

NEAR-EARTH ASTEROID LIGHTCURVE ANALYSIS AT THE CENTER FOR SOLAR SYSTEM STUDIES: 2020 APRIL - JUNE

Brian D. Warner
Center for Solar System Studies / MoreData!
446 Sycamore Ave.
Eaton, CO 80615 USA
brian@MinorPlanetObserver.com

Robert D. Stephens
Center for Solar System Studies / MoreData!
Rancho Cucamonga, CA 91730

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Lightcurves for 29 near-Earth asteroids (NEAs) obtained at the Center for Solar System Studies (CS3) from 2020 April to June were analyzed for rotation period, peak-to-peak amplitude, and signs of satellites or tumbling.

CCD photometric observations of 29 near-Earth asteroids (NEAs) were made at the Center for Solar System Studies (CS3) from 2020 April to June. Table I lists the telescopes and CCD cameras that are combined to make observations.

Up to nine telescopes can be used for the campaign, although seven is more common. All the cameras use CCD chips from the KAF blue-enhanced family and so have essentially the same response. The pixel scales ranged from 1.24-1.60 arcsec/pixel.

Telescopes	Cameras
0.30-m f/6.3 Schmidt-Cass	FLI Microline 1001E
0.35-m f/9.1 Schmidt-Cass	FLI Proline 1001E
0.40-m f/10 Schmidt-Cass	SBIG STL-1001E
0.40-m f/10 Schmidt-Cass	
0.50-m f/8.1 Ritchey-Chrétien	

Table I. List of available telescopes and CCD cameras at CS3. The exact combination for each telescope/camera pair can vary due to maintenance or specific needs.

All lightcurve observations were unfiltered since a clear filter can cause a 0.1-0.3 mag loss. The exposure duration varied depending on the asteroid's brightness and sky motion. Guiding on a field star sometimes resulted in a trailed image for the asteroid.

Measurements were made using *MPO Canopus*. The Comp Star Selector utility in *MPO Canopus* found up to five comparison stars of near solar-color for differential photometry. Comp star magnitudes were taken from ATLAS catalog (Tonry et al., 2018), which has Sloan *griz* magnitudes that were derived from the GAIA and Pan-STARR catalogs, among others, and are the "native" magnitudes of the catalog.

To reduce the number of times and amount of resetting nightly zero points, we use 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.

Unless otherwise indicated, the Y-axis of lightcurves is ATLAS SR "sky" (catalog) magnitudes. During period analysis, the magnitudes were normalized to the comparison stars used in the earliest session and to the phase angle given in parentheses using

$G = 0.15$, unless another value is given. The X-axis shows rotational phase from -0.05 to 1.05 . If the plot includes the amplitude, e.g., "Amp: 0.65", this is the amplitude of the Fourier model curve and *not necessarily the adopted amplitude for the lightcurve*.

Our initial search for previous results started with the asteroid lightcurve database (LCDB; Warner et al., 2009) found on-line at <http://www.minorplanet.info/lightcurvedatabase.html>. Readers are strongly encouraged to obtain, when possible, the original references listed in the LCDB. From here on, we'll use only "LCDB" to reference the paper by Warner et al. (2009).

1685 Toro. The estimated size of this well-studied NEA is about 4 km. Higgins (2008) reported a period of 10.1995 h based on observations in 2007. His amplitude of 0.47 mag at $L_{PAB} = 251^\circ$ and phase angle $\alpha = 5.8^\circ$ is the smallest reported to-date in the LCDB. The largest amplitude to-date, 1.80 mag, was found by Warner (2013a) in 2012 August with $L_{PAB} = 29^\circ$ and $\alpha = 96.5^\circ$. A direct comparison of the two amplitudes at different L_{PAB} values is complicated because the phase angles are significantly different.

Zappala et al. (1990) developed Eq. 1 to determine the amplitude at 0° phase angle based on the amplitude at a given angle (α).

$$A(0^\circ) = A(\alpha)/(1 + m\alpha) \quad (\text{Eq. 1})$$

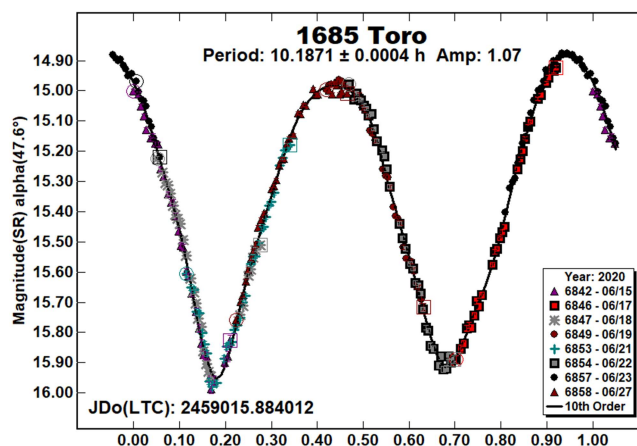
where m is a coefficient depending on approximate taxonomic class. Binzel et al. (2019) determined Toro to be a type Sq and so the Zappala et al. value of $m = 0.030$ was used in Eq. 1 to compare the resulting $A(0^\circ)$ values.

$$A(0^\circ) = A(5.8^\circ)/(1 + 0.030 \cdot 5.8) = 0.40 \text{ mag}$$

$$A(0^\circ) = A(96.5^\circ)/(1 + 0.030 \cdot 96.5) = 0.46 \text{ mag}$$

Given the uncertainties in the value for m and the amplitudes, the two results are in good agreement.

The 2020 observations at CS3 led to a period of 10.1871 h and amplitude 1.07 mag at $\alpha = 49.5^\circ$ ($A(0^\circ) = 0.43$ mag). These data were combined with our dense data sets from past apparitions (ALCDEF, 2020) and sparse data from the Catalina Sky Survey (CSS; 2020) downloaded from the AstDys (2020) web site to try to model the spin axis and shape. We used *MPO LCInvert* to implement the lightcurve inversion methods developed by the late Mikko Kaasalainen (Kaasalainen and Torpa, 2001; Kaasalainen et al., 2001). The results are shown in Fig 1-5 in the callout box below.



SPIN/SHAPE MODEL FOR 1685 TORO

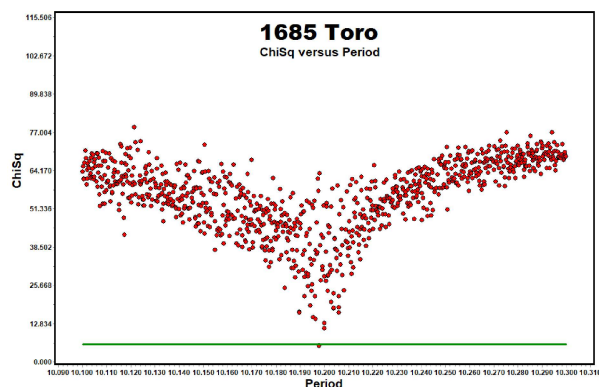


Figure 1. The initial period search results.

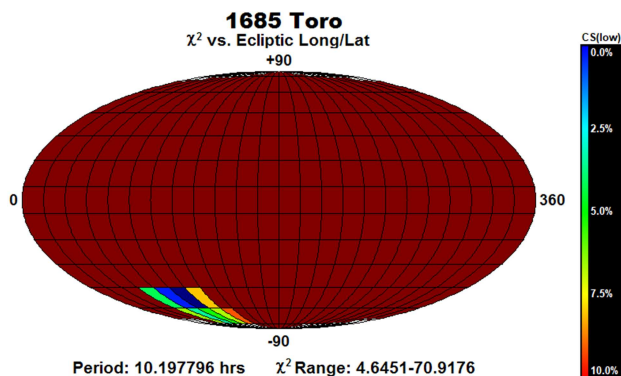


Figure 2. The pole search found two probable solutions.

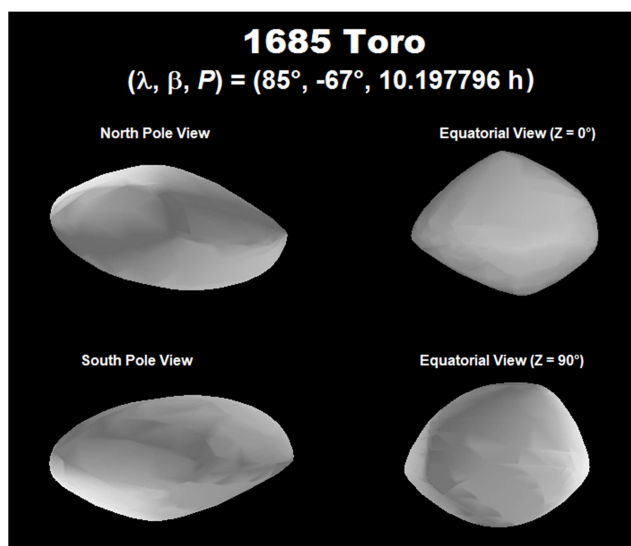


Figure 3. The shape of the asteroid based on the preferred pole solution.

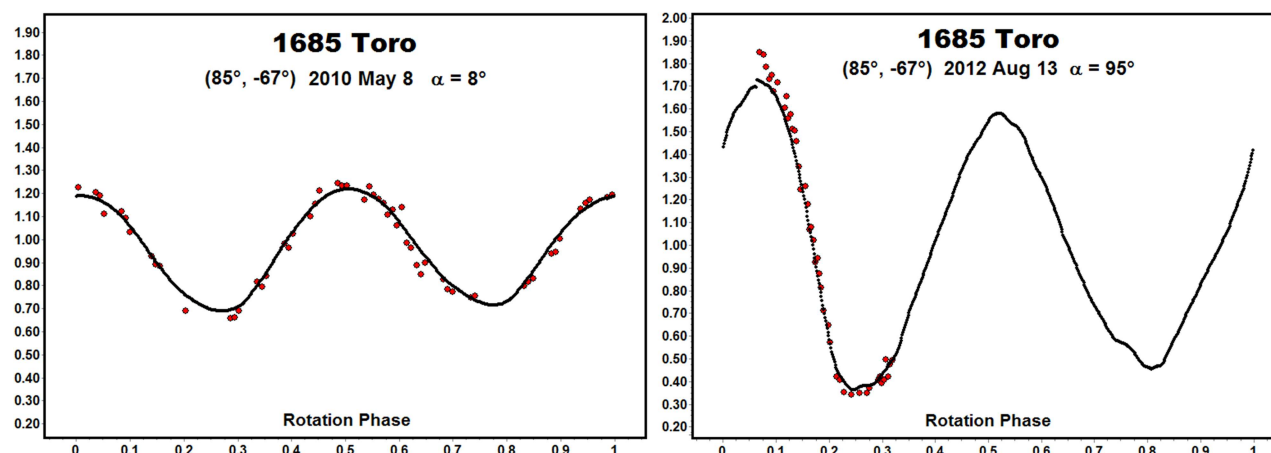


Figure 4/5. The comparison plots are against the adopted pole solution. The red dots indicate the data used for modeling while the black line is the smoothed lightcurve for generated by the shape at the time of the observations. The match is very close in 2010 but not quite so much for 2012. The fit to the 2020 data is also not ideal. Even so, when taking into account the possibility of the YORP effect changing the spin rate of the asteroid, the overall model is good.

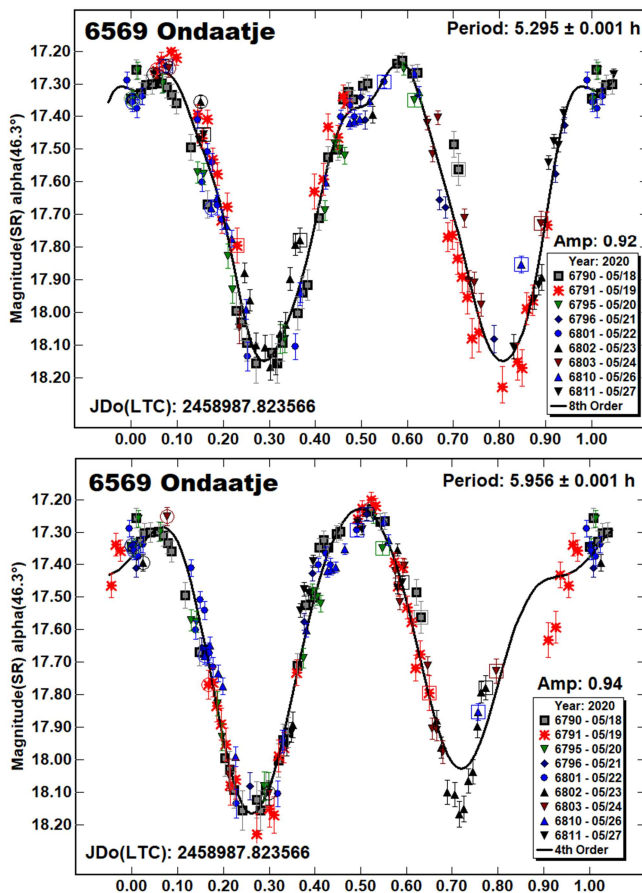
The green line in Fig. 1 represents a value that is 10% greater than the smallest χ^2 value. With only the one point below the line, the fixed period solution (see below) seemed secure, as was the pole search, which found a single solution near

$(\lambda, \beta) = (75^\circ, -60^\circ)$. The refined search led to a final solution of $(\lambda, \beta, P) = (85^\circ, -67^\circ, 10.197796 \text{ h})$. This is in good agreement with Āurech et al. (2018), who found $(\lambda, \beta, P) = (71^\circ, -69^\circ, 10.19782 \text{ h, Epoch 1972 July 8.5})$.

Noting the epoch is important when trying to determine if the YORP effect (Rubincam, 2000) is causing the asteroid's rotation rate to change over time. Based on data through 2017, they found an inconclusive result that the spin rate was decreasing (the period increasing) such that there would be a phase shift of about 22° over the 44 years covered by their data. When removing data from 1996, the difference between a fixed period solution and one influenced by YORP became almost negligible. It's hoped that these latest data can help lead to a more certain result.

6569 Ondaatje. Pravec et al. (1996) reported a period of 5.959 h. Waszczak et al. (2015) found a similar period of 5.916 h using sparse wide-field survey data. The 2020 data set from CS3 found a similar period, but only if using a looser-fitting Fourier solution (4th order). Given the large amplitude of 0.94 mag, a higher order Fourier solution (8th order) seemed more appropriate. It found a significantly different period of 5.295 h.

We have adopted the shorter period for this paper based on 1) the longer period solution has a significant gap in the lightcurve that hints at a *fit by exclusion*, which is where the Fourier analysis finds a local minimum by minimizing the number of overlapping data points, and 2) the data from May 19 do not have a good fit to the Fourier curve. The shorter period with the higher-order solution, however, has no noteworthy gaps in coverage and more accurately follows the deep minimums.

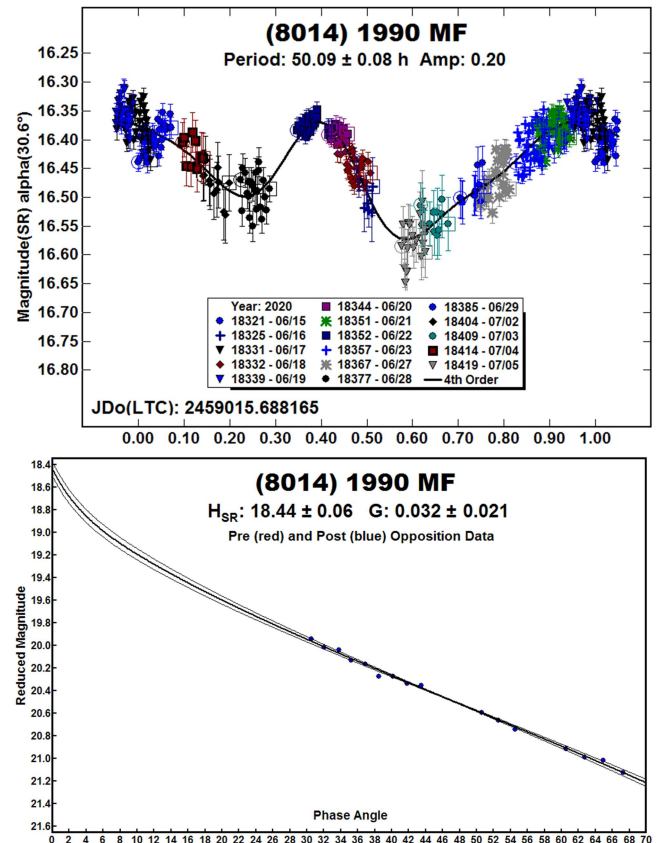


(8014) 1990 MF. There were no previous entries in the LCDB for this 500-meter NEA. The nightly runs were short in comparison to the derived period. The high-confidence in the nightly zero points using the ATLAS catalog (Tonry et al., 2018) was vital in this case. The H-G plot shows a good fit to the linear portion of the solution. When the Sloan r' (SR) magnitudes were converted to

approximate V magnitudes, the result was $H = 18.62$, which is close to the value of $H = 18.7$ listed in the MPCOrb file from the Minor Planet Center (MPC; 2020).

Something to bear in mind is that the H-G system is not as well-defined at phase angles $> \sim 50^\circ$ and so the low value for G , which would be indicative of a low albedo (dark) asteroid (Warner et al., 2009), is suspect. Also not taken into account is the well-known but often ignored phase reddening effect (Alan Harris, private communications), which causes an asteroid's color to be more red as the phase angle increases. If reddening had been taken into account, the value for G might be larger and so come closer to values typical of type S asteroids (Warner et al., 2009).

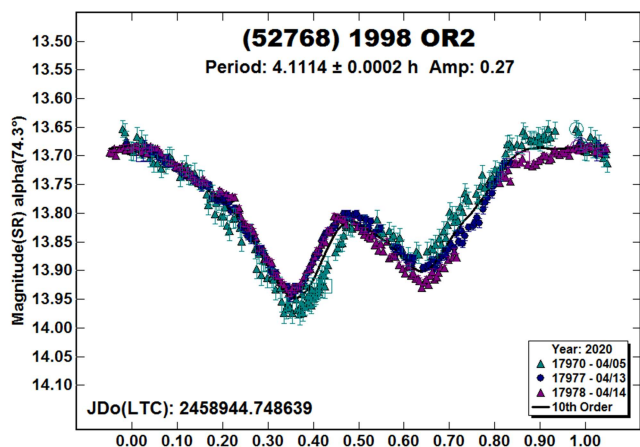
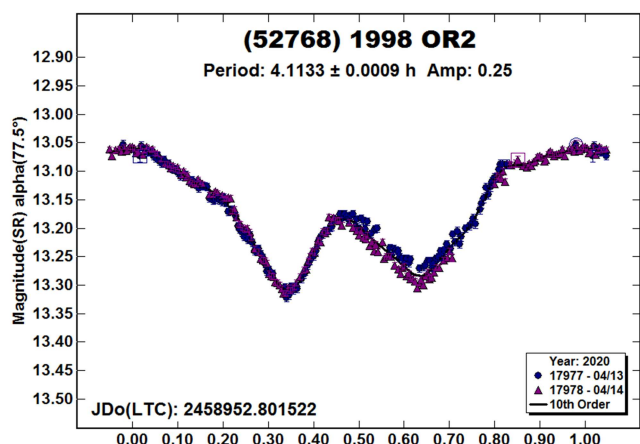
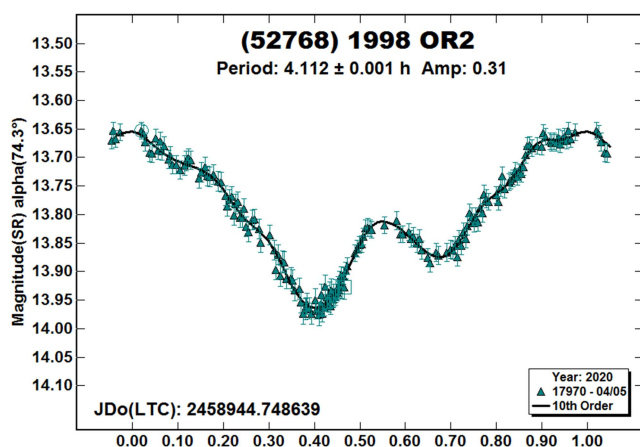
However, it is not automatic that type S asteroids have moderate albedos. The LCDB features at least seven asteroids where the measured taxonomic class is in the S-complex and the measured albedo is < 0.10 , e.g., 542 Susanna ($p_V = 0.0897$, Tholen type S).



(52768) 1998 OR2. The estimated diameter of 1990 MF is about 2 km (Radar Team, 2020). Betzler and Novaes (2009) found a period of 3.198 h. A more likely solution of 4.112 h was reported by Koehn et al. (2014) based on observations made shortly before those by Betzler and Novaes.

Our 2020 data set showed a significant evolution of the lightcurve over just a few days. The plot for April 5 shows two “dips” with noticeably different depths and shapes. About a week later, the two were more equal in depth and the overall amplitude of the lightcurve was 0.06 mag smaller.

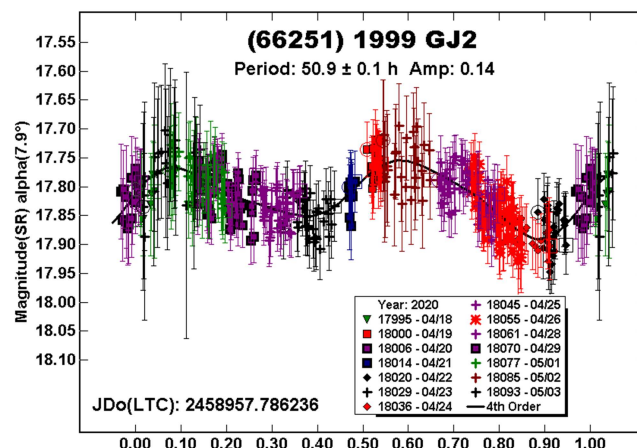
The differences are more dramatic when trying to find a period using the entire data set. Despite those differences, the combined set still allowed finding a refined synodic period of 4.1114 h.



(66251) 1999 GJ2. Pravec et al. (2005web) reported a period of 2.4621 h but their lightcurve is not available. Polishook (2012) reported a low-quality solution of 2.5 h. The 2020 data set from CS3 does not support a short period but, in fact, leads to a period of 50.9 h when setting all nightly zero points to 0.0, i.e., assuming that the ATLAS catalog magnitudes were good to 0.01–0.02 mag.

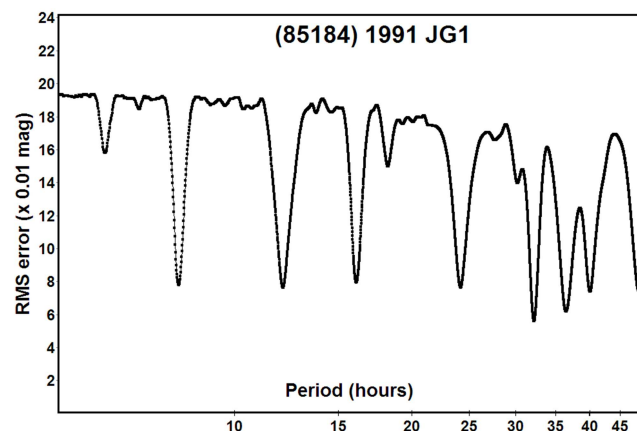
We tried forcing the solution to $2 < P < 3$ h. The result was a noisy “flat line” with essentially no signal in the period spectrum. Our data are not the highest quality, which may taint the analysis to some degree, and it’s possible that the different viewing circumstances (Pravec et al., $L_{PAB} = 7^\circ$, $\alpha = 40^\circ$; this work, $L_{PAB} = 216^\circ$, $\alpha = 6^\circ$) played a role as well.

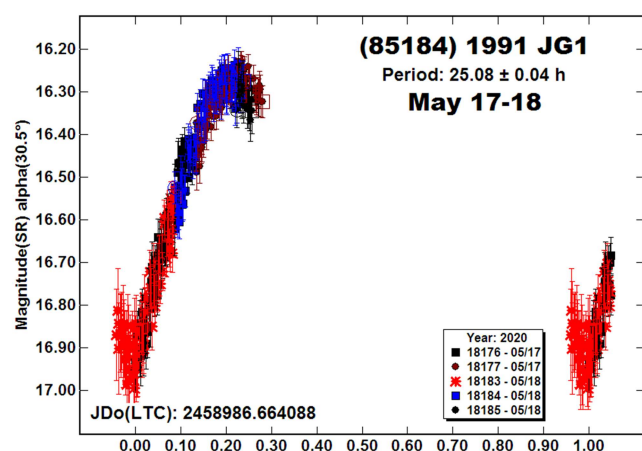
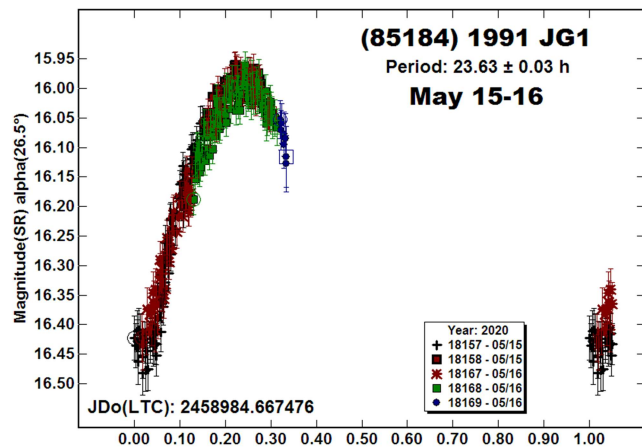
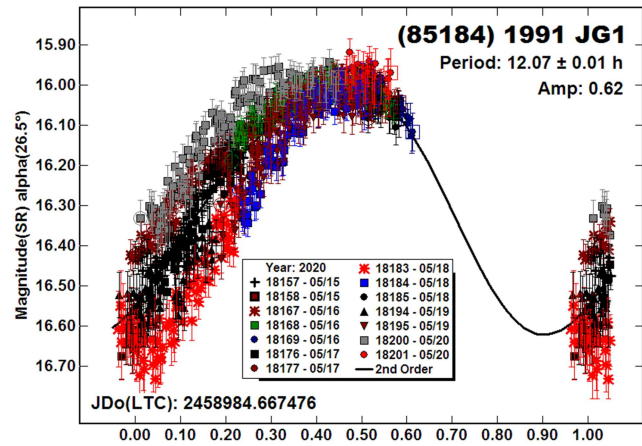
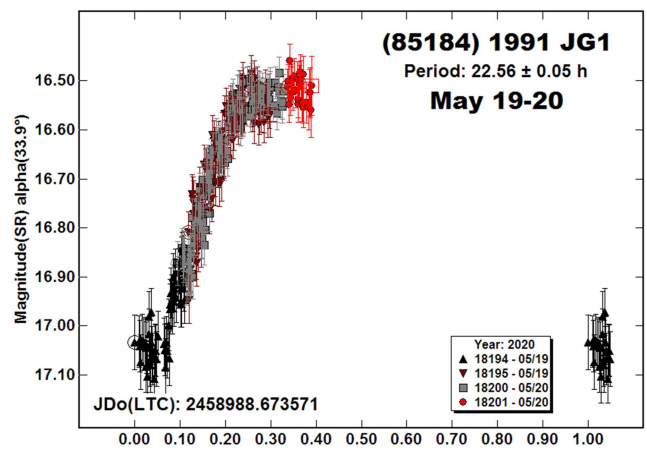
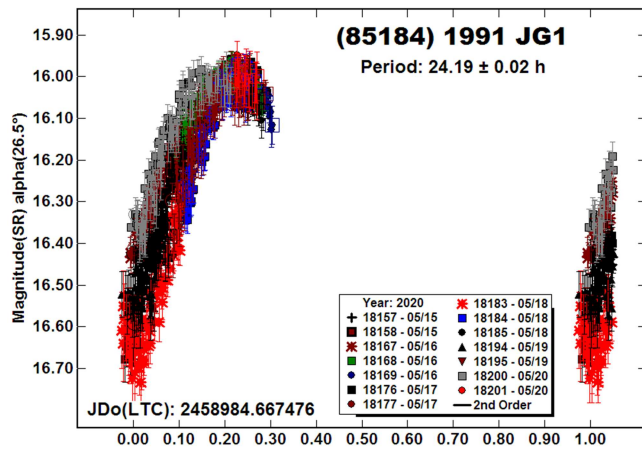
A good chance to solve the mystery comes in 2022 June ($V \sim 17.1$, $\delta \sim 8^\circ$) and in 2024 September ($V \sim 15.2$, $\delta \sim 13^\circ$).



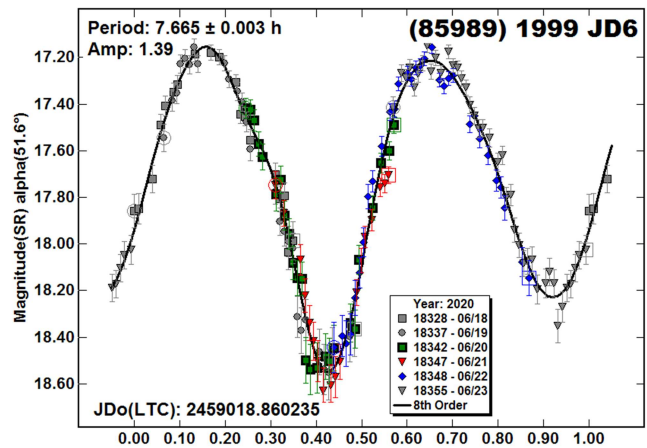
(85184) 1991 JG1. This NEA was well south of the equator in early 2020 May. By the time it was observable at CS3, it was fading and heading for high declinations. As the period spectrum shows, all the potential solutions were nearly commensurate with an Earth day, which made finding a solution nearly impossible from a single station.

Pravec et al. (2020web) reported a period of 24.02 h. This is close to what we found, with the solution changing slightly based on which subset of data that was used. Given the amplitude and not too extreme phase angle, a bimodal lightcurve was very likely (Harris et al., 2014) and so we adopted a period of 24.19 h for this work. This is based on using the entire dataset. The additional lightcurves show the apparent evolution of shape and amplitude during the apparition.

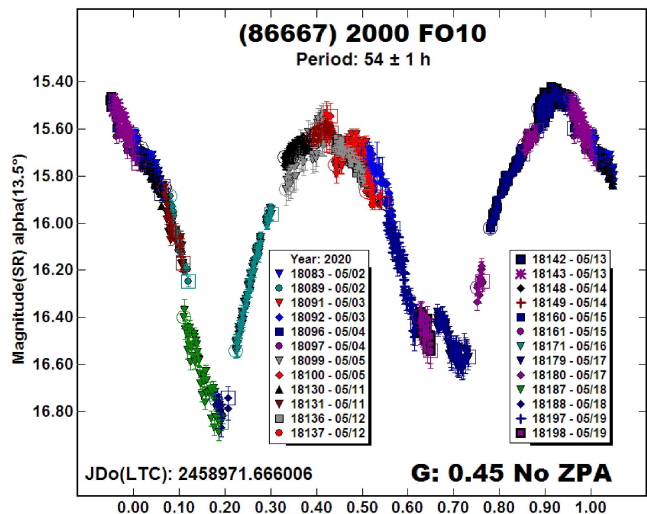


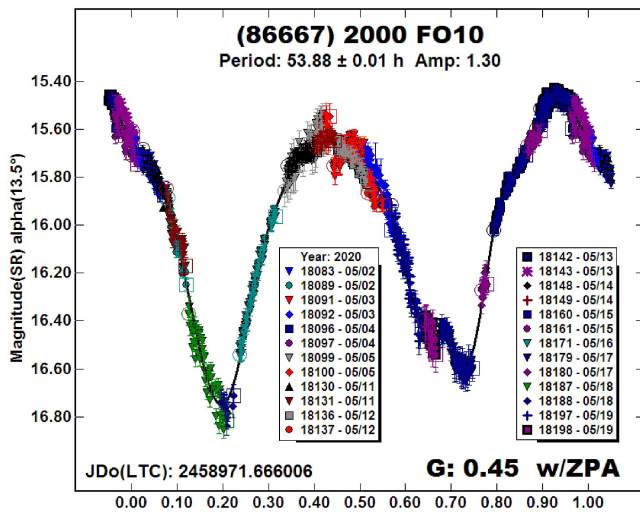


(85989) 1999 JD6. This 1.2 km NEA has been worked numerous times in the past, e.g., Pravec et al. (1999web; 7.666 h), Polishook and Brosch (2008; 7.6638 h), and Warner (2014; 7.667 h).

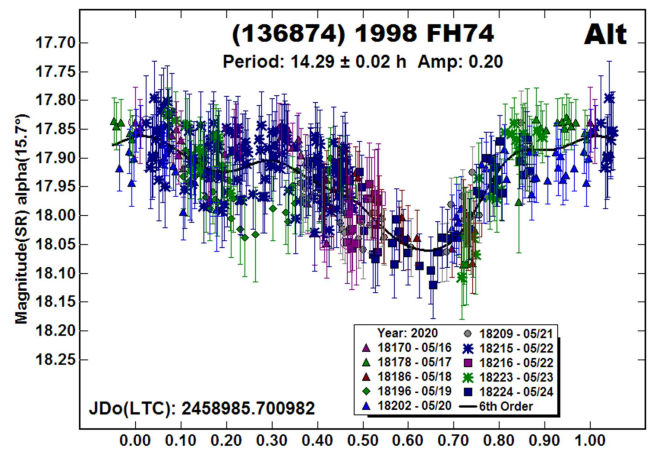
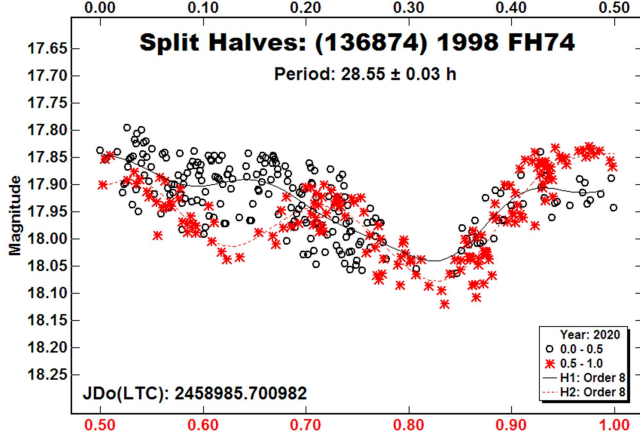
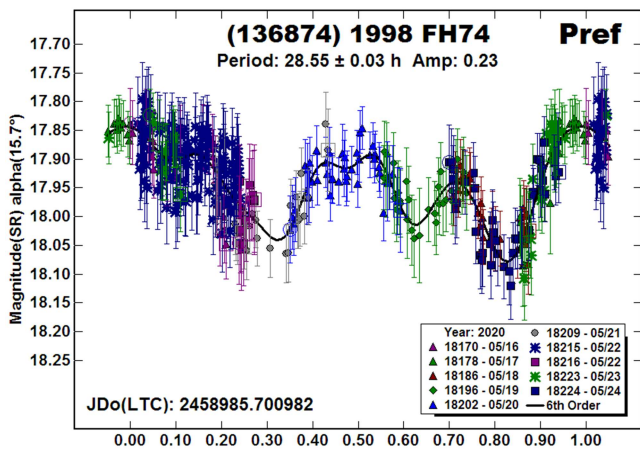


(86667) 2000 FO10. Polishook and Brosch (2008) found a low-quality solution of 26 h. Using $G = 0.45$ gave a better fit to our data without having unusually large zero-point adjustments. With some minor adjustments (4 sessions at $< [0.04]$ mag), the fit to the Fourier curve was even tighter.

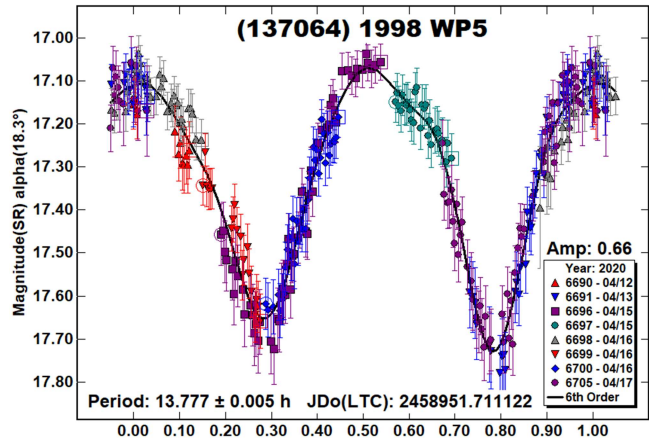




(136874) 1998 FH74. This appears to be the first reported lightcurve rotation period in the LCDB. The period spectrum shows two strong possibilities with the preferred solution being the longer one of 28.55 h. The split halves plot (see Harris et al., 2014) shows significant differences between the two halves, which helped exclude, but not quite formally, the half-period of 14.29 h.

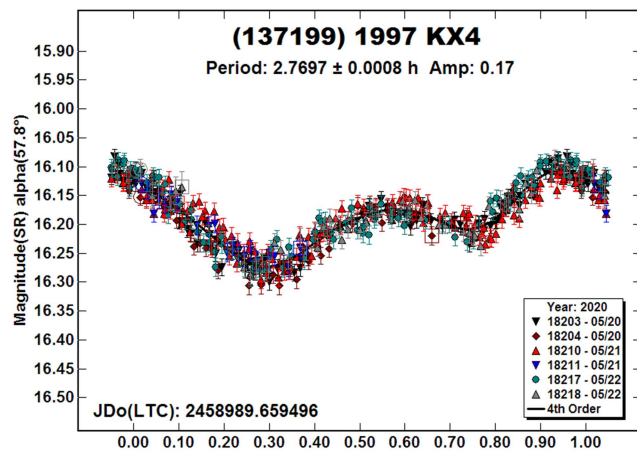


(137064) 1998 WP5. Pravec et al. (2020web) observed this 500-meter NEA about the same as we did, mid-April. There was enough difference in viewing aspects, however, to show the phase angle-amplitude relationship (Zappala et al., 1990). The phase angle for Pravec et al. was about 8.6° and amplitude 0.52 mag. Our observations were near 16° phase angle and, as expected, the amplitude was larger: 0.66 mag.



(137199) 1999 KX4. Our previous observations (Warner, 2013b) led to a period of 2.767 h, which is nearly the same as our result from the most recent observations. In contrast, data from 2019 December (Warner and Stephens, 2020) led to a period of 2.860 h, which is well outside the error bars for the two data sets.

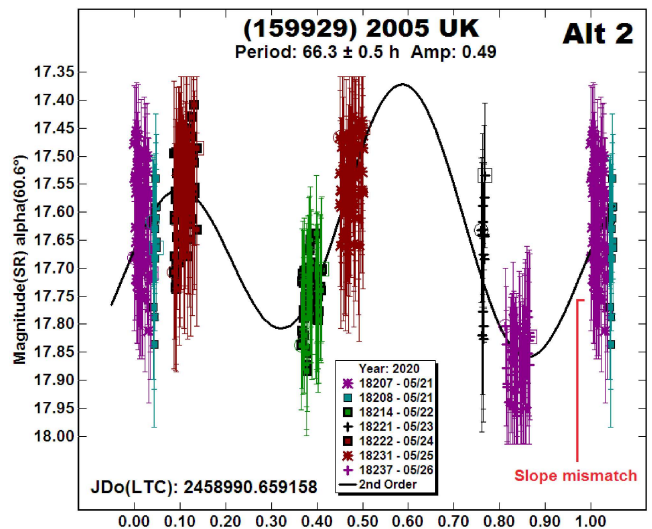
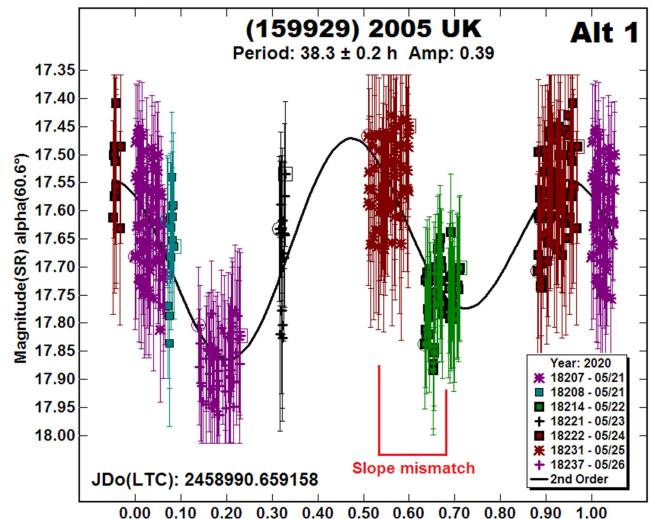
The significant difference may be due to the large change in phase angle bisector longitude (L_{PAB}), which was 100° in 2019 December and 225° in 2020 May. In addition, the fact that the rotation period decreased as the asteroid moved away from opposition (and presumably increased as it moved towards opposition) is a likely indicator that the asteroid's spin axis rotation is retrograde.



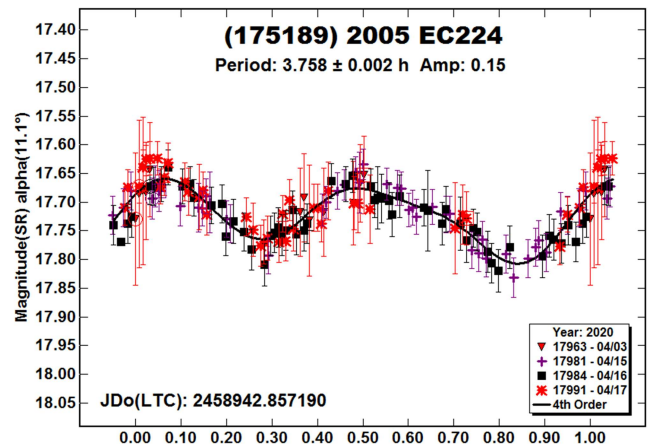
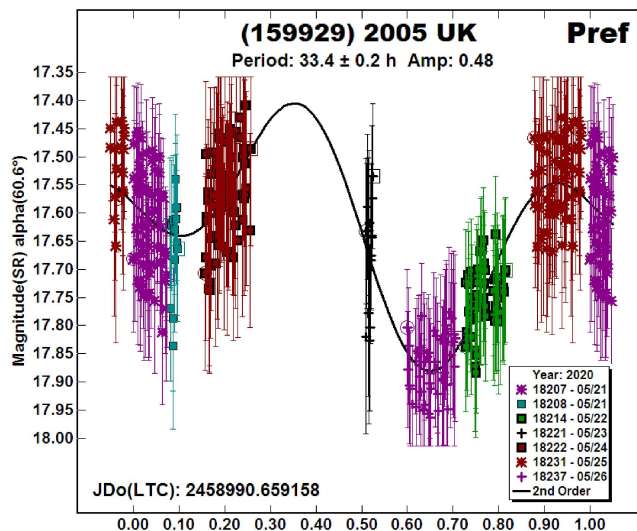
(159929) 2005 UK. There were no rotation periods previously listed in the LCDB. The period spectrum shows several possibilities, none of them overly convincing because of the low-quality data and poor coverage of the lightcurve at any of the potential periods.

We have adopted a period of 33.4 h based on the somewhat marginal evidence of how the slope of the data for each session compared to the slope of the Fourier model curve. Despite the odd shape of the lightcurve for 33.4 h, the data slopes match the Fourier slopes. The large phase angle and associated shadowing effects probably combined to make for the unusual shape.

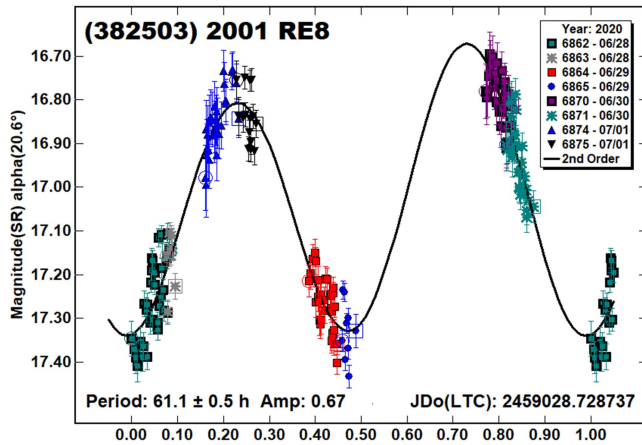
Looking at the $P = 38.3$ h solution (“Alt1”), the slope of the two marked sessions appear to be positive while the slope of the Fourier curve at those points is negative. The opposite argument can be made for the 66-hour solution (“Alt2”). Here the evidence is much thinner and, since the lightcurve shape is more symmetrical, it’s about equally possible that the 66-hour double period might be the better choice for the preferred period. Looking ahead, the next time 2005 UK makes an appearance $V < 19$ is 2033 May, when it passes only 0.13 au from Earth and reaches $V \sim 13.5$ at $\delta = -17^\circ$.



(175189) 2005 EC224. This was the first rotation period entry in the LCDB for this 650 m NEA. Fortunately, it was a relatively easy target and the solution is considered secure.

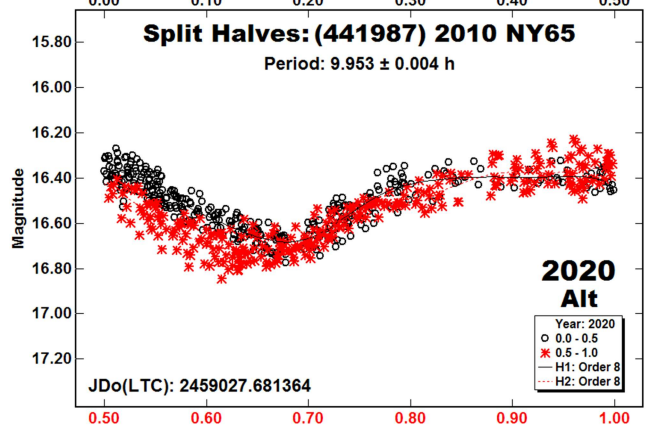
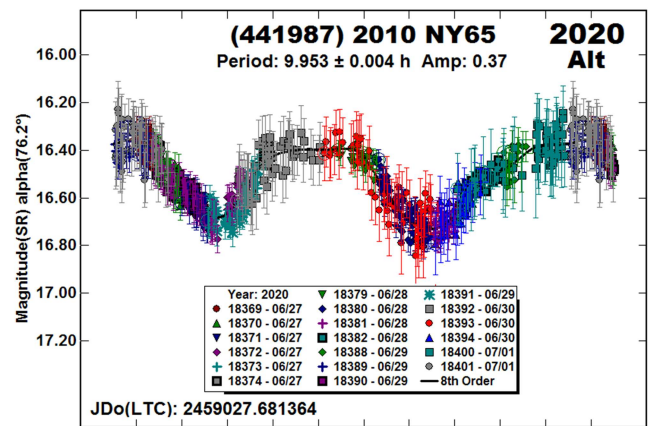
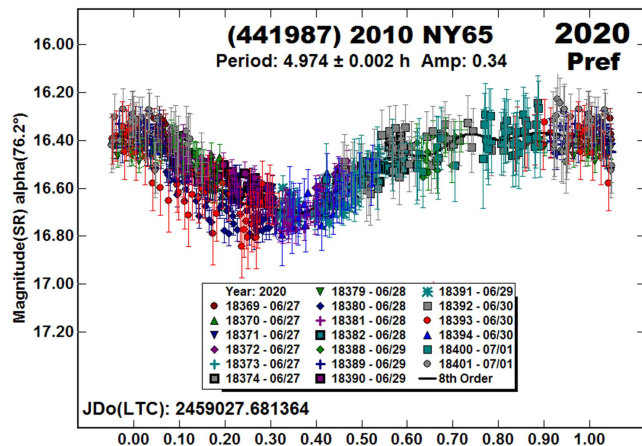
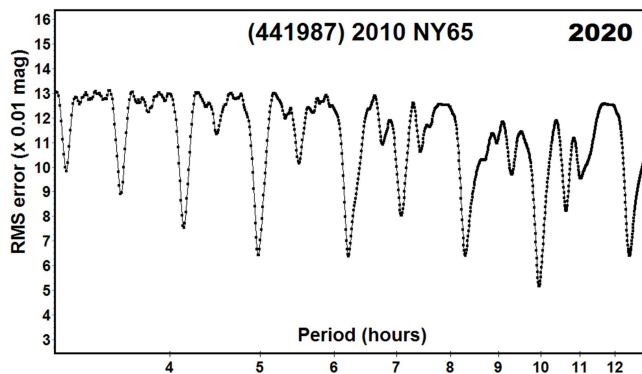


(382503) 2001 RE8. There were no previous entries in the LCDB for 2001 RE, which has an estimated diameter of 500 m. While the lightcurve has large gaps, reasonable coverage near the extrema, along with the large amplitude at a relatively low phase angle make the solution good enough for rotation statistical studies.



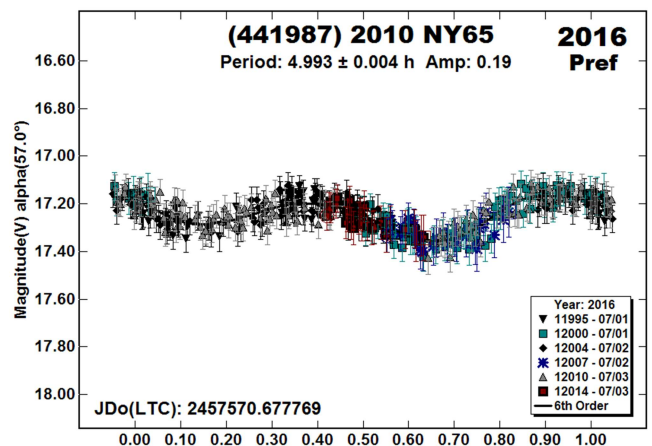
(441987) 2010 NY65. This NEA has been problematic for us over the years. The first observations (Warner 2016; 2017) found a period near 4.79 h. Data obtained in 2018 (Warner and Stephens, 2019) led to a period of 5.541 h, which is about one rotation less over 48 hours. The data from the earlier dates could be fit to a period near 5.55 h and so the 5.541 h period was adopted.

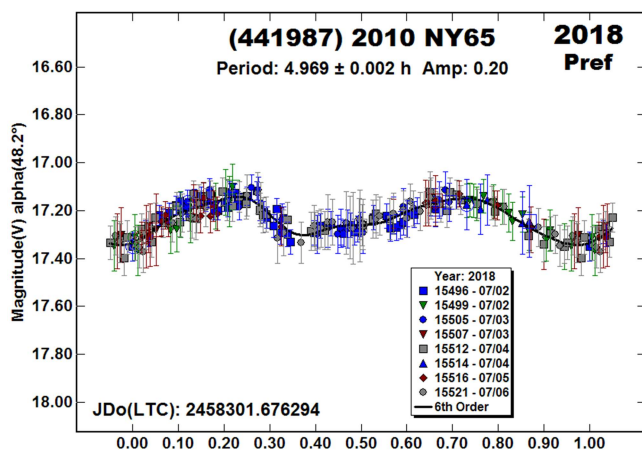
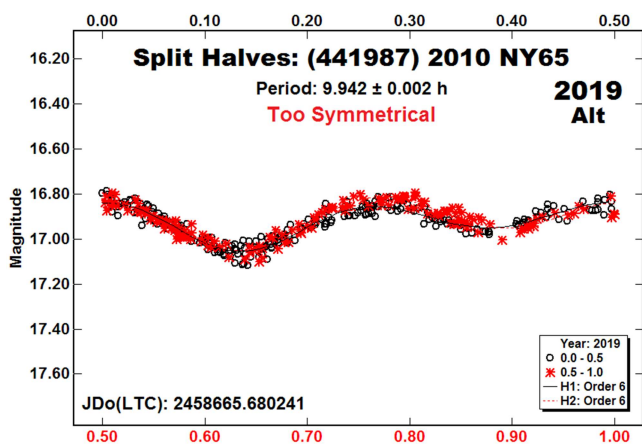
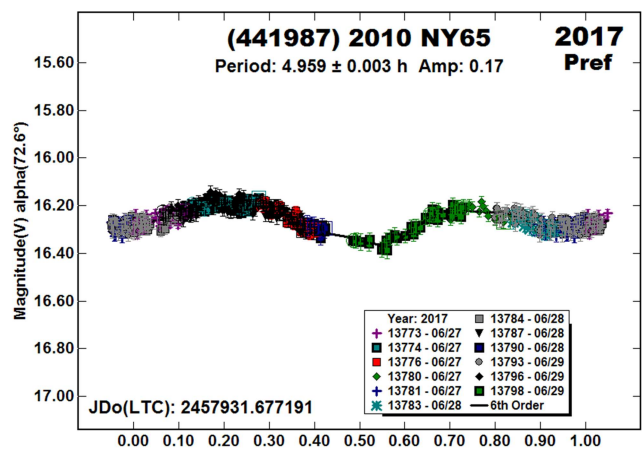
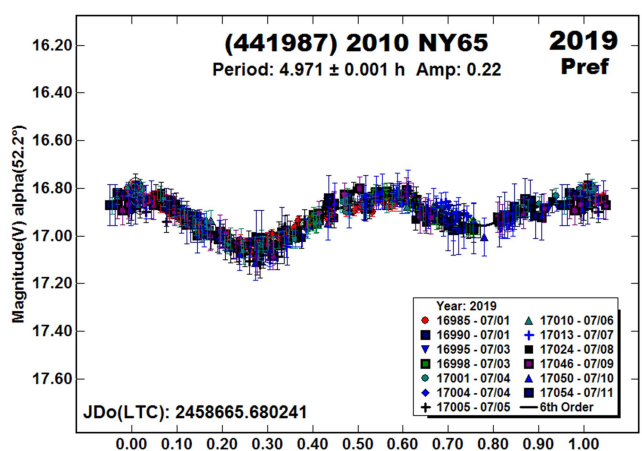
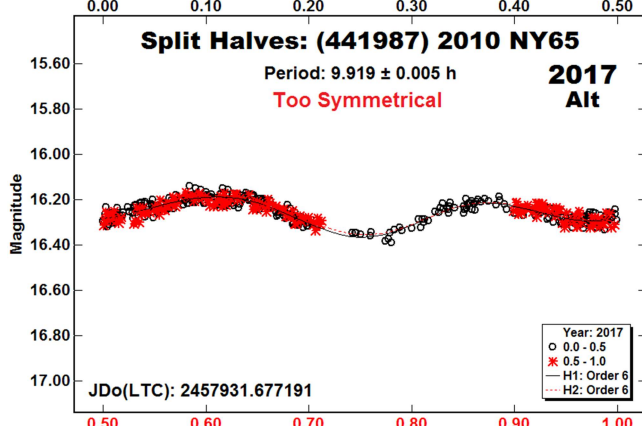
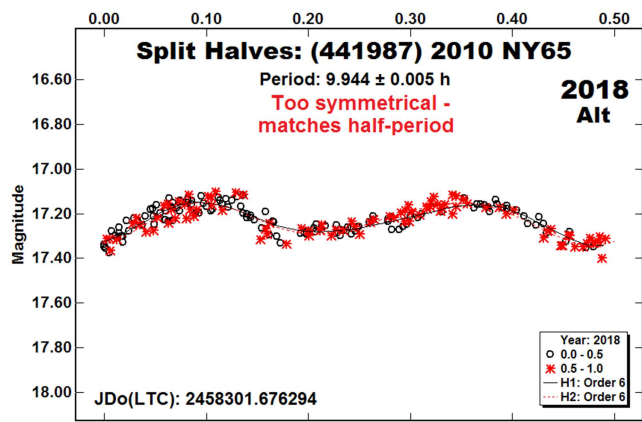
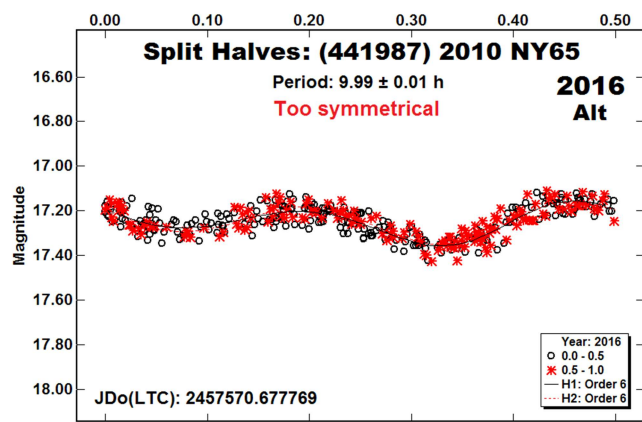
The period spectrum for our 2020 observations favors the 4.9-hour solution as an *alternate* solution, the dominant solution being 9.953 h. Once again, we redid the analysis on previous data sets.



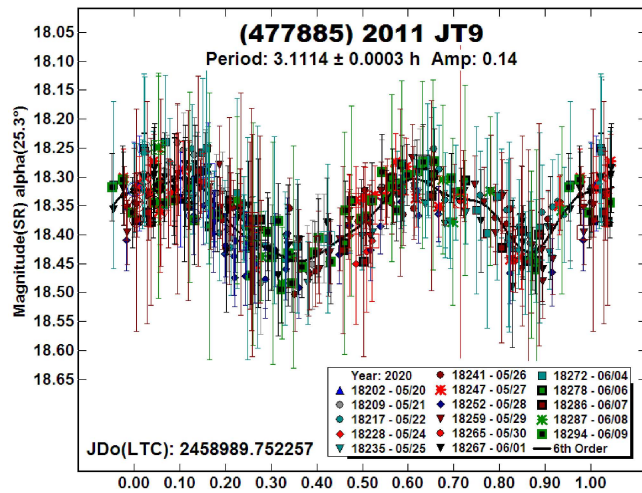
We have adopted a period of $P = 4.794$ h for this work, which closely matches our original results because the previous data sets produce lightcurves forced to near 9.9 h that are too symmetrical about their two halves. This is an indication that the half period is possible and, in many cases, more likely.

The results of our re-analysis of the earlier data sets are shown below without comment.

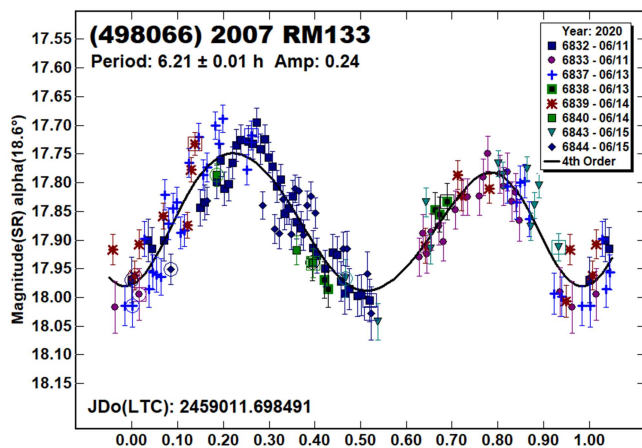
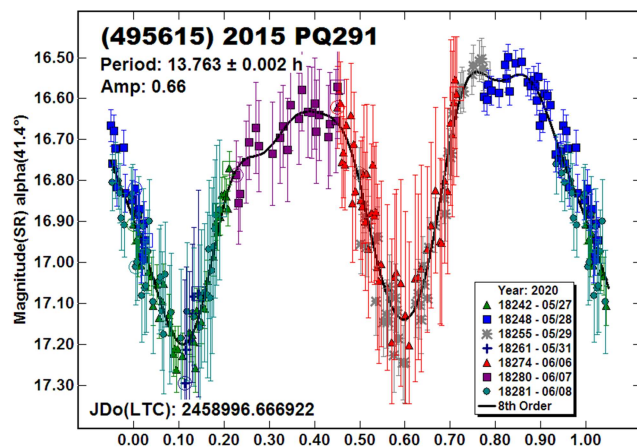




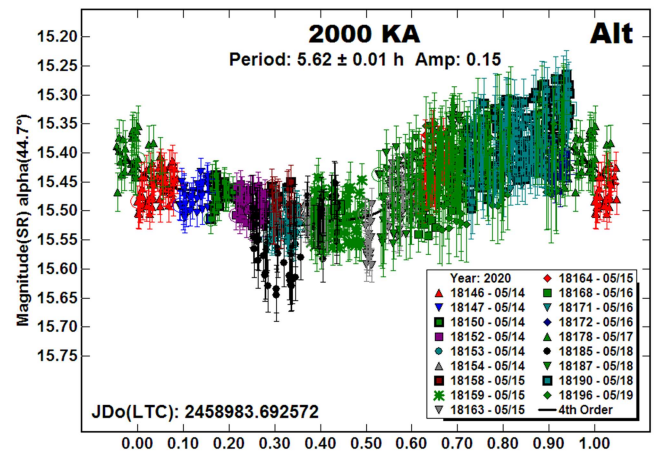
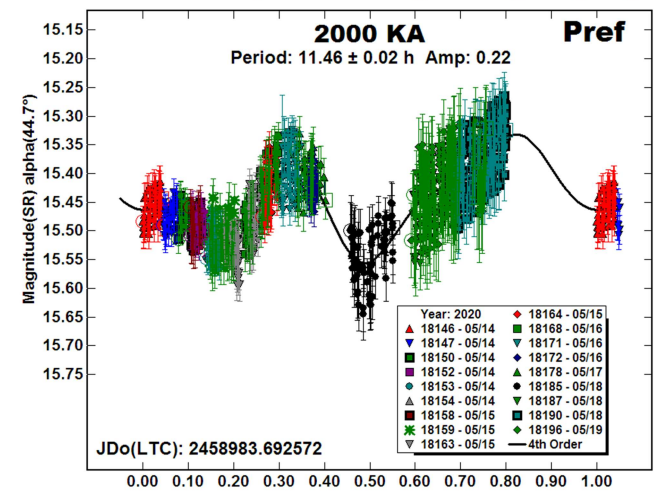
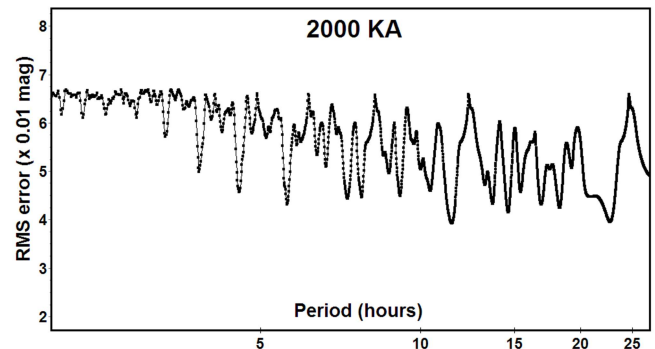
(477885) 2011 JT9. Pravec et al. (2020web) reported a period of 3.325 h based on observations towards the end of 2020 June. Our observations about a month earlier led to a slightly shorter period.



(495615) 2015 PQ291, (498066) 2007 RM133. There were no previous entries in the LCDB for these two NEAs. 2015 PQ29 has an estimated diameter of 850 m. 2007 RM133 has an effective diameter of about 700 m. Despite the gap in the lightcurve for 2007 RM133, the solution is reasonably but not completely secure given the amplitude and phase angle (Harris et al., 2014).

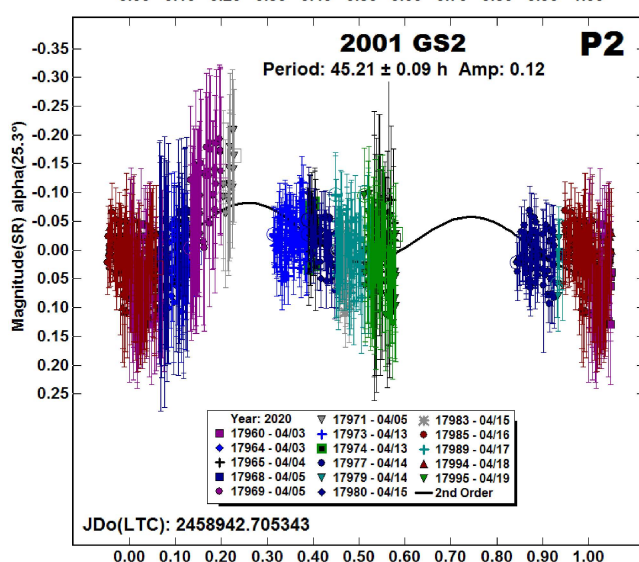
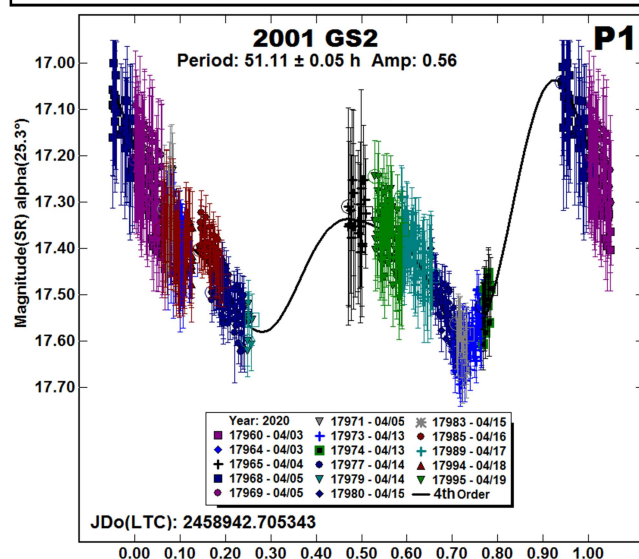
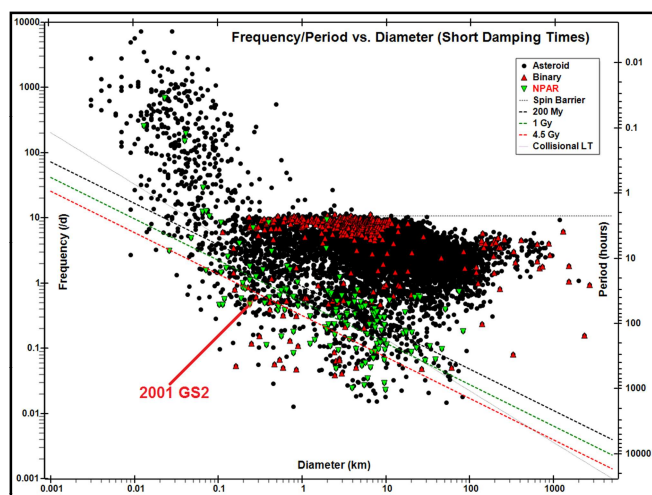


2000 KA. Pravec et al. (2020web) found a period of 5.690 h. Our result is about double that: 11.46 h. The fit to the longer period could be a *fit by exclusion* (minimized overlapping data points) but when the data are forced to the half-period, the divergence from 0.8 to 1.0 rotation phase places doubt on that solution.



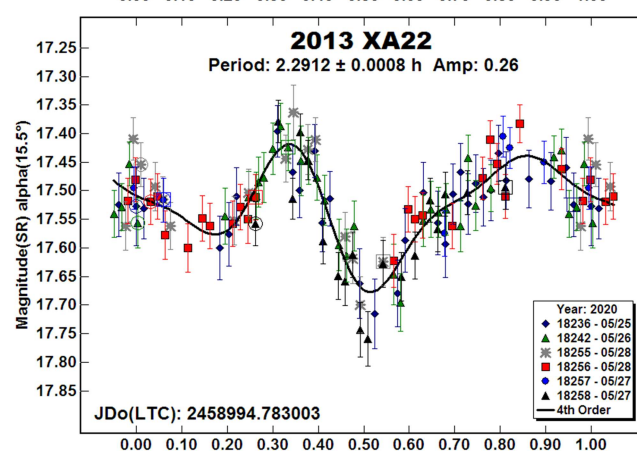
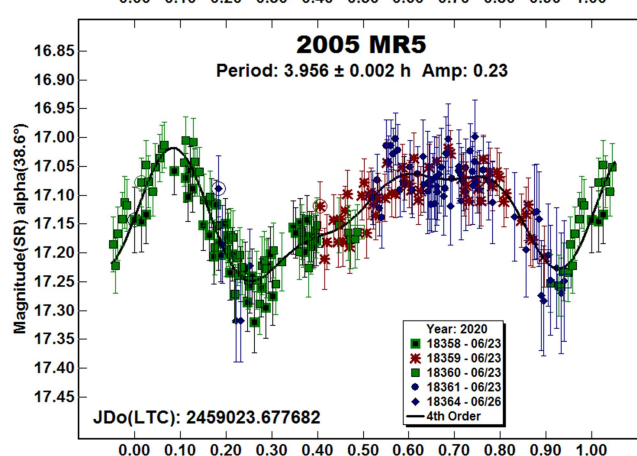
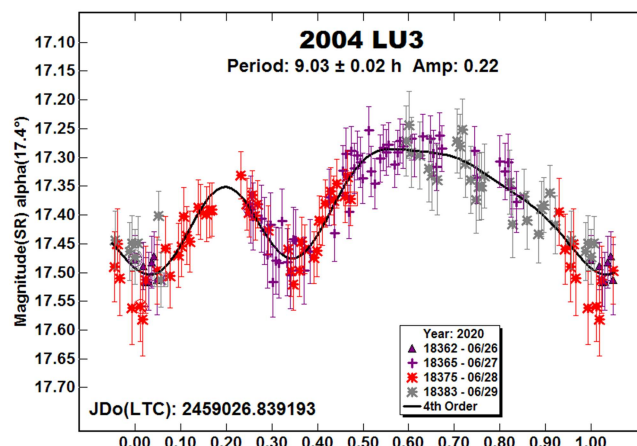
2001 GS2. Even the longer damping time for this NEA to go from tumbling to single-axis rotation is much greater than the age of the Solar System (Pravec et al., 2014; 2005). This neglects, however, the collisional life time (CLT) for this asteroid, which lies well below the CLT line in the frequency-diameter plot from the LCDB.

Since *MPO Canopus* does not properly handle tumbling asteroids, the plots represent the dominant periods found by the program. They may or may not be the true periods of rotation and precession.



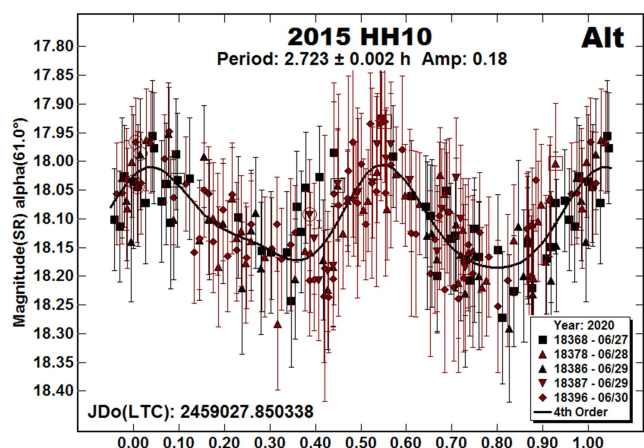
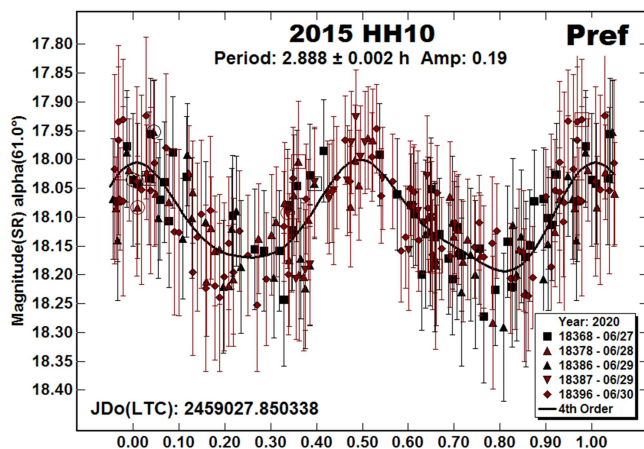
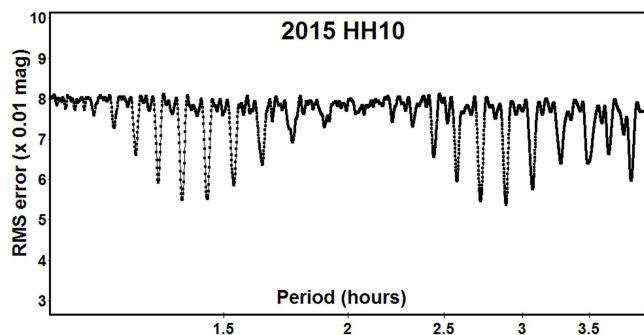
2004 LU3, 2005 MR5, 2013 XA22. There were no previous entries in the LCDB for 2004 LU3, a 600 m NEA with an unusually-shaped lightcurve. The shape, however, seems to be accurate since the period spectrum shows no other solution with a similarly low RMS.

There were also no previous entries for 2005 MR5 and 2013 XA22. The estimated diameter for 2005 MR5 is 250 m and its period of 3.956 h is considered secure. Likewise, the period for the 80-m 2013 XA22 is considered unambiguous.

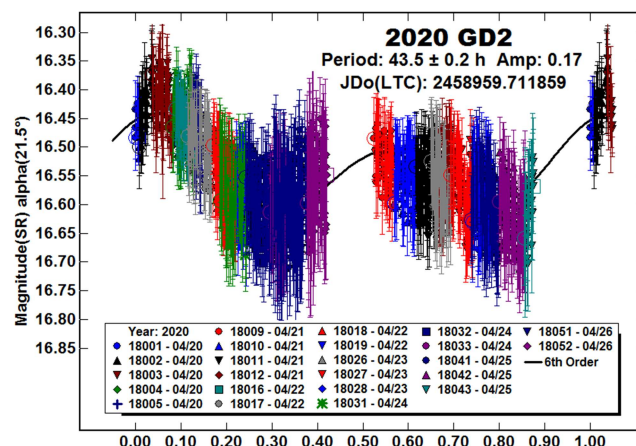


2015 HH10. The period spectrum shows several, nearly equal solutions in two distinct groups. Those near 1.4 h represent the half-periods of the two periods adopted for this paper. The adopted solution is 2.888 h but the one at 2.723 h, which equates to one-half more rotations over 24 hours, can be said to be equally possible.

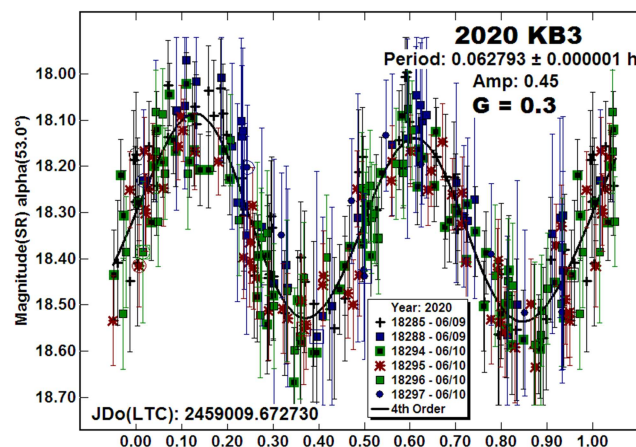
It's interesting to note that the period spectrum slightly favors the half-period for 2.723 h. Given the noisy data, it's hard to say if one of the two 2-h solutions is a *fit by exclusion*, i.e., it minimizes the RMS error by minimizing overlapping data points.



2020 GD2, 2020 KB3. There were no previous entries in the LCDB for either NEA. 2020 GD2 has an estimated diameter of 250 m.



2020 KB3 has a period of only 226 seconds. Its estimated diameter is 33 m.



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Number	Name	2020 mm/dd	Phase	L _{PAB}	B _{PAB}	Period(h)	P.E.	Amp	A.E.
1685	Toro	06/15-06/27	47.5, 52.3	317	6	10.1871	0.0004	1.07	0.02
6569	Ondaatje	05/18-05/27	46.3, 44.8	276	28	5.295 ^A 5.956	0.001 0.001	0.92	0.02
8014	1990 MF	06/15-07/05	30.7, 67.4	246	8	50.09	0.08	0.20	0.02
52768	1998 OR2	04/05-04/14	74.3, 77.5	158	8	4.1114	0.0002	0.27	0.03
66251	1999 GJ2	04/18-05/03	*7.9, 9.4	216	7	50.9	0.1	0.14	0.03
85184	1991 JG1	05/15-05/20	*26.7, 35.6	207	17	24.19	0.02	0.65	0.05
85989	1999 JD6	06/18-06/23	51.6, 53.4	313	15	7.665	0.003	1.39	0.05
86667	2000 FO10	05/02-05/19	13.7, 48.6	210	13	53.88	0.01	1.30	0.03
136874	1998 FH74	05/16-05/24	15.7, 17.0	242	23	28.55 ^A 14.29	0.03 0.02	0.23	0.03
137064	1998 WP5	04/12-04/17	18.1, 11.7	208	11	13.777	0.005	0.66	0.02
137199	1999 KX4	05/20-05/22	57.8, 56.3	225	39	2.7697	0.0008	0.17	0.02
159929	2005 UK	05/21-05/26	60.7, 63.3	195	11	33.4 ^A 38.3 ^A 66.3	0.2 0.2 0.5	0.48	0.05
175189	2005 EC224	04/03-04/17	11.1, 4.8	207	4	3.758	0.002	0.15	0.02
331471	1984 QY1	05/29-06/08	40.2, 27.4	258	29	45.81 ^T 37.8	0.08 0.1	0.38	0.05
349063	2006 XA	06/11-06/14	28.9, 26.2	287	8	2.436	0.002	0.23	0.03
373428	1999 TC5	04/03-04/05	2.7, 5.5	194	3	3.45	0.01	0.21	0.05
382503	2001 RE8	06/28-07/01	20.6, 23.0	281	14	61.1	0.5	0.67	0.05
441987	2010 NY65	06/27-07/01	75.0, 54.5	254	25	4.974 ^A 9.953	0.003 0.004	0.32	0.04
477885	2011 JT9	05/20-06/09	25.3, 26.1	251	27	3.1114	0.0003	0.14	0.02
495615	2015 PQ291	05/27-06/08	41.5, 50.1	217	8	13.763	0.002	0.66	0.05
498066	2007 RM133	06/11-06/15	18.6, 16.4	269	11	6.21	0.01	0.24	0.05
	2000 KA	05/14-05/19	42.8, 10.5	234	12	11.46 ^A 5.62	0.02 0.01	0.22	0.03
	2001 GS2	04/03-04/19	*25.2, 10.2	205	2	51.15 ^T 45.21	0.05 0.09	0.54	0.05
	2004 LU3	06/26-06/29	17.4, 19.3	266	10	9.03	0.02	0.22	0.03
	2005 MR5	06/23-06/26	38.9, 45.4	267	25	3.956	0.002	0.23	0.03
	2013 XA22	05/25-05/28	15.6, 21.9	238	6	2.2912	0.0008	0.26	0.03
	2015 HH10	06/27-06/30	60.9, 66.2	323	14	2.888 ^A 2.723	0.002 0.002	0.19	0.04
	2020 GD2	04/21-04/26	17.1, 8.5	209	4	43.5	0.2	0.17	0.03
	2020 KB3	06/09-06/10	52.7, 48.5	235	11	0.062793	0.000001	0.45	0.05

Table II. Observing circumstances. ^AAlternate period in ambiguous solution. ^TSecond period in a suspected tumbler. The phase angle (α) is given at the start and end of each date range. If there is an asterisk before the first phase value, the phase angle reached a maximum or minimum during the period. L_{PAB} and B_{PAB} are, respectively the average phase angle bisector longitude and latitude (see Harris et al., 1984).

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