

**ASTEROID LIGHTCURVE ANALYSIS
AT THE CENTER FOR SOLAR SYSTEM STUDIES
PALMER DIVIDE STATION:
2023 JANUARY-FEBRUARY**

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(Received: 2023 April 10)

CCD photometric observations of twelve asteroids were made at the Center for Solar System Studies Palmer Divide Station during 2023 January and February. Data analysis found a weak to moderate secondary period for the Hilda asteroids 1268 Libya and 2312 Duboshin, both possibly as sign of (unexpected) tumbling, the NEA (68359) 2001 IZ13 presents an unusual lightcurve with a very large amplitude of ~ 1.8 mag, and that NEA (98943) 2001 CC21 is a probable tumbler.

CCD photometric observations of twelve asteroids were carried out at the Center for Solar System Studies Palmer Divide Station (CS3-PDS) during 2023 January and February as part of an ongoing general study of asteroid rotation periods with a concentration on near-Earth, Hungaria, and Hilda group/family asteroids.

Telescope	Camera
0.30-m f/6.3 SCT	SBIG STL-1001E
0.35-m f/9.1 SCT (x3)	FLI Microline 1001E
0.50-m f/8.1 Ritchey-Chrétien	FLI Proline 1001E

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

Table I lists the five telescope/CCD cameras pairs used at CS3-PDS. All the cameras use CCD chips from the KAF 1001 blue-enhanced family and so have essentially the same response. The pixel scales ranged from 1.24-1.60 arcsec/pixel. All lightcurve observations were made with no or a clear filter. The exposures varied depending on the asteroid's brightness.

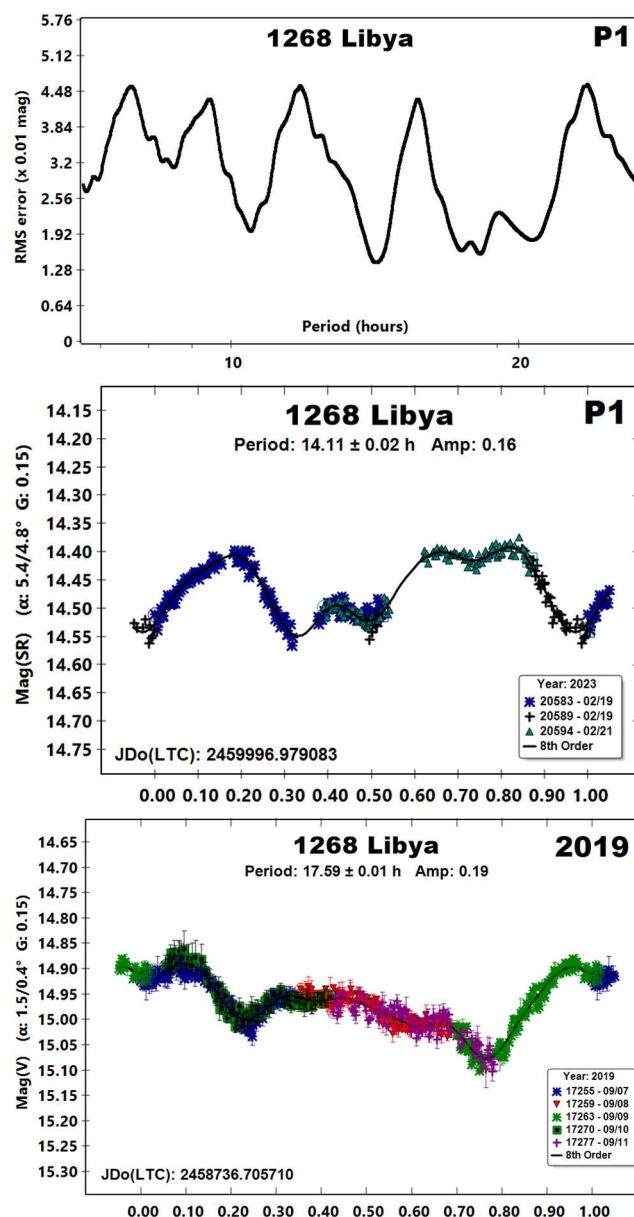
To reduce the number of times and amounts of adjusting nightly zero-points, the ATLAS catalog r' (SR) magnitudes (Tonry et al., 2018) are used. Those adjustments are usually $\leq \pm 0.03$ mag. The rare greater corrections may have been related in part to using unfiltered observations, poor centroiding of the reference stars, and not correcting for second-order extinction. Another cause may be selecting what appears to be a single star but is actually an unresolved pair.

The Y-axis values are ATLAS SR “sky” (catalog) magnitudes. The values in the parentheses give the phase angle(s), α , along with the value of G used to normalize the data to the comparison stars used in the earliest session. This, in effect, adjusts all the observations so that they seem to have been made at a single fixed date/time and phase angle. Presumably, any remaining variations are due only to the asteroid's rotation and/or albedo changes.

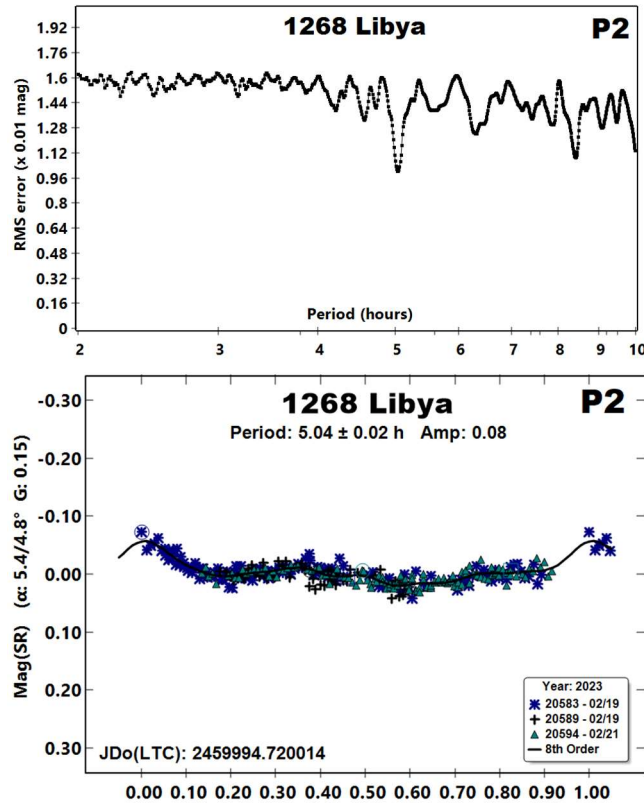
There can be up to three phase angles. If two, the values are for the first and last night of observations. If three, the middle value is the extrema (maximum or minimum) reached between the first and last observing runs. The X-axis shows rotational phase from -0.05 to 1.05. If the plot includes the amplitude, e.g., “Amp: 0.65,” this is the amplitude of the Fourier model curve and *not necessarily the adopted amplitude for the lightcurve*.

For brevity, only some of the previous results are referenced. A more complete listing is in the asteroid lightcurve database (Warner et al, 2009; “LCDB” from here on).

1268 Libya. Dahlgren et al. (1998) reported a period of 14.05 h, which is in reasonable agreement with the 2023 CS3-PDS result of 14.11 h. That's the good news. Warner and Stephens (2020) found what seems to be a reliable solution of 17.572 h based on data from 2019 September. The period spectrum for the 2023 data shows a weaker solution near the longer period. Trying to force the data from each year to the solution for the other year produced a lightcurve too unusual and large of RMS to be acceptable.

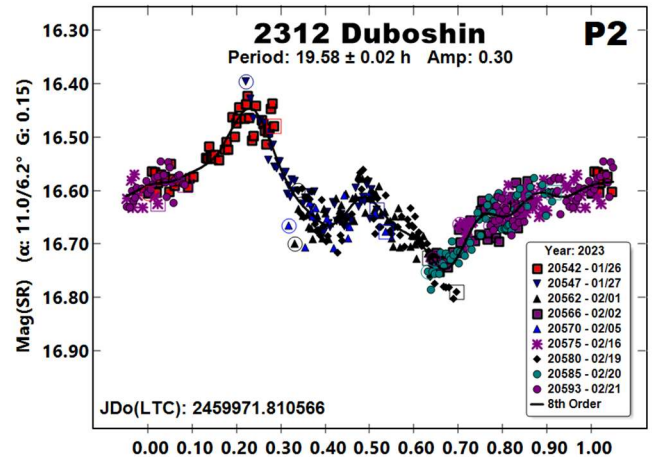
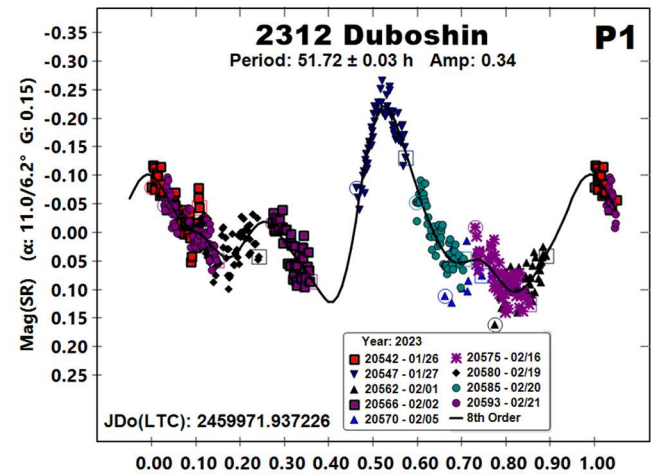
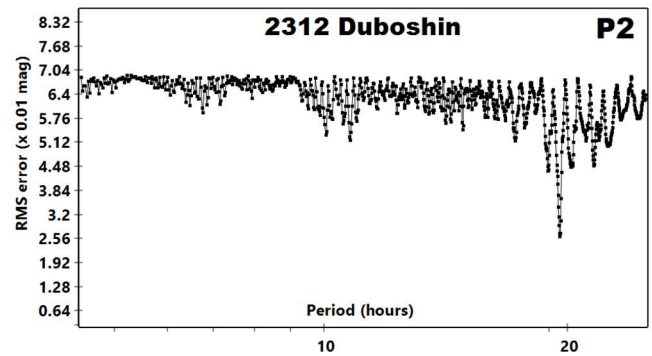
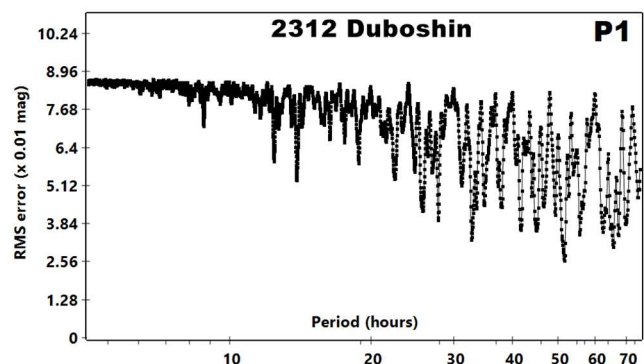


The 2023 data also led to finding a secondary period that significantly improved the fit of the data to P_1 . It stands out enough in the period spectrum to dismiss it entirely even though the resulting lightcurve has $A_2 = 0.08$ mag.



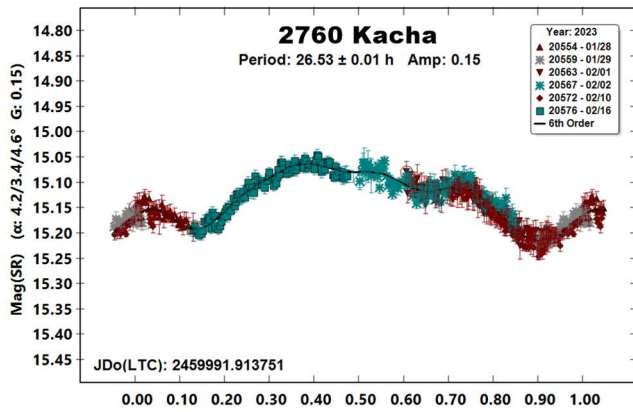
Based on the rules of thumb from Pravec et al. (2005; 2014), the asteroid is a poor candidate for tumbling. Additional observations in the future may help resolve the conundrum.

2312 Duboshin. Stephens (2016) found a period of 50.78 h based on data obtained in 2016. This is in reasonable agreement with the period of 51.72 h derived from the 2023 data. As seen in the P_1 period spectrum, that solution is hardly unique and less than fully reliable especially given the shape of the lightcurve.



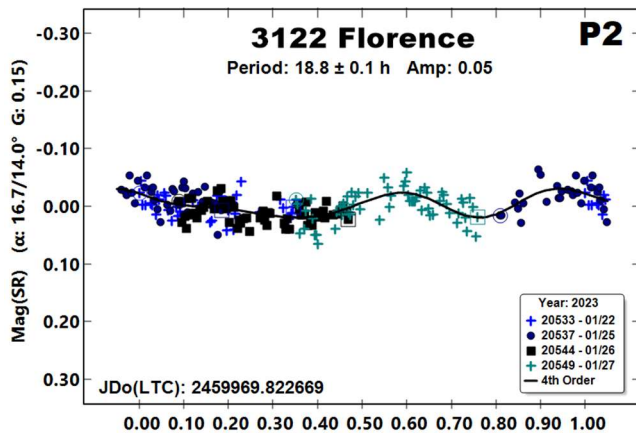
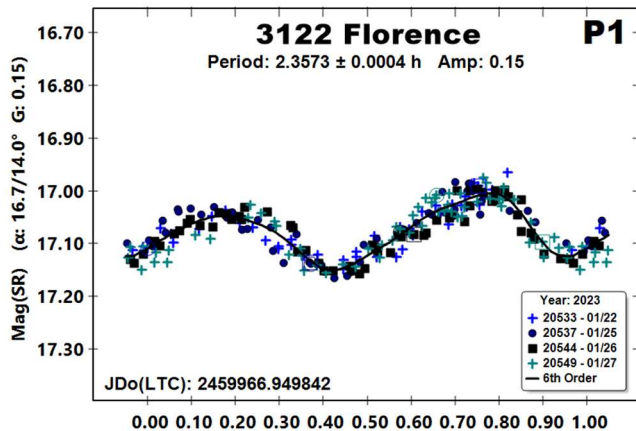
Again, the rules of thumb from Pravec et al. (2005; 2014) for tumbling makes this a very unlikely candidate for tumbling and yet there is undoubtedly a strong solution for a secondary period of 19.58 h. More probable is that P_2 is a harmonic artifact of the analysis since $(P_1 * 3)$ is very close to $(P_2 * 8)$.

2760 Kacha. There were three previous solutions in the LCDB: Dahlgren et al. (1998; 13.0 h), Durech and Hanus (2018; 53.040 h sidereal), and Warner and Stephens (2021; 26.247 h). The most recent CS3-PDS result of 26.53 h is in good agreement with the last of the three. It's worth noting that the sidereal period from Durech and Hanus (2018) is almost exactly twice the result from 2023. Trying to fit those data to the doubled period produced large gaps in the lightcurve and some sessions not following the shape of the Fourier curve.

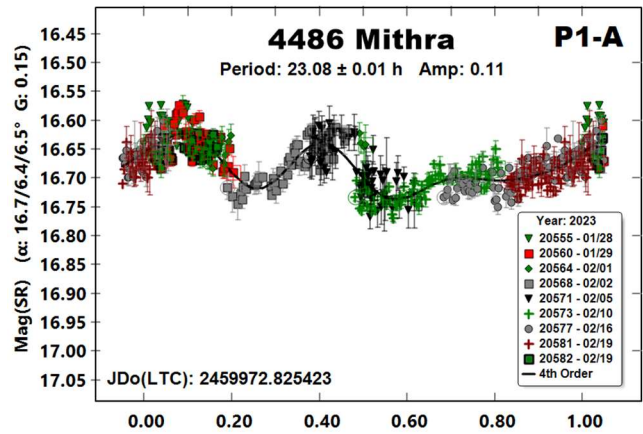


3122 Florence. In addition to numerous solutions found in the LCDB for this NEA, Benner et al. (2017), using the Arecibo radar, discovered that this is a three-body system. The two satellites are between 100 to 300 m in size, making them about 5% the size of the asteroid and so should not contribute much to the lightcurve of the asteroid as a whole. Even so, a weak secondary period of $P_2 = 18.8$ h was found. Subtracting its lightcurve from the analysis improved the P_1 fit considerably.

Benner et al. (2017) estimated the orbits of the inner and outer satellites to be about 8 h and 24 h, respectively. It may be that the secondary period reported here is the result of finding harmonics of one or both of those orbital periods.

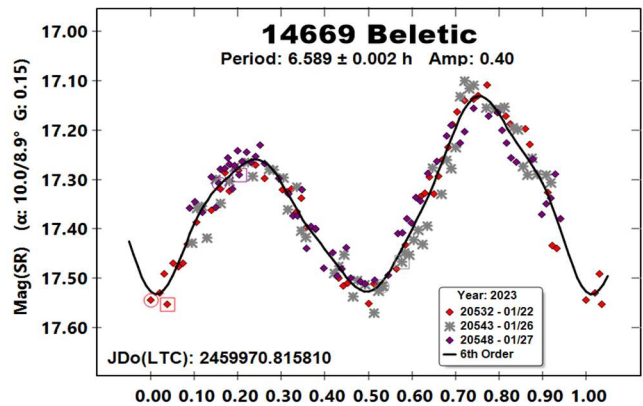


4486 Mithra. Brozovic et al. (2010) used radar to estimate a rotation period about 67.5 h for this contact binary asteroid.

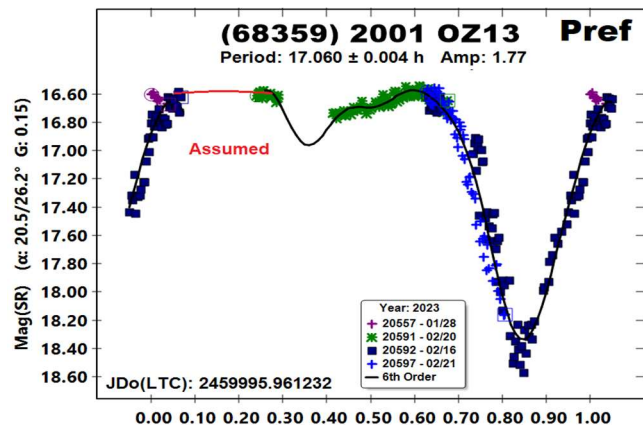


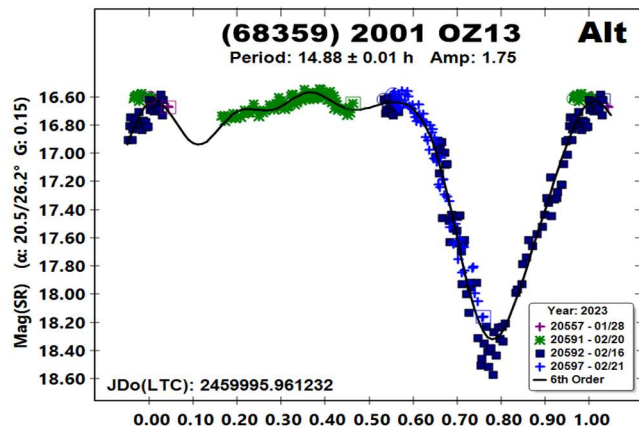
It's hard to argue against radar results, so it's hard to explain the period of 23.08 h found from the 2023 observations as CS3-PDS. Trying to force the solution to something near the radar period produced a multimodal lightcurve with large gaps. "More data!" needs to echo over the years with the hope that the new data will lead to a reliable solution.

14669 Beletic. This appears to be the first rotation period reported for this 27-km Hilda group member. Given the amplitude and low phase angles, the solution is reliable (Harris et al., 2014).



(68359) 2001 OZ13. The period spectrum showed a few possible solutions between 15 and 22 h. The lightcurves for the two more favorable, based on RMS fit to the Fourier curve, are given here.





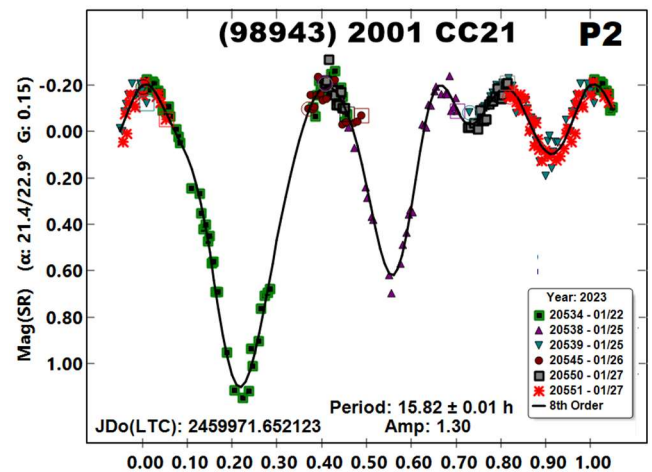
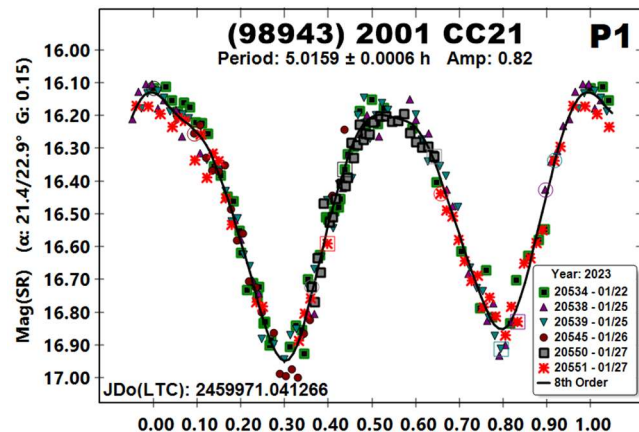
The only previous result in the LCDB was 2.91031 h from Pal et al. (2020) using dense TESS data. The CS3-PDS data seem to reject that solution outright. The preferred solution of 17.060 h is more symmetrical in that the two minimums are closer to 0.5 rotation apart than in the alternate solution. However, both meet a general criterium that the estimated width of the deep attenuation be close to 0.5 rotation phase. Many other solutions were tried and rejected based on this requirement, let alone that they led to multimodal lightcurves.

The problem is to explain the unusual shape of either lightcurve, i.e., to imagine a body, or bodies, that would produce such a lightcurve. Unfortunately, there is seemingly no simple solution.

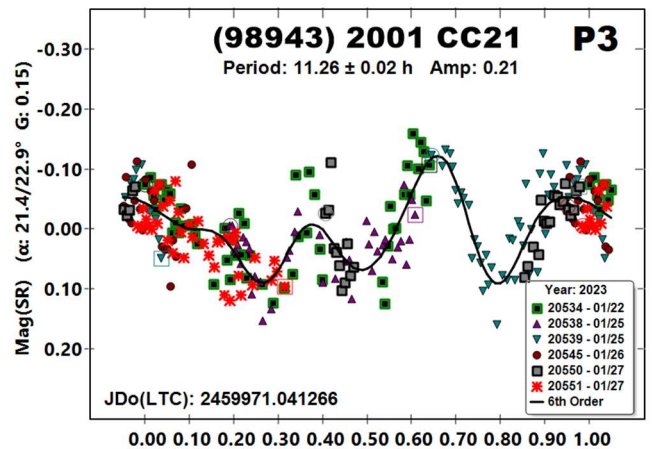
(98943) 2001 CC21. Pravec et al. (2002web) found a reliable solution of 5.017 h and then, two decades later, a period of 5.0247 h (Pravec et al., 2022web). Analysis of the CS3-PDS data found 5.0159 h, which is in good agreement. However, the reasonably clean fit in the “P1” plot was possible *only* by subtracting two other periods.

The three may be harmonically related:

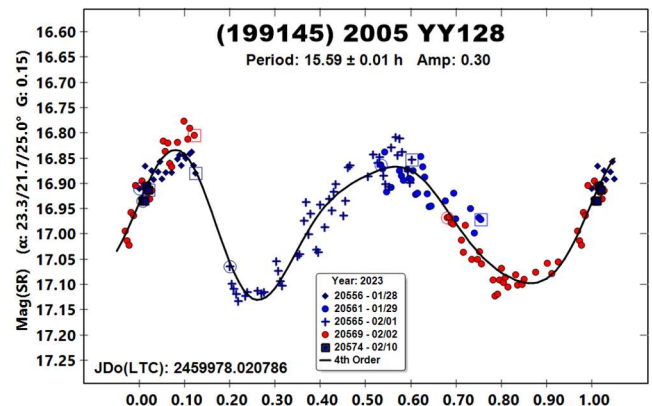
$$5.0159/24 \equiv ((15.82 - 11.26) / 24)$$



Were the two secondary period amplitudes of low amplitude, it would be easier to accept that they are artifacts of the Fourier analysis. The large amplitude of P_2 seems to argue against that. Since the phase angles were not severe during the period of observations and there was little change in the phase angle bisector, deep shadowing leading to the unusual solution also seems improbable. No explanation is offered at this time and, once again, a call for additional observations at future apparitions is made.



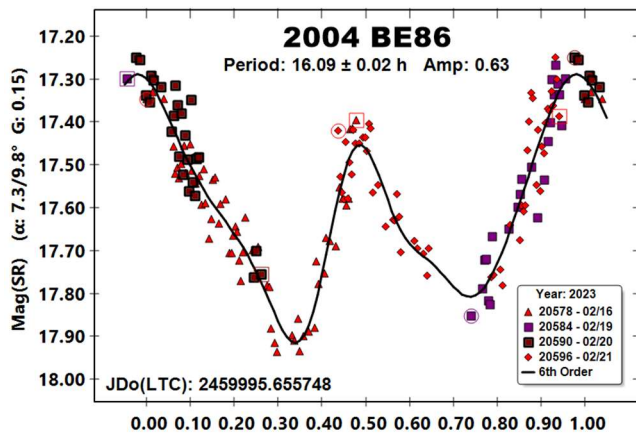
(199145) 2005 YY128. There were no previous entries of any kind in the LCDB for this 650-m NEA.



Number	Name	2023/mm/dd	Phase	L _{PAB}	B _{PAB}	Period(h)	P.E.	Amp	A.E.	Grp
1268	Libya	02/19-02/21	5.4, 4.8	168	0	^D 14.11 5.04	0.01 0.02	0.11 0.08	0.02 0.01	HIL
1268	Libya	2019/09/07-09/11	1.5, 0.4	350	0	17.59	0.01	0.19	0.02	HIL
2312	Duboshin	01/26-02/21	11.0, 6.2	176	5	^D 51.72 19.58	0.03 0.02	0.34 0.30	0.03 0.03	HIL
2760	Kacha	01/28-02/16	*4.2, 4.6	136	10	26.53	0.01	0.15	0.02	HIL
3122	Florence	01/22-01/27	16.7, 14.0	150	7	^P 2.3573 18.8	0.0004 0.1	0.15 0.05	0.02 0.01	NEA
4486	Mithra	01/28-02/19	*16.7, 6.4	148	5	^A 23.08 42.33	0.04 0.04	0.11 0.14	0.02 0.02	NEA
14669	Beletic	01/22-01/27	10.0, 8.9	158	-4	6.589	0.002	0.40	0.03	HIL
68359	2001 OZ13	01/29-02/21	*20.4, 26.2	170	15	^A 17.06 14.88	0.004 0.01	1.77 1.86	0.08 0.08	NEA
98943	2001 CC21	01/22-01/27	21.3, 22.8	127	14	^D 5.0159 15.82 11.26	0.0006 0.01 0.02	0.82 1.30 0.21	0.04 0.03 0.05	NEA
199145	2005 YY128	02/01-02/10	*22.0, 25.1	149	-6	15.59	0.01	0.30	0.03	NEA
2004	BE86	02/16-02/21	7.4, 9.9	145	-2	16.09	0.02	0.63	0.04	NEA
2006	BE55	02/20-02/21	19.3, 20.8	158	9	5.61	0.02	0.60	0.03	NEA
2015	RD2	01/22-01/27	18.8, 15.6	135	6	18.493	0.008	1.19	9.03	NEA

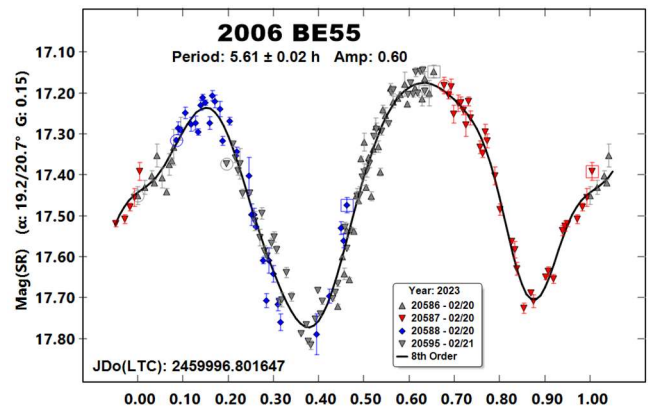
Table II. Observing circumstances and results. ^APreferred period of an ambiguous solution. ^PPeriod of primary with one or more satellites. ^DDominant period of a multi-period solution. Unless flagged as ambiguous, subsequent lines are additional, not alternate, periods. The phase angle is given for the first and last date. If preceded by an asterisk, the phase angle reached an extremum during the period. LPAB and BPAB are the approximate phase angle bisector longitude/latitude at mid-date range (see Harris et al., 1984).

2004 BE86. Hergenrother and Whiteley (2011) reported a period of 2.422 h with an amplitude of 0.68 mag based on data from 2004. The data from 2023 don't seem to support this, leading instead to a period of 16.09 h. These two periods are not unusual for a binary asteroid, with 2.4 h being the rotation of the primary and 16 h the orbital period of a satellite.

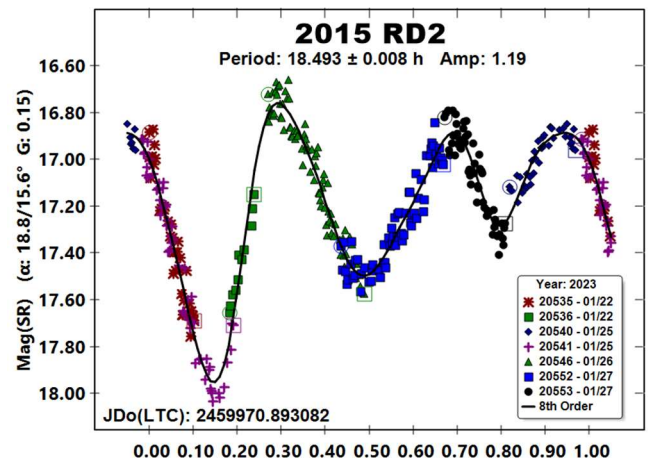


Hergenrother and Whiteley (2011) observed on only two consecutive nights. On the off chance that their data set didn't pick up on a longer period, a dual-period analysis of the 2023 data was done, forcing the short period to 2-3 h. This did find one of 2.4 h; however, it was hard to see a valid lightcurve in the noisy data set.

2006 BE55. There were no previous entries of any kind in the LCDB for this 120-m NEA.



2015 RD2. Mainzer et al. (2019), using data from the WISE mission, found the albedo for this NEA to be near 0.1, about half the usually assumed value for NEAs, which leads to a diameter of about 3.5 km.



Analysis of the 2023 photometry data showed a trimodal lightcurve with a maximum amplitude of 1.19 mag that is too asymmetrical to be an alias of a shorter period. All attempts to extract one or more additional periods to produce a more typical dominant bimodal lightcurve were fruitless. For now, it appears that this is an unusually-shaped asteroid, or that it is indeed tumbling and that *MPO Canopus* could not handle the data set properly. The possibility of tumbling is likely according to Pravec et al. (2005; 2014).

Acknowledgements

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 author gratefully acknowledges a Shoemaker NEO Grants from the Planetary Society (2007). This was used to purchase some of the equipment used in this research.

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