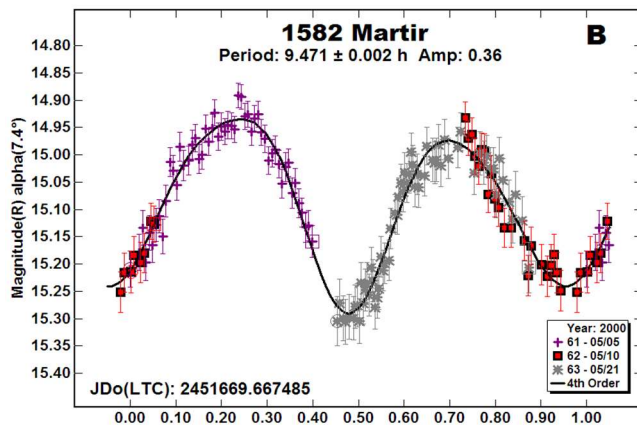
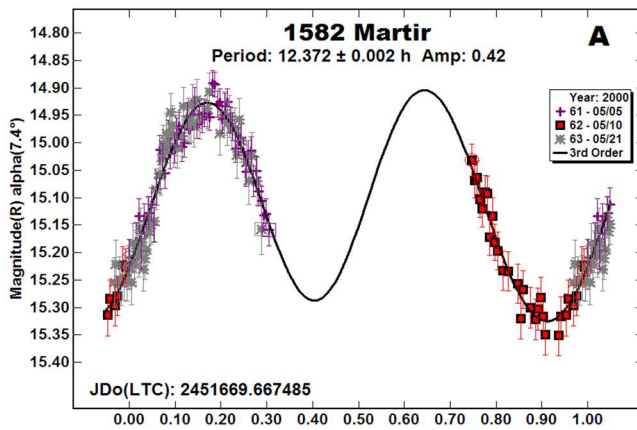
572 Rebekka. This inner main-belt asteroid has been studied several times in the past. We (Warner, 2007) observed it in 2007 finding a period of 5.656 h. Behrend (2009web; 2020web) reports periods of 5.6497 h and 5.650 h. Lagerkvist et al. (1998) reported a period of 5.65 h. Hanuš et al. (2013) reported a spin axis model with $(\lambda, \beta) = (1^\circ, 54^\circ)$ or $(158^\circ, 39^\circ)$ and a sidereal period of 5.65009 h. Our results this year are in good agreement.



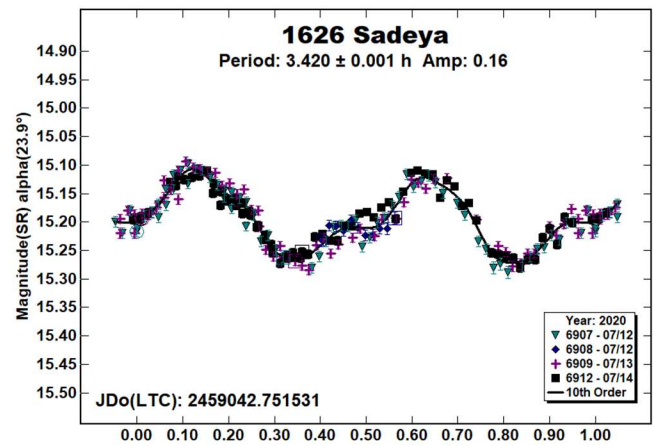
586 Thekla. This outer main-belt asteroid was a target of opportunity in the same field as 4030 Archenhold on four nights. Despite being such a low numbered asteroid, the LCDB has only three previous rotation periods: Behrend (2004web; 2007web) and Warner (2010b) each reported a period near 13.67 h, in good agreement with the results from this year.



1582 Martir. We observed this outer main-belt object in 2010 May reporting a period of 9.84 h (Warner, 2010b). Recent observations from the Transiting Exoplanet Survey Satellite (TESS; McNeil et al., 2019; Pál et al., 2020) found periods near 12.37 h. Using our original data, we changed the comparison star magnitudes to SR (r') values from the ATLAS catalog. With some minor zero-point adjustments, we could fit the data to either our original period (B) or the 12.37 h period (A) found in the TESS data. A half-period plot (C) favors the 12.37 h period, which we are adopting for this paper, but the 9.47-h solution cannot be formally excluded.



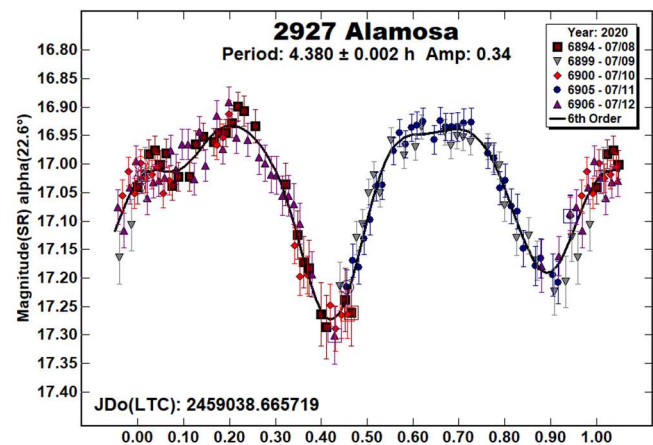
1626 Sadeya. This 16-km member of the Phocaea family/group has been observed many times in the past. Florczak et al. (1997), Behrend (2007web), Benishek (2015), and Warner (2010a; 2014a) each time finding rotational periods near 3.42 h, in good agreement with this year's result. In 2020 August, Sadeya was observed by the Photometric Survey for Asynchronous Binary Asteroids (Pravec et al. 2020web) which found it to be a binary asteroid with a $P_1 = 3.42010$ h and $P_2 = 51.15$ h.



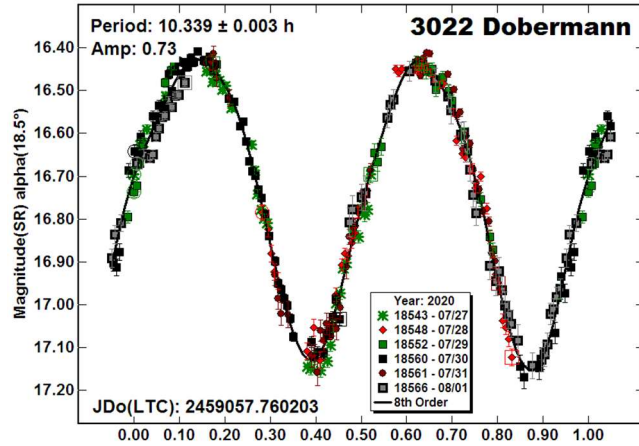
Because of the availability of dense data from Oey in the Asteroid Lightcurve Data Exchange Format database (ALCDEF, 2020), sparse data at the Asteroids - Dynamic web site (AstDyS-2, 2020), and our dense data from two apparitions, we attempted to solve for the sidereal period and pole position and create 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 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 pole model showed a unique solution with J2000 ecliptic coordinates of $(\lambda, \beta, P) = (152^\circ, -9^\circ, 3.421367$ h). We note that the effects of the satellite were not removed from the data set when developing the shape/spin axis model. The full set of inversion graphics are given at the end of this paper.

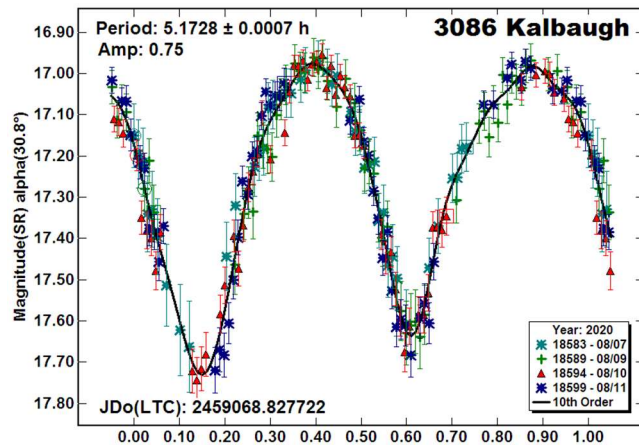
2927 Alamosa. This inner main-belt object was observed by Odden et al. (2012) who found a rotational period of 4.38232 h. Our result this year is in good agreement.



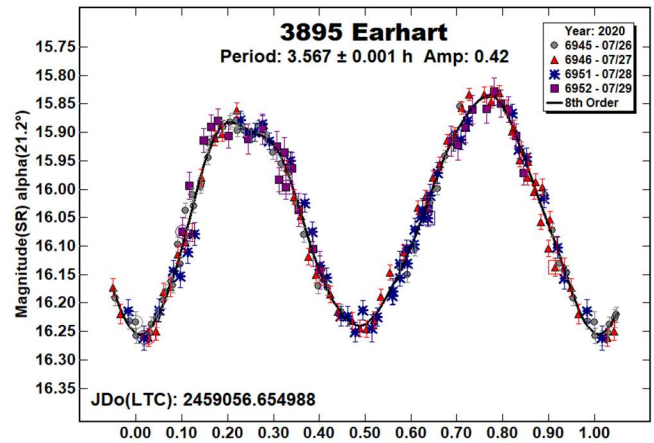
3022 Dobermann. We have worked this member of the Hungaria family/group many times in the past to develop a shape/pole model (Warner, 2005a; 2011; 2013a; 2014b; 2017) each time finding a period near 10.33 h. In addition, using data from the Transiting Exoplanet Survey Satellite (TESS), Pál et al. (2020) reported a rotational period of 10.329 h. Our results this year are in good agreement with these prior findings.



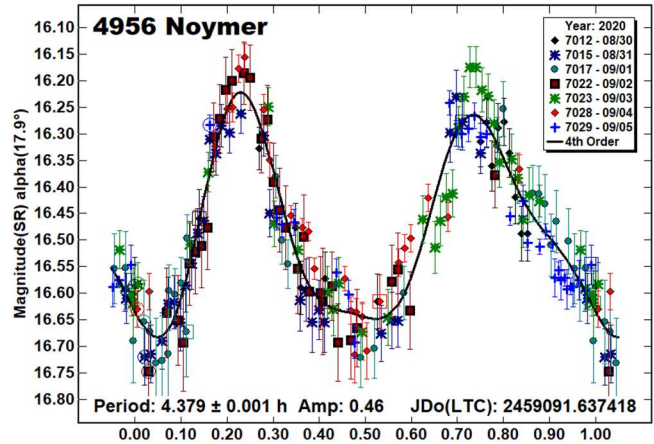
3086 Kalbaugh. We observed this member of the Hungaria family/group in the past to acquire data for a shape/pole model (Warner 2005b; 2008; 2010a; 2013b) each time finding a period of 5.18 h. Skiff et al. (2019) reports a period of 5.177 h. Using sparse data from the Lowell Observatory Database (Durech et al., 2016) found a sidereal period of $(\lambda, \beta, P) = (63^\circ, -51^\circ, 5.17907 \text{ h})$.



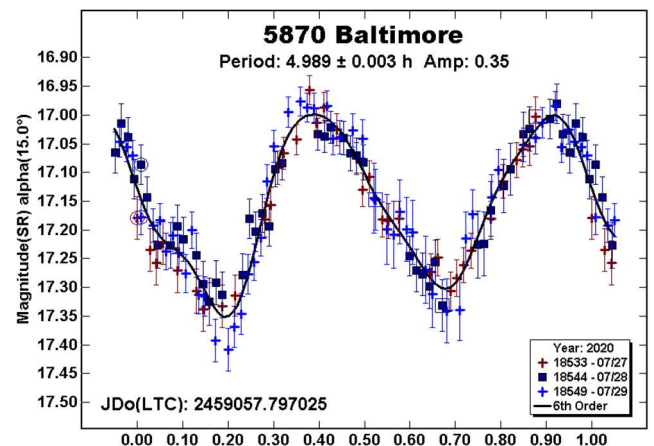
3895 Earhart. This member of the Phocaea family/group is estimated to be 11 km in size. It has been observed several times in the past (Behrend, 2009web, 3.56451 h; Behrend 2016web, 3.56445 h; Warner, 2009, 3.564 h; Aznar Macias et al., 2016, 3.556 h). Our result at this apparition is in good agreement.



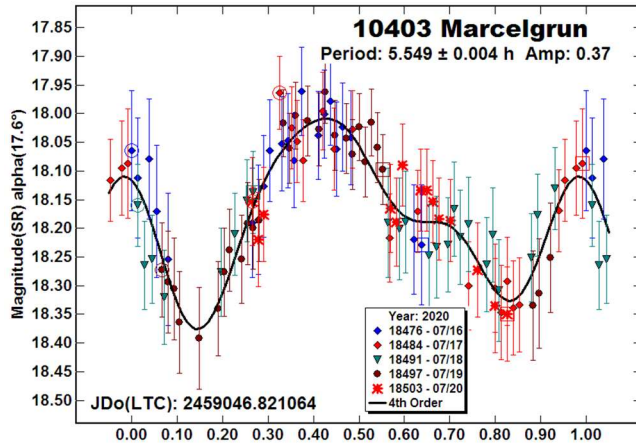
4956 Noymer. This member of the Phocaea family/group was observed in 2012 July by Waszczak et al. (2015) as part of the Palomar Transient Factory survey. They found a period of 4.366 h, which is consistent with our results this year.



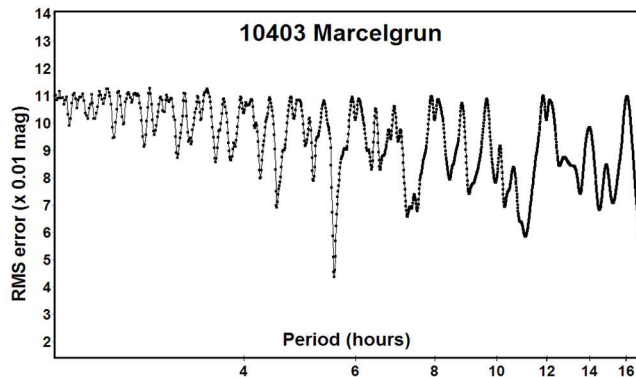
5870 Baltimore. We could not find any entries in the LCDB for this Mars-crosser, which is estimated to be 7 km in size.



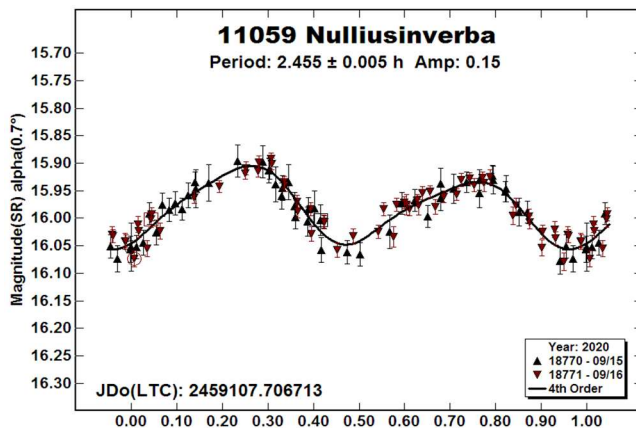
10403 Marcelgrun. Using data from the Transiting Exoplanet Survey Satellite (TESS), Pál et al. (2020) reported a rotational period of 10.3703 h for this 4-km member of the Flora family/group. This result seems to be double the period we found.



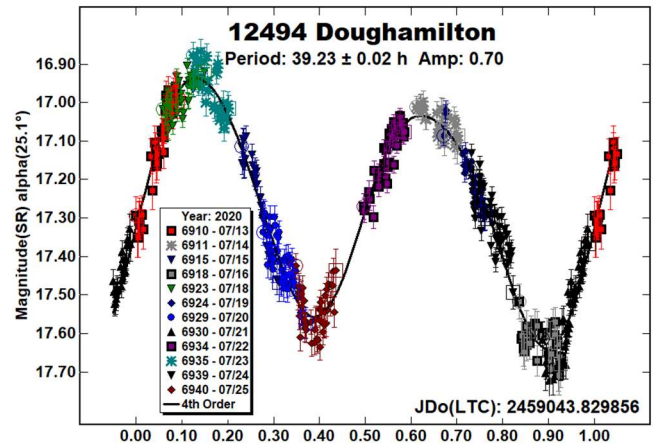
It appears this wide-field survey used only single-frequency analysis, then assumed it to be the second harmonic of the actual frequency (bimodal lightcurve; Harris, private communications). This is based on Pál et al. (2020) Eq. 1 on page 5, which implies a fit to only a single frequency, then assumed it to be the second harmonic of a bimodal curve. A single-frequency solution assumed to be 2nd-harmonic can often miss periods found with 4th-order analysis.



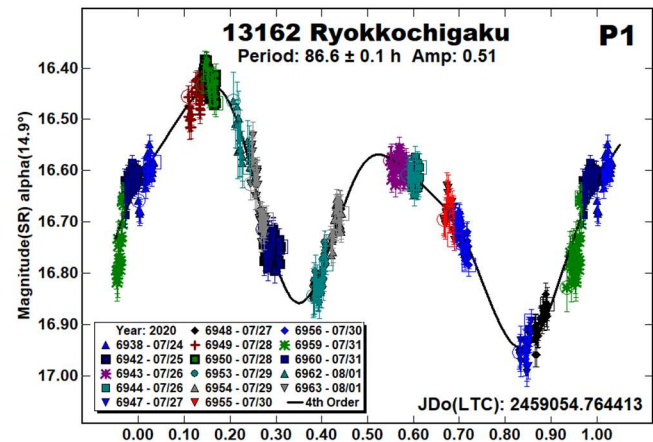
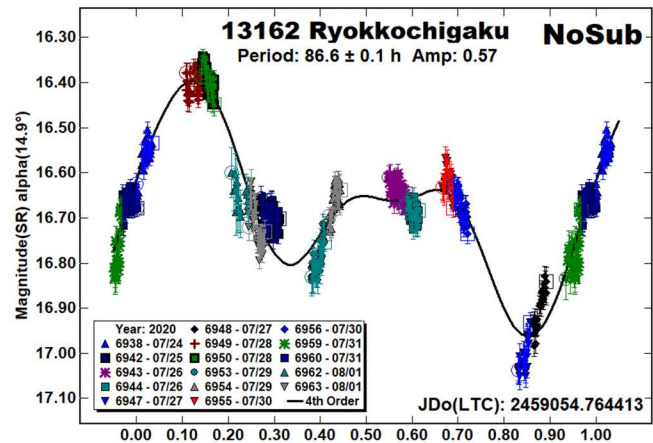
11059 Nulliusinverba. This member of the Eunomia family/group was a target of opportunity, being in the same field of 7174 Semois for two nights. There are no periods reported in the LCDB. 'Nullius in verba' is the motto of the Royal Society and is taken to mean 'take nobody's word for it'. That said, we feel this result is pretty secure.

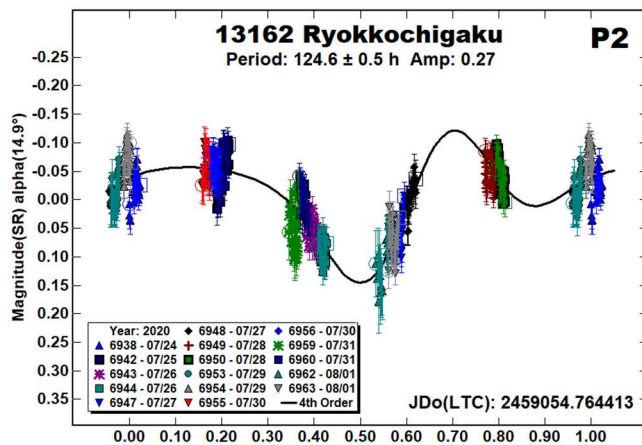


12494 Doughamilton. Using data from the Transiting Exoplanet Survey Satellite (TESS), Pál et al. (2020) reported a rotational period of 39.2603 h for this member of the Hungaria family/group. Our result is in good agreement.

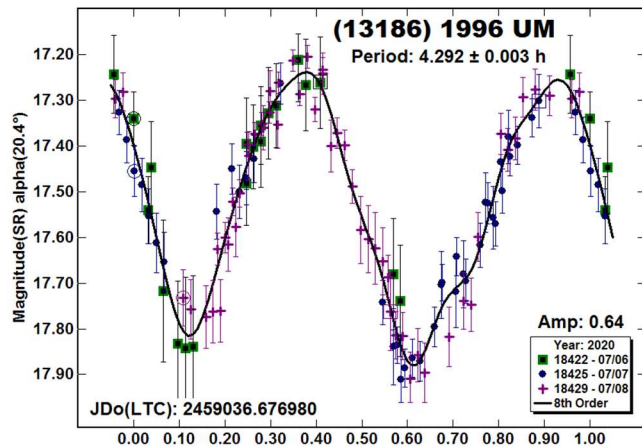


13162 Ryokkochigaku. There are no previous entries in the LCDB for this 5 km sized Vestoid. A general rule-of-thumb (Pravec et al., 2005; 2014) makes this asteroid likely to be in non-principal axis rotation (NPAR; tumbling). The fact that *MPO Canopus* found two dominant periods, neither one indicative of a satellite, adds credence to the argument for tumbling. *MPO Canopus* cannot directly analyze tumbling asteroids, so these two periods may or may not be the true periods of rotation and precession.

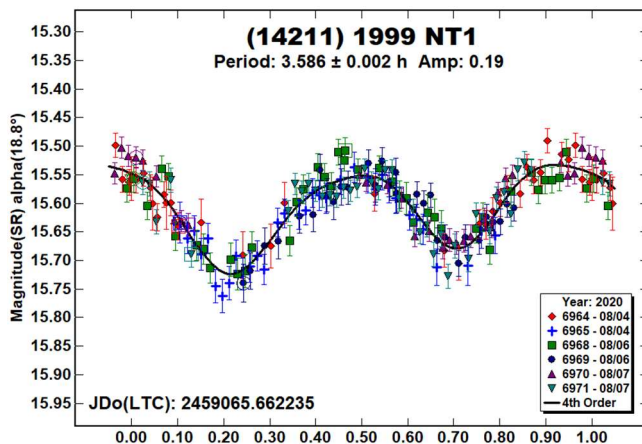




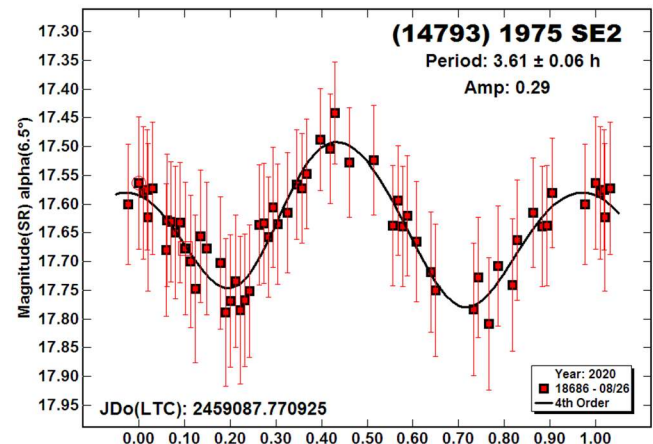
(13186) 1996 UM. This is a 3-km Hungaria that has been observed by CS3 at four previous apparitions: Warner (2013a), Warner (2014b), Warner (2016), and Stephens (2017). Each time, as in 2020, a period close to 4.30 hours was found. The amplitudes have ranged from 0.34 to 0.69 mag. The 2020 and 2012 observations were at nearly the same viewing aspect and so the amplitudes were similar, 0.69 mag in 2012 and 0.64 mag in 2020.



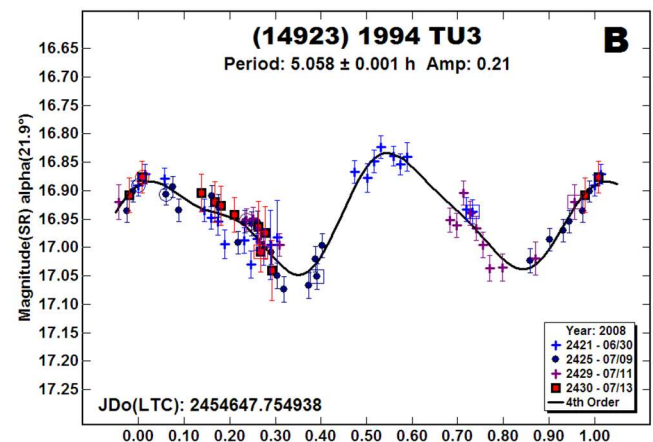
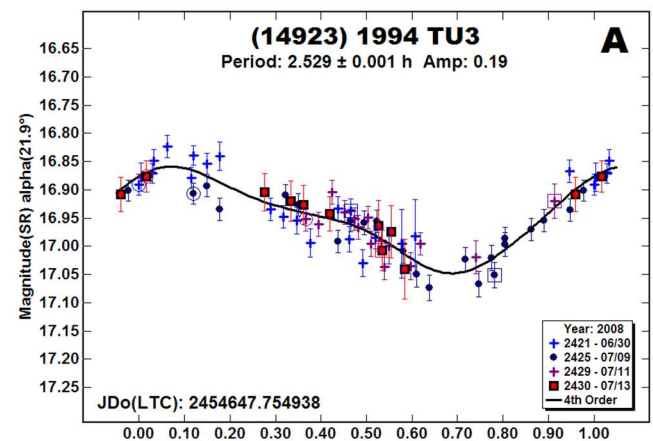
(14211) 1999 NT1. This Mars-crosser was observed three times in the past (Pray et al., 2007; Pravec et al., 2012web; 2013web), each time finding a period near 3.585 h. Our result this year is in good agreement.

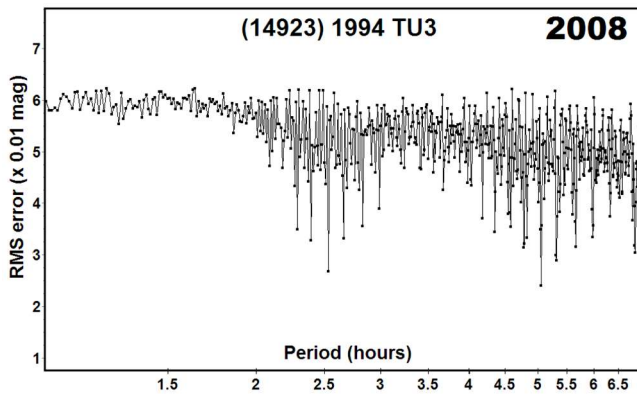


(14793) 1975 SE2. There are no previous periods in the LCDB for this 2.7 km Vestoid. It was in the field of the NEA (159402) 1999 AP10 and only observed a single night.

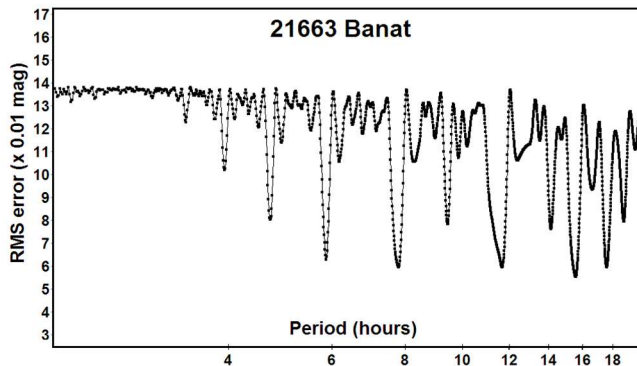
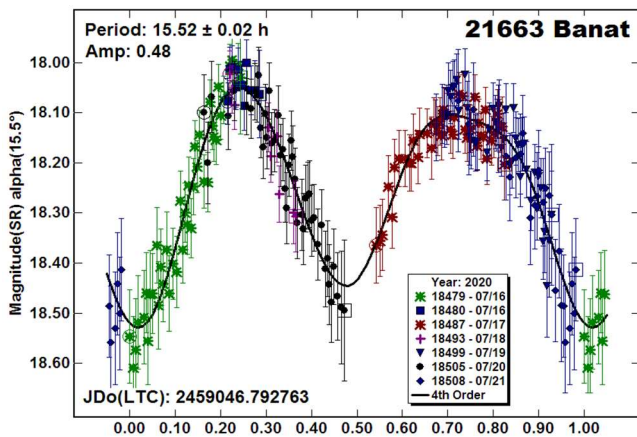


(14923) 1994 TU3. Reviewing recently published results with a period of 2.6531 h (Dose 2020) caused us to revisit our observations from 2008 which had a period of 7.300 h. We reset the comparison star magnitudes to SR values from ATLAS and redid the period search finding two solutions. These solutions are only in general agreement with the Dose results because of the sparse data. We prefer the 2.529 h period (A), which is a monomodal lightcurve. The bimodal result with a period of 5.058 h would require the Dose result to be a highly unlikely quadramodal solution.

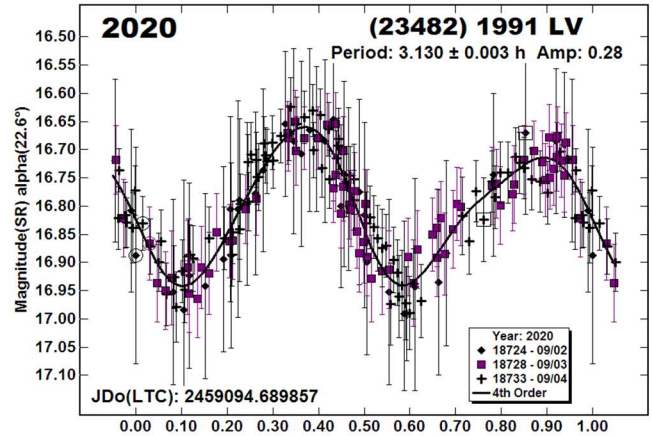
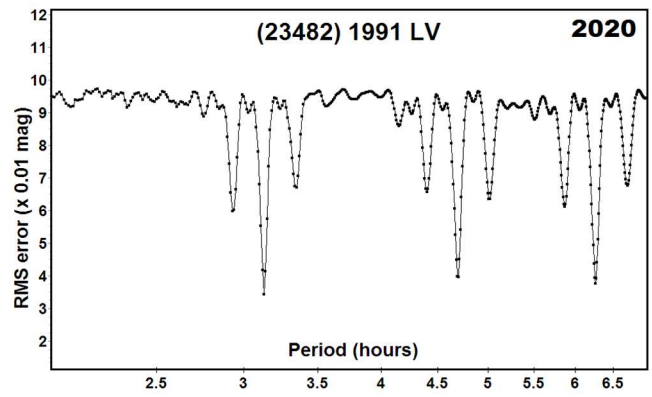




21663 Banat. Behrend (2005web) previously reported a period of 9.6 h for this outer main-belt object. Although the period spectrum for our observations this year shows many possibilities, the 15.5 h solution is the only plausible choice.



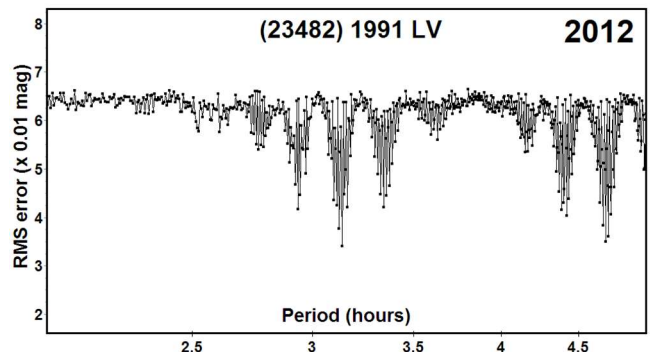
(23482) 1991 LV. We've observed this Hungaria group/family member for three apparitions: 2012 July, 2015 September, and 2020 September. After the most recent observations, we believe we have determined the true unique period.

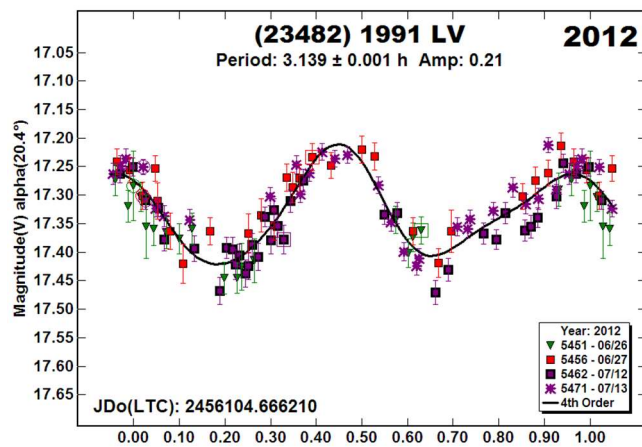


From the 2020 data, the densest set of the four apparitions, the period was uniquely-defined at 3.130 h. The two prominent solutions at longer periods produced a tri- or quadramodal lightcurve. Given the relatively low phase angle and amplitude, a bimodal solution was virtually assured (Harris et al., 2014).

The weaker “wing” at 3.357 h becomes important when looking at the results from the two previous apparitions and taking into account that the difference between 3.130 h and 3.357 h is almost exactly a one-half rotation difference over 24 hours.

The period spectrum using the 2012 data set also favors a period near 3.13 h, but not as strongly as in 2020, and the 3.35-h wing is more prominent. The slight ambiguity is likely due to the sparser dataset and the gap between the two sets of consecutive nights.

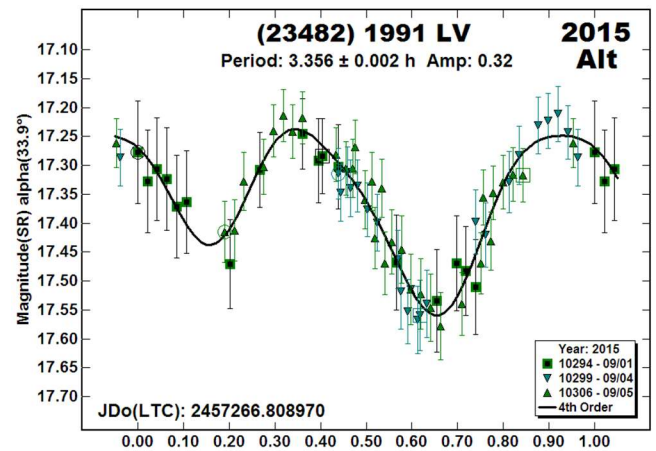
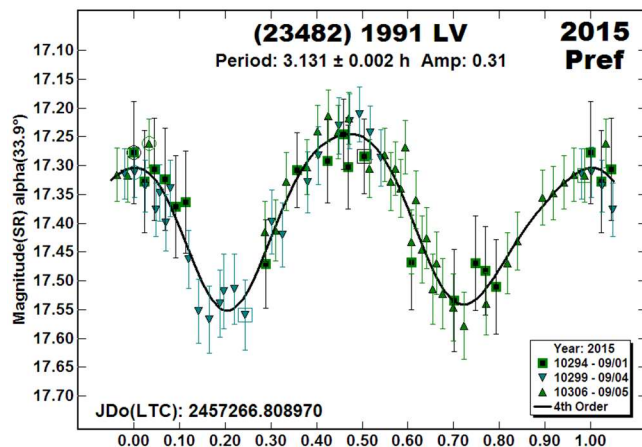
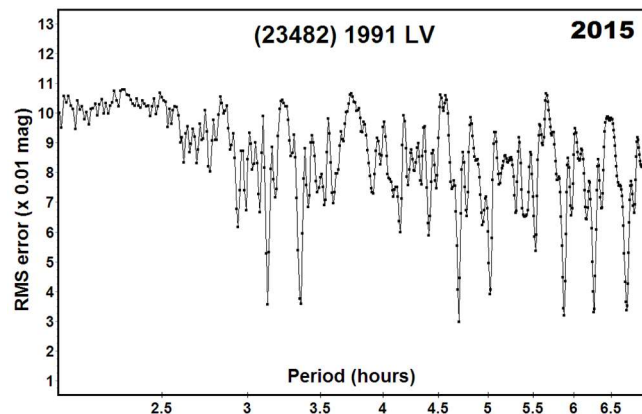




Even so, we still consider the solution of 3.139 h to be secure. Our original solution was 3.1388 h (2012). This is too precise given the dataset. The small difference between it and 3.130 h from 2020 can be attributed to the natural small differences in synodic period from one apparition and another and, again, the sparse data set.

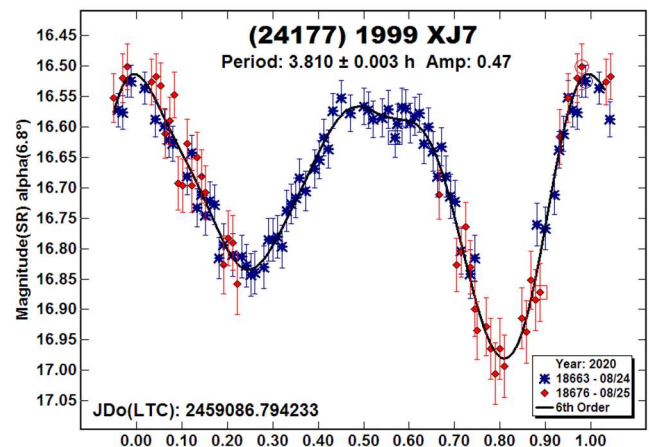
An even sparser dataset in 2015 produced an ambiguity that led to the unfortunate adoption of a period of 3.357 h (Warner, 2016) even though the only acceptable fit of the 2012 data was 3.126 h.

We reanalyzed the 2015 data after changing the comparison star magnitudes from V in the APASS catalog (Henden et al., 2009) to Sloan r' (SR) from the ATLAS star catalog (Tonry et al., 2018) and resetting any zero-point offsets to 0. This produced almost equally valid solutions near 3.13 and 3.35 h. The lightcurve for the latter has a shape that is more asymmetrical. Based on this, we adopted $P = 3.131$ h but could not formally exclude 3.356 h.

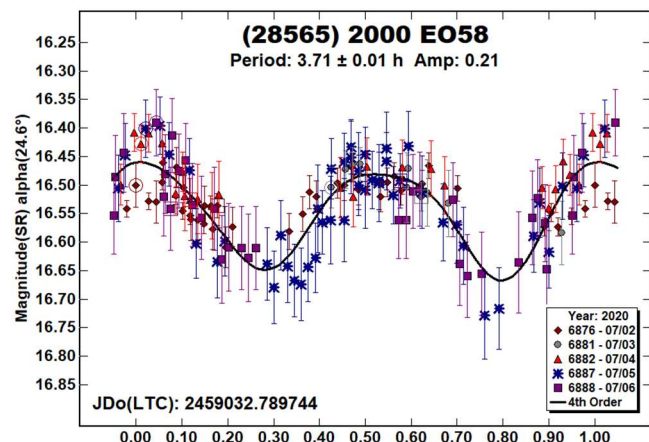


On the whole, the preponderance of evidence so strongly favors a solution of about 3.13 h that we feel safe in saying that it is the true period and that 3.35 h can be excluded.

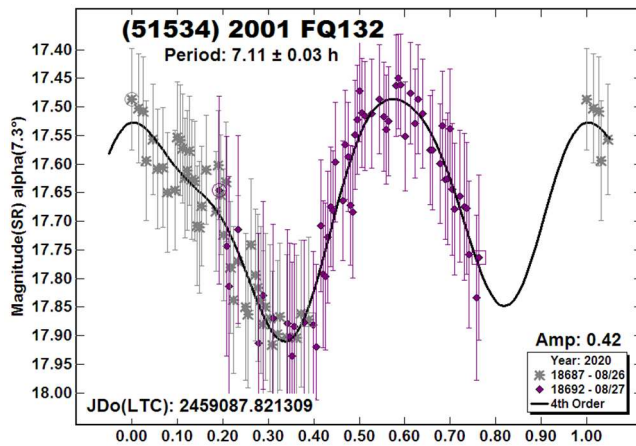
(24177) 1999 XJ7. This member of the Flora family/group was a target of opportunity in the field of the NEA (159402) 1999 AP10. The 16.3 mag asteroid was passing over a 10.5 mag star for a good part of the last night. It was previously observed by Erasmus et al. (2020) who found a period of 3.821 h.



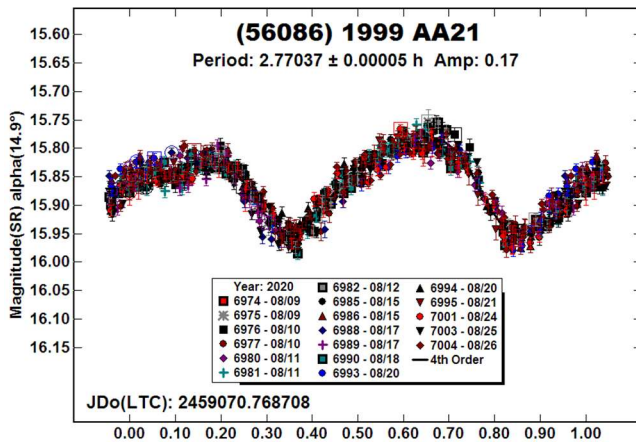
(28565) 2000 EO58. Behrend (2004web; 2020web) observed this 3-km Mars-crosser twice. Their 2004 observations report a period of 3.83 h. The scatter in the data was twice that of the 0.04 mag amplitude. They report a 11.1796 h period from their 2020 August data that shows six extrema. That reported period is a 3:1 alias of our 3.71 h period.



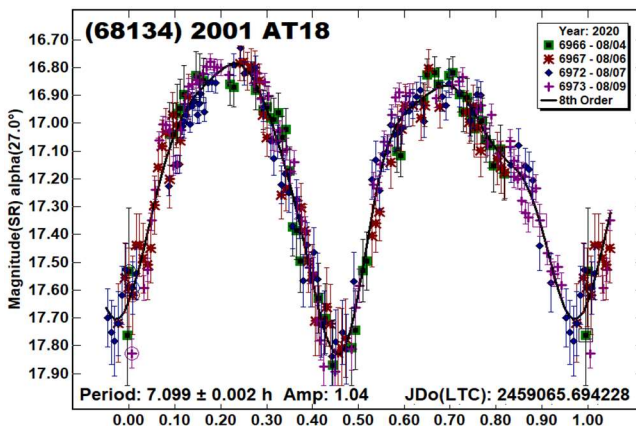
(51534) 2001 FQ132. There are no entries in the LCDB for this 2-km inner main-belt asteroid. It was a target of opportunity in the field of (159402) 1999 AP10 for two nights.



(56086) 1999 AA21. This member of the Phocaea family/group was previously observed by Pál et al. (2020) using data from the Transiting Exoplanet Survey Satellite (TESS). They reported a rotational period of 2.76957 h. Our data initially showed some variations which made us suspect the presence of a secondary period near 25 h. However, due to its low amplitude and being nearly commensurate with an Earth day, we do not have confidence that the minor deviations of a secondary period is based on a physical effect.



(68134) 2001 AT18. Skiff et al. (2019) observed this Mars-crosser in 2010 reporting a period of 7.104 h. Our result this year is in good agreement.

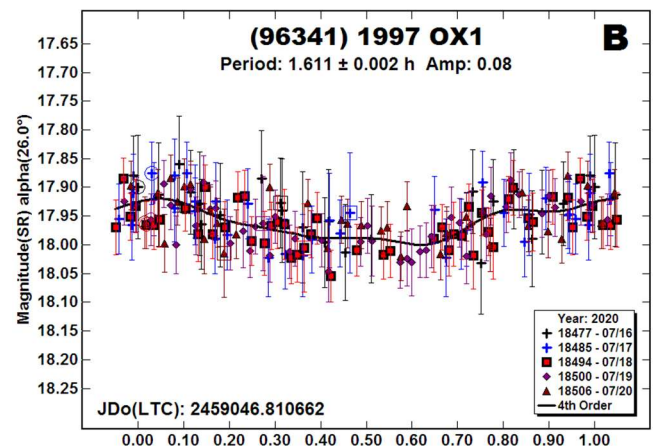
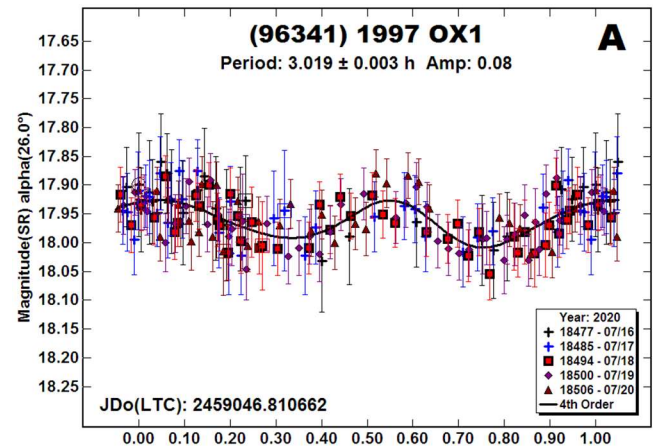


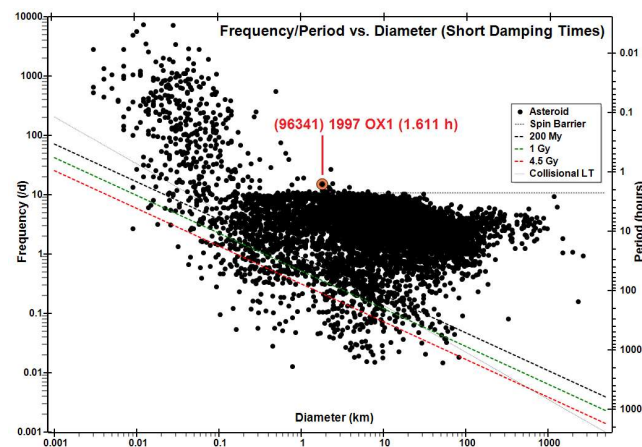
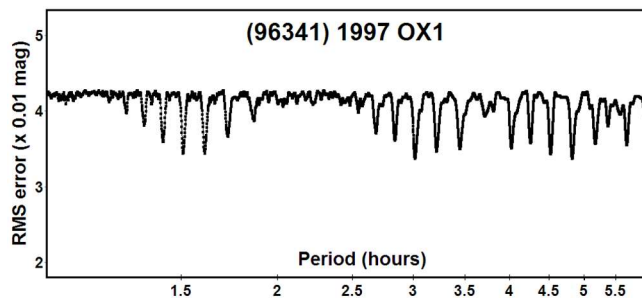
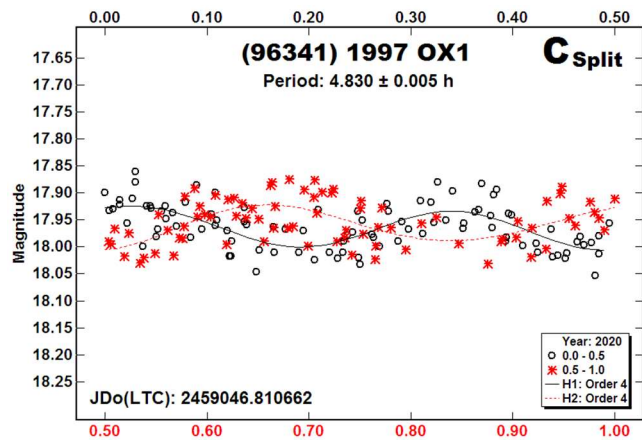
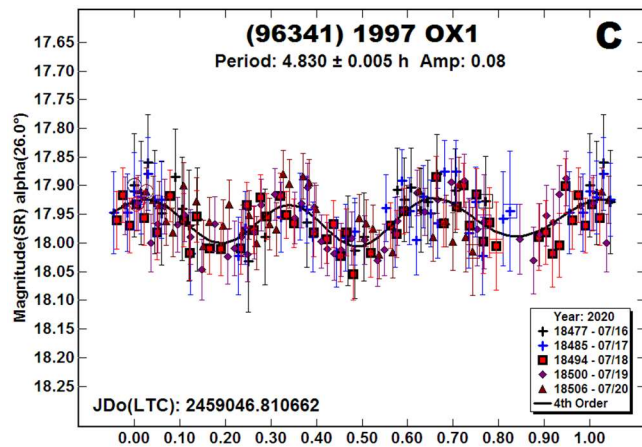
Because of the availability of dense data from Skiff in the Asteroid Lightcurve Data Exchange Format database (ALCDEF, 2020), sparse data at the Asteroids - Dynamic web site (AstDyS-2, 2020), and our dense data from two apparitions, we attempted to solve for the sidereal period and pole position and create a shape model. This data was combined using *MPO LCInvert* (Bdw Publishing).

As is often the case, the pole model showed two possible solutions 180° apart; $(\lambda, \beta, P) = (25^\circ, -19^\circ, 7.107274 \text{ h})$ and $(\lambda, \beta, P) = (323^\circ, -79^\circ, 7.107278 \text{ h})$. Our preferred solution is $(323^\circ, -79^\circ)$ because the $(25^\circ, -19^\circ)$ solution would be nearly pole-on at some point, and because of the distribution of the L_{PAB} , the lightcurve amplitude should have been significantly different between the 2010 and the 2020 apparitions. Since the observed amplitude has always been > 1.0 mag., it would require an unusually large, maybe implausible, a/b axis ratio to not have a nearly equatorial view at the two apparitions.

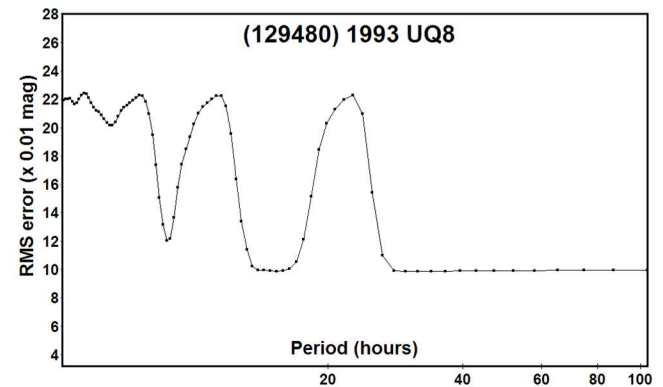
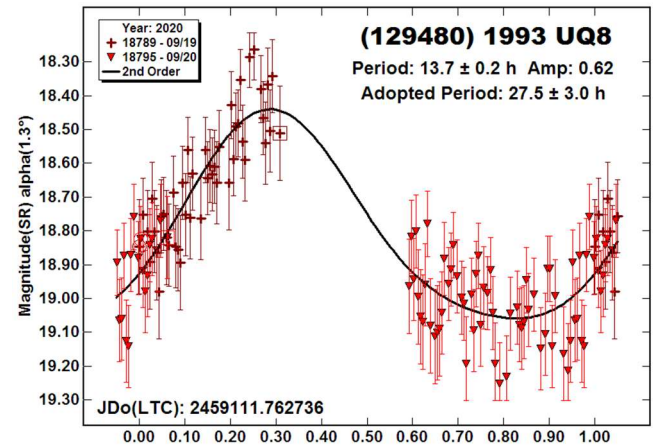
The full set of inversion plots is given at the end of this paper.

(96341) 1997 OX1. There are no previous lightcurve entries in the LCDB for this 2-km inner main-belt object that was a target of opportunity. There are many possible solutions for this slow amplitude, high phase angle target. We prefer the 3.019 h solution, but the 1.611 h and 4.830 h periods are possible. The 4.830 h solution cannot be ruled out because the split halves plot shows it to be asymmetrical. The position of the 1.611 h period on a frequency-diameter plot shows it to be not particularly outstanding or anomalous.

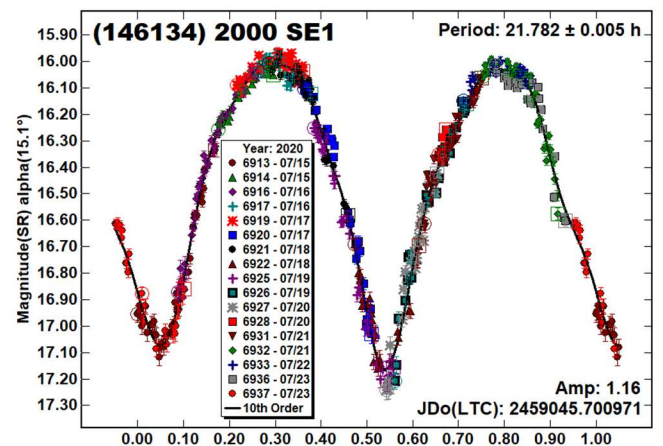




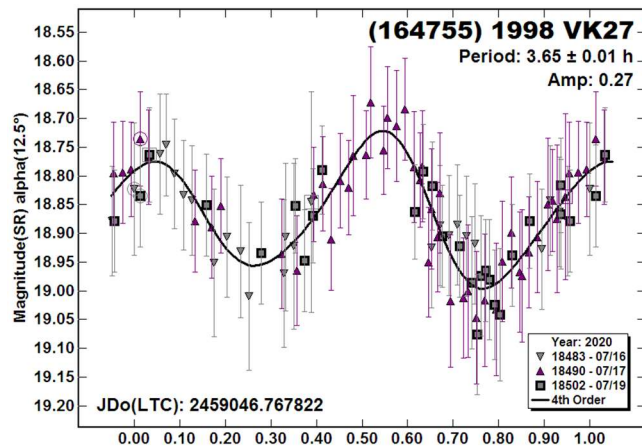
(129480) 1993 UQ8. This outer main-belt object was a target of opportunity in the field of 7174 Semois, so we only got two nights on the target. There are no previous lightcurve entries in the LCDB and, with the limited dataset, we had to estimate the period to be 27.5 h based upon a plot of the half period.



(146134) 2000 SE1. The only period found in the LCDB for this Mars-crosser was from Waszczak (2015). Their period of 21.762 h is in good agreement with this work.



(164755) 1998 VK27. There are no entrees in the LCDB for this outer main-belt object. It was a target of opportunity in the field of the Hilda (16970) 1998 VV2.



Acknowledgements

Observations at CS3 and continued support of the asteroid lightcurve database (LCDB; Warner et al., 2009) are supported by NASA grant 80NSSC18K0851. This work includes data from the Asteroid Terrestrial-impact Last Alert System (ATLAS) project. ATLAS is primarily funded to search for near earth asteroids through NASA grants NN12AR55G, 80NSSC18K0284, and 80NSSC18K1575; byproducts of the NEO search include images and catalogs from the survey area. The ATLAS science products have been made possible through the contributions of the University of Hawaii Institute for Astronomy, the Queen's University Belfast, the Space Telescope Science Institute, and the South African Astronomical Observatory. The authors gratefully acknowledge Shoemaker NEO Grants from the Planetary Society (2007, 2013). These were used to purchase some of the telescopes and CCD cameras used in this research.

Number	Name	2020 mm/dd	Phase	L _{PAB}	B _{PAB}	Period(h)	P.E.	Amp	A.E.	Grp
572	Rebekka	09/02-09/06	16.3,17.7	313	11	5.653	0.0006	0.26	0.01	MB-I
586	Thekla	09/16-09/19	1.1,2.1	351	2	13.681	0.003	0.27	0.01	MB-O
1582	Martir	2010/05/05-05/21	7.4,12.0	214	12	12.372	0.002	0.42	0.03	MB-O
1626	Sadeya	07/12-07/14	23.9,23.7	340	24	3.420	0.001	0.16	0.01	PHO
	Pole (λ , β , P)	(152°, -9°, 3.421367 h)	a/b: 1.56	a/c: 1.19						
2927	Alamosa	07/08-07/12	22.6,22.9	219	18	4.380	0.002	0.34	0.02	MB-I
3022	Dobermann	07/28-08/01	18.3,17.3	321	25	10.339	0.003	0.73	0.03	H
3086	Kalbaugh	08/07-08/11	30.8,30.7	26	21	5.1728	0.0007	0.75	0.03	H
3895	Earhart	07/26-07/29	21.2,21.6	261	26	3.567	0.001	0.42	0.02	PHO
4956	Noymer	08/30-09/05	18.0,19.8	312	17	4.379	0.001	0.46	0.03	PHO
5870	Baltimore	07/27-07/29	15.1,14.4	336	4	4.989	0.003	0.35	0.03	MC
10403	Marcelgrun	07/16-07/20	17.6,16.3	331	6	5.549	0.004	0.37	0.03	FLOR
11059	Nulliusinverba	09/15-09/16	0.7,0.2	354	0	2.455	0.005	0.15	0.01	EUN
12494	Doughamilton	07/13-07/25	25.1,20.0	331	-1	39.23	0.02	0.70	0.03	H
13162	Ryokkochigaku	07/24-08/01	14.9,11.4	325	7	86.6	0.1	0.5	0.1	V
						^T 124.6	0.5	0.3	0.1	
13186	1996 UM	07/06-07/08	20.4,20.7	274	32	4.292	0.003	0.64	0.04	H
14211	1999 NT1	08/04-08/07	18.8,18.8	323	22	3.586	0.002	0.19	0.02	MC
14793	1975 SE2	08/26-08/26	6.5	339	-9	3.61	0.06	0.27	0.03	V
14923	1994 TU3	2008/06/30-07/13	21.9,22.0	293	33	2.529	0.001	0.19	0.02	PHO
21663	Banat	07/16-07/21	15.5,14.0	330	5	15.52	0.02	0.48	0.04	MB-O
23482	1991 LV	09/02-09/04	22.6,22.1	359	27	3.130	0.003	0.28	0.03	H
		2015/08/30-09/05	34.1,33.5	37	16	3.358	0.002	0.31	0.03	
						^A 3.356	0.002	0.32	0.03	
		2012/06/26-07/13	18.7,18.6	300	23	3.139	0.001	0.21	0.03	
24177	1999 XJ7	08/24-08/25	6.8,6.5	339	-9	3.810	0.003	0.47	0.03	FLOR
28565	2000 EO58	07/02-07/06	*24.6,23.1	271	7	3.71	0.01	0.21	0.04	MC
51534	2001 FQ132	08/26-08/27	7.3,7.0	339	-8	7.11	0.03	0.42	0.05	MB-I
56086	1999 AA21	08/09-08/26	14.9,5.9	341	2	2.77037	0.00005	0.17	0.01	PHO
68134	2001 AT18	08/04-08/09	27.0,26.7	344	31	7.099	0.002	1.04	0.03	MC
	Pole (λ , β , P)	(25°, -19°, 7.107274 h)	(323°, -79°, 7.107278 h)	a/b: 2.29	a/c: 1.09					
96341	1997 OX1	07/16-07/20	*26.1,24.5	311	7	3.019	0.003	0.08	0.02	MB-I
						^A 1.611	0.002	0.08	0.02	
						^A 4.830	0.005	0.08	0.02	
129480	1993 UQ8	09/19-09/20	1.3,1.8	354	0	27.5	0.5	0.62	0.05	MB-O
146134	2000 SE1	07/15-07/23	*15.1,14.2	304	12	21.782	0.005	1.16	0.02	MC
164755	1998 VK27	07/16-07/19	12.6,11.5	317	10	3.65	0.01	0.27	0.04	MB-O

Table III. Observing circumstances and results. ^AThe alternate period of an ambiguous solution. ^TSecond period in a suspected tumbler. 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): EUN, Eunomia; FLOR, Flora; H, Hungaria; MC, Mars-crosser; MB-(I/O): Main belt (inner/outer); PHO, Phocaea; V,

SPIN/SHAPE MODEL FOR 1662 SADEYA

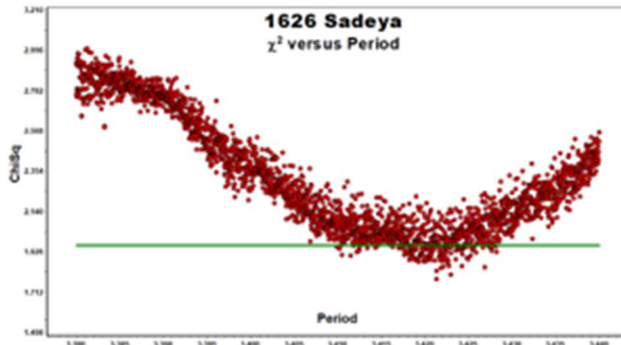


Figure 1. The initial period search results.

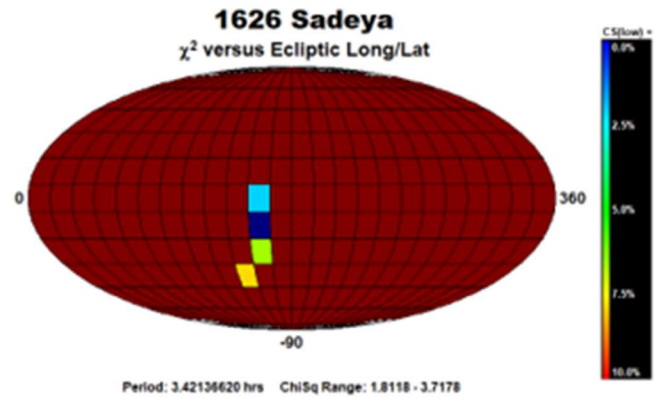


Figure 2. The pole search found two probable solutions.

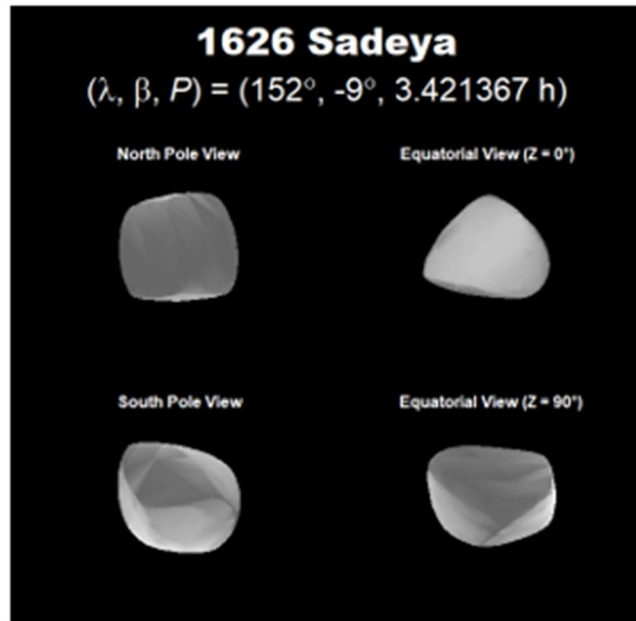


Figure 3. The shape of the asteroid based upon the secondary solution.

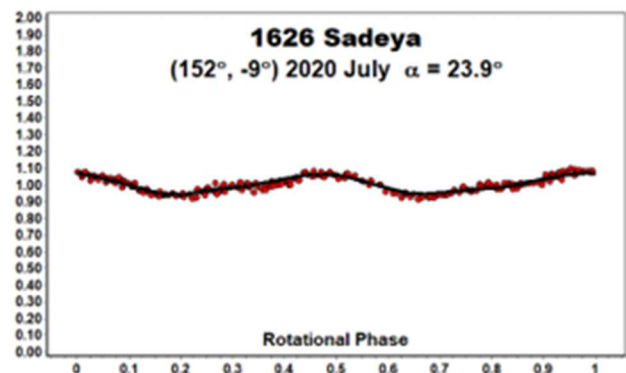
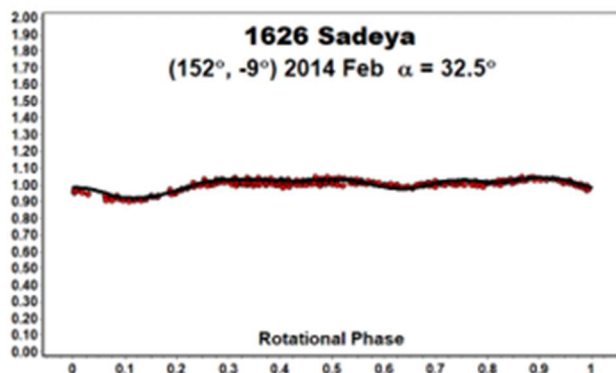


Figure 4/5. The comparison plots are against the preferred pole solution. The red dots indicate the data used for modeling while the black line is the smoothed lightcurve for generated by the shape at the time of the observations. The match is very close on both occasions, which gives confidence in the shape/spin axis model.

SPIN/SHAPE MODEL FOR (68134) 2001 AT18

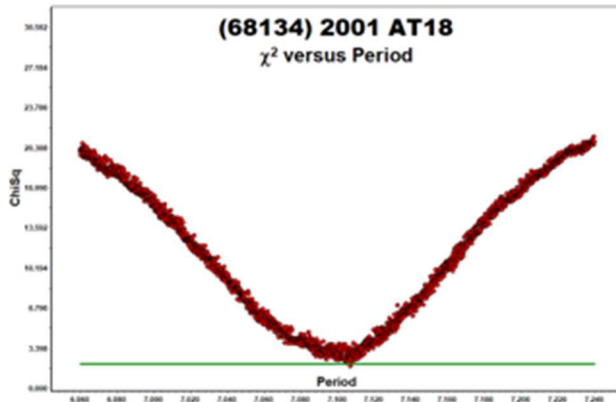


Figure 1. The initial period search results.

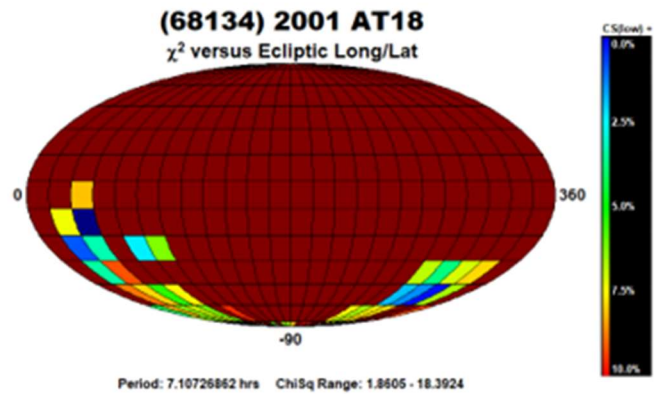


Figure 2. The pole search found two probable solutions.

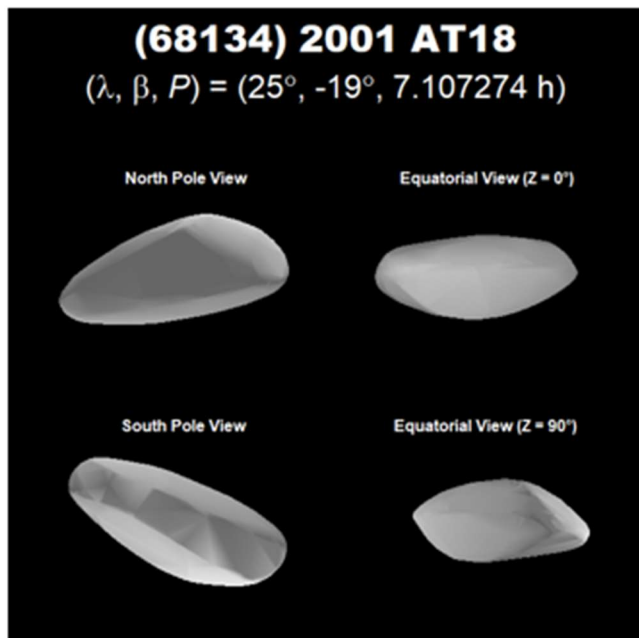


Figure 3. The shape of the asteroid based on the preferred solution.

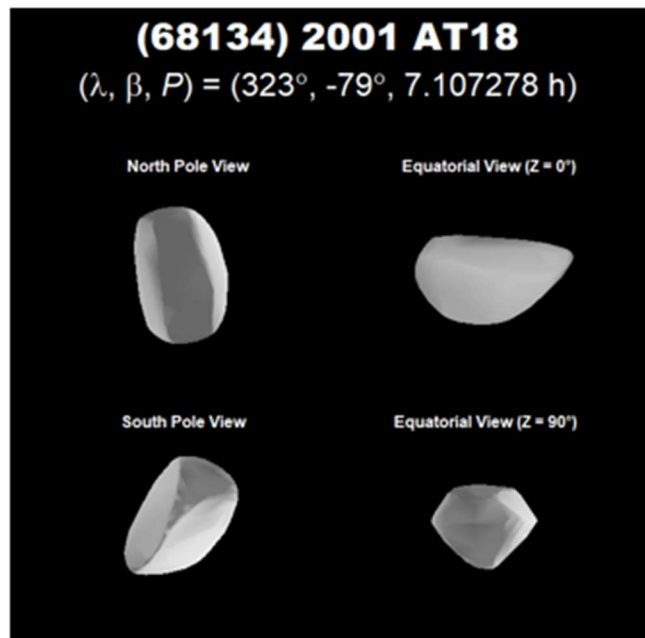


Figure 4. The shape of the asteroid based upon the secondary solution.

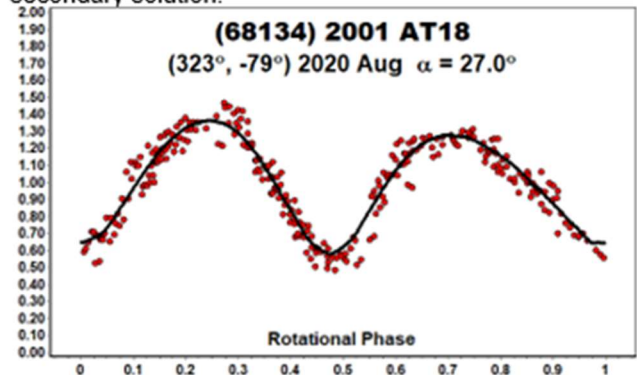
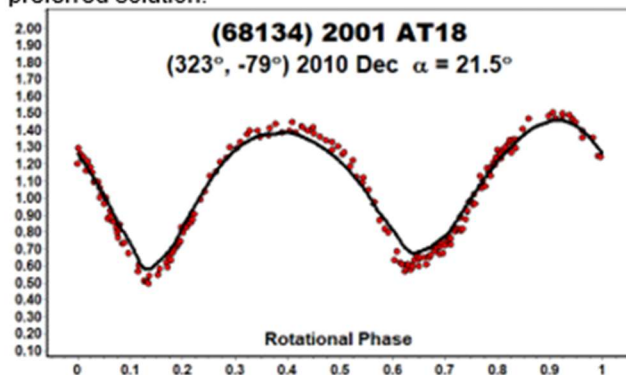


Figure 5/6. The comparison plots are against the preferred pole solution. The red dots indicate the data used for modeling while the black line is the smoothed lightcurve for generated by the shape at the time of the observations. The match is very close on both occasions, which gives confidence in the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

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LIGHTCURVES OF NINETEEN ASTEROIDS

Eric V. Dose
3167 San Mateo Blvd. NE #329
Albuquerque, NM 87110
mp@ericdose.com

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Using a previously described workflow based on applying dozens of comparison stars from the ATLAS refcat catalog to each image, we have obtained and present lightcurves and synodic periods for nineteen asteroids. We also describe refinements to magnitude correction for airmass (altitude of the field of view), especially useful during periods of high extinction, for example, through atmospheric smoke resulting from recent forest fire events near the U.S. Pacific coast.

The present photometry workflow is based on that described previously (Dose, 2020b), relying on intensive application of very numerous (typically 30-150) ATLAS refcat catalog stars (Tonry et al., 2018) to each image.

Since that description, two improvements have been made to handling of atmospheric extinction, both prompted by this summer's widespread forest fires in the western United States which resulted in atmospheric smoke over the author's observing site in northern New Mexico. While prevailing upper-atmosphere winds very efficiently transported the smoke to the author's site at 1000-1500 km from the fires, extinction at the observing site changed only slowly, so that a single extinction coefficient sufficed for each night. ATLAS catalog stars were numerous enough to allow restriction of comp stars to a very narrow range of color index, so that observations continued through nights with extinction coefficients (Clear filter) up to about 0.70, where at 30° altitude only 25-30% of the light penetrates the atmosphere to reach the telescope. Exposure times were lengthened to compensate. Data from three nights with local extinction found to exceed 0.70 were rejected altogether.

In the first workflow improvement, one nightly extinction coefficient is first computed from comp stars for the night's asteroid target having the widest range in airmass; then, that extinction coefficient is applied to all targets for that night. The mixed-model regression (Gelman and Hill, 2006) on which the current workflow is based will segregate any remaining image-to-image systematic errors resulting from minor misestimation of the extinction. The advantage of starting with a good extinction estimation is not so much to get better photometric precision and accuracy, but more in clarifying the error structure so that outlier images, comp stars, and individual comp star observations can be removed properly. Nightly extinction estimation and application is not difficult and is now included in all the author's asteroid photometry.

The second workflow improvement computes an individual airmass value for each asteroid and comp star in each image, replacing the usual photometric practice of applying a center-image airmass value to all targets in that image. With extinction of 0.7, the extinction gradient near 30° above the horizon reaches 0.7 millimagnitude per arcminute of altitude; in the author's case, image corner-to-corner extinction range reached 30 millimagnitudes – much larger than ATLAS catalog magnitude uncertainties. Per-target airmasses are never worse than per-image