Opposition Date	Declination (°)	Magnitude	PAB (°) Lon	Lat
2022 Nov 05	20	16.3	42	4
2024 Feb 24	17	16.0	154	7
2025 Sep 14	-9	15.7	350	-5

Table III. Observing circumstances for upcoming oppositions

Acknowledgements

The authors would like to express gratitude to Brian Skiff for his indispensable mentoring in data acquisition and reduction. Thanks also go out to Brian Warner for support of his *MPO Canopus* software package. Petr Pravec provided helpful guidance. The research work at Blue Mountains Observatory is supported by the 2018 Shoemaker NEO Grant.

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NEAR-EARTH ASTEROID LIGHTCURVE ANALYSIS AT THE CENTER FOR SOLAR SYSTEM STUDIES: 2021 OCTOBER-DECEMBER

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(Received: 2022 January 12)

Lightcurves of 16 near-Earth asteroids (NEAs) obtained at the Center for Solar System Studies (CS3) from 2021 October through December were analyzed for rotation period, peak-to-peak amplitude, and signs of satellites or tumbling. The minor planets (87024) 2000 JS66 and 2019 XS were found to be in a tumbling state.

CCD photometric observations of 16 near-Earth asteroids (NEAs) were made at the Center for Solar System Studies (CS3) from 2021 October through December. Table I lists the telescopes and CCD cameras that were available to make observations.

Up to nine telescopes can be used but 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*/10 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.

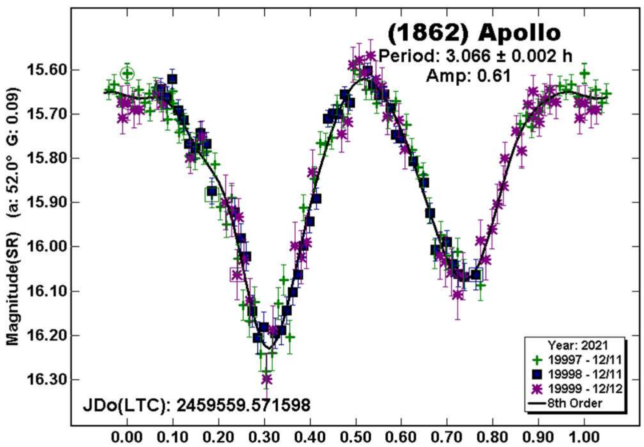
All lightcurve observations were unfiltered since a clear filter can cause a 0.1-0.3 mag loss. The exposure duration varied depending on the asteroid's brightness and sky motion. Guiding on a field star sometimes resulted in a trailed image for the asteroid.

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. To reduce the number of times and amounts of adjusting nightly zero points, we use the ATLAS catalog r´ (SR) magnitudes (Tonry et al., 2018). Those adjustments are usually $|\Delta| \leq 0.03$ mag. The larger corrections, which are rare, 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.

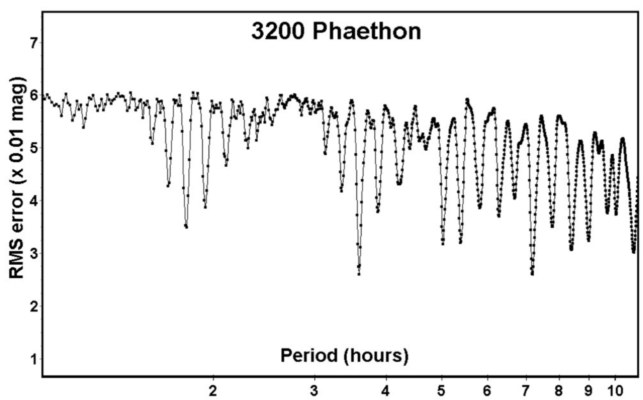
The Y-axis values are ATLAS SR "sky" (catalog) magnitudes. The two values in the parentheses are the phase angle (a) and the value of *G* used to normalize the data to the comparison stars used in the earliest session. This, in effect, corrected all the observations to seem to have been made at a single fixed date/time and phase angle, leaving any variations due only to the asteroid's rotation and/or albedo changes. 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*.

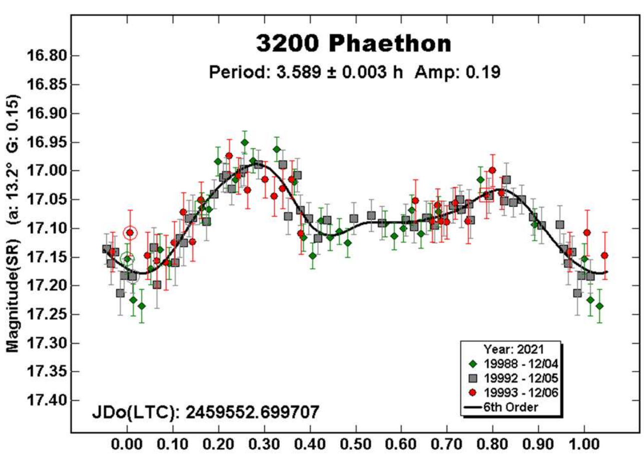
"LCDB" substitutes for "Warner et al. (2009)" from here on.

1862 Apollo. A rotation period of about 3.065 h has been long-established for this namesake of a subclass of NEAs (e.g., Harris et al., 1987). The amplitude during late-2021 observations (0.61 mag) at CS3 was about mid-way between the known extremes of 0.15 to 1.15 mag.



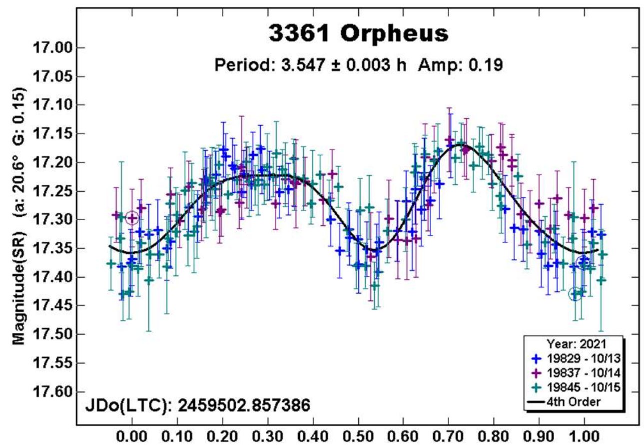
3200 Phaethon. There are numerous rotation periods listed in the LCDB, all of about 3.60 h, e.g., Pravec et al. (2004web, 3.6048 h).



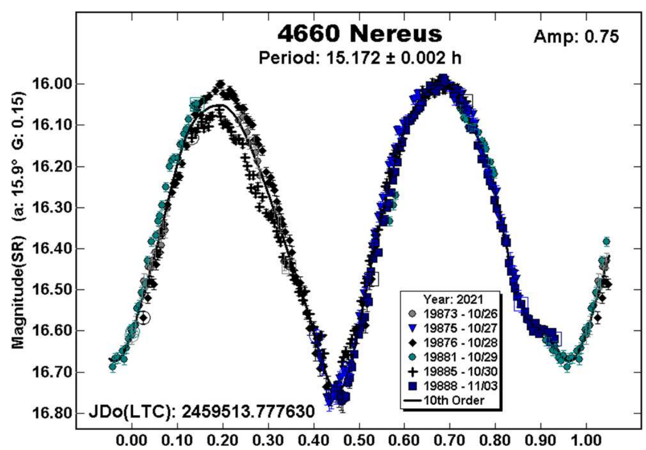


As discussed in Harris et al. (2014), the low amplitude and phase angle make solutions other than bimodal a possibility. This is borne out by the period spectrum, which shows a number of nearly equal solutions. The 3.589 h period is considered to be the correct result.

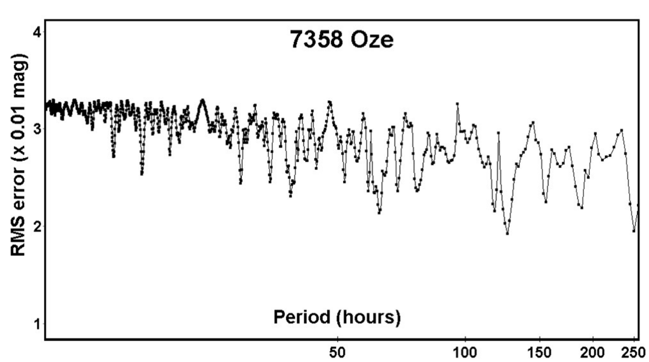
3361 Orpheus. Wisniewski (1991) has the earliest entry in the LCDB with a period of 3.58 h. Subsequent results (e.g., Pravec et al., 2019web) shortened the period to near 3.538 h. The result using the most recent CS3 data in good agreement with the shorter period.

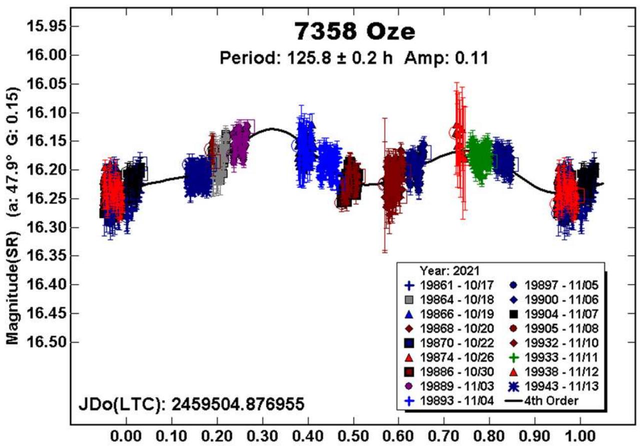


4660 Nereus. Pravec et al. (2021web) found Nereus to be tumbling, with periods of 15.4749 h and 12.457 h. There were insufficient data to try to duplicate those results but they may explain the lower amplitude near 0.2 rotation phase on some nights.



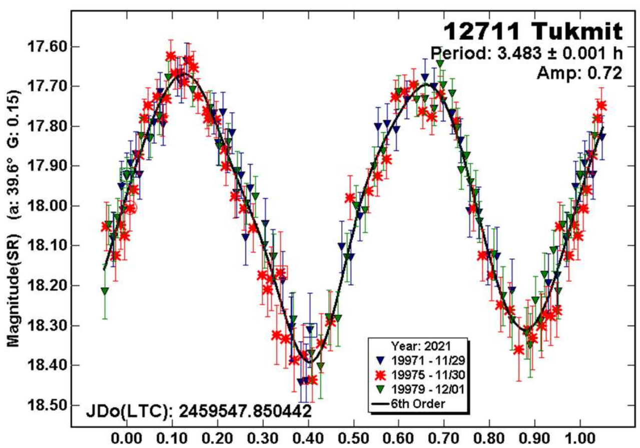
7358 Oze. Previous solutions for Oze have included 5.433 h (Skiff et al., 2012), 24.4 h (Skiff et al., 2019), and 125.8 h (this work). The period spectrum using the CS3 data lacked a clear solution.



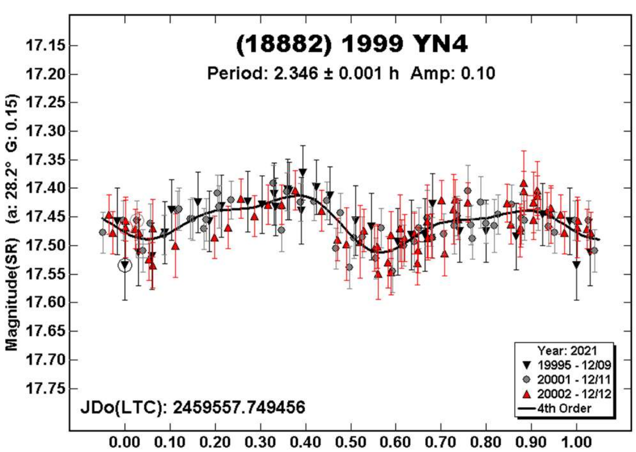


The two shorter periods have a close to 23:1 or 5:1 ratio with the period reported here. This could be a good indication of *rotational aliasing*, which is when the true number of rotations over the total duration of a data set is ambiguous.

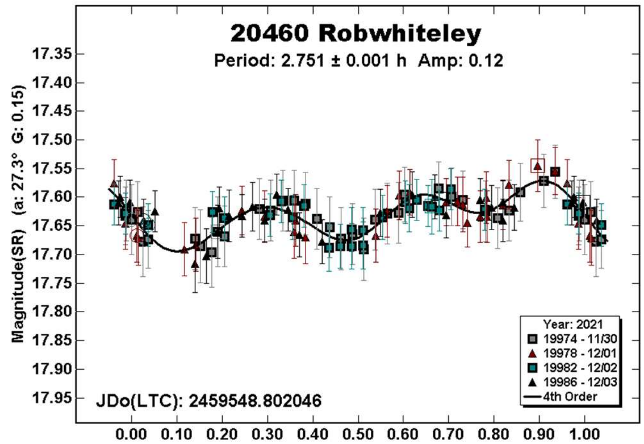
<u>12711 Tukmit</u>. The only previous period in the LCDB is from Pravec et al. (2000web), who found 3.4848 h.



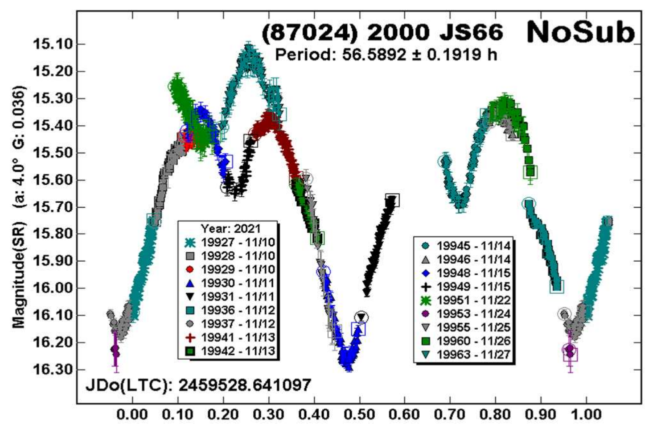
<u>(18882) 1999 YN4</u>. This appears to be the first reported rotation period of 1999 YN4. Despite the low amplitude and almost symmetrical halves of the lightcurve, the half period of 1.173 h doesn't seem likely given the diameter of 1.8 km. A higher modal lightcurve, and longer period, cannot be formally excluded (Harris et al., 2014).



<u>20460 Robwhiteley</u>. The period spectrum using the latest CS3 data shows an essentially unique solution of 2.751 h; this is in good agreement with a previous result of 2.7209 h (Warner, 2018) and that of Pravec et al. (2017web; 2.7228 h), who also reported indications, unconfirmed, of a satellite.



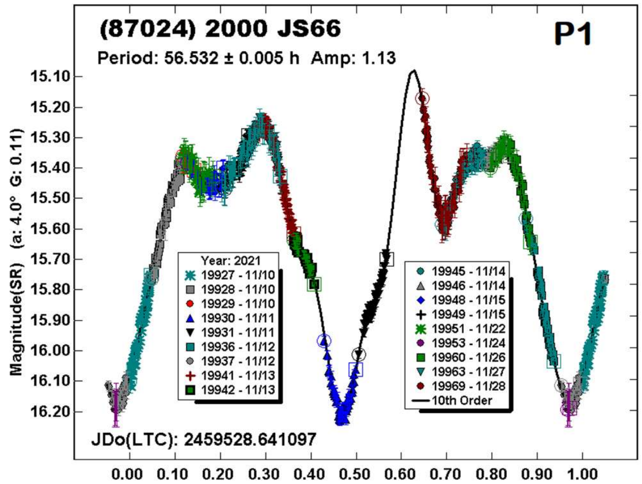
<u>(87024) 2000 JS66</u>. Pravec et al. (2021web) determined this NEA to be in non-principal axis rotation (NPAR), otherwise known as *tumbling*. They reported two periods of 28.2 h and 37.2 and a PAR of -2 (see Pravec et al., 2005; 2014).

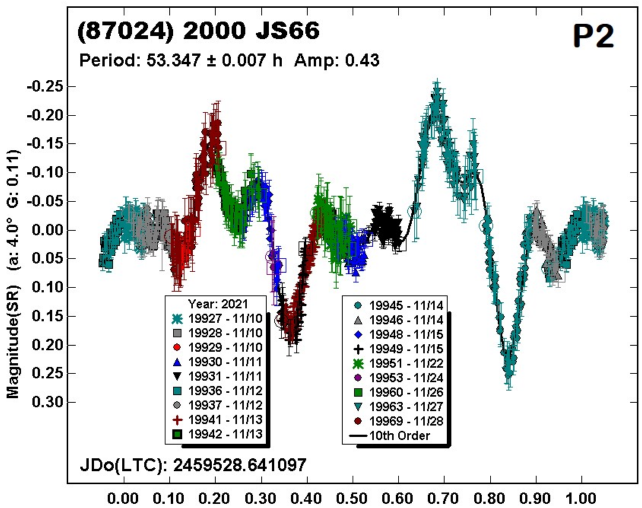


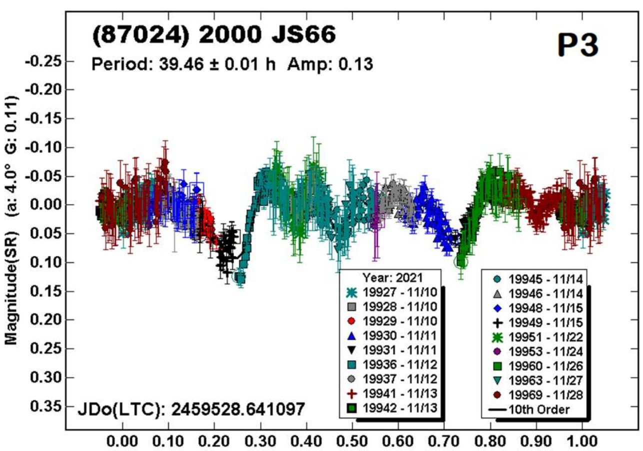
It was apparent from the raw data and attempts to find a single period (NoSub) that the asteroid was tumbling. *MPO Canopus,* even though it is not properly designed to handle tumbling asteroids, was used to try to extract possible two-period solutions. It was only after finding three periods and subtracting pairs, e.g., subtract P_2 and P_3 to find P_1, that the data would closely fit Fourier curves that did not have completely improbable shapes.

Interestingly, the dominant period is almost exactly double the "primary" period found by Pravec et al. (2021web). However, the close asymmetry of the two halves in the P_1 and P_2 plots means the half periods are possible. This would put the dominant period given here close to that found by Pravec et al. (2021web).

The value of P_3 = 39.46 h is close to the second period found by Pravec et al. (2021web). While the CS3 results differ significantly in some respects, they provide independent confirmation that the asteroid is tumbling.

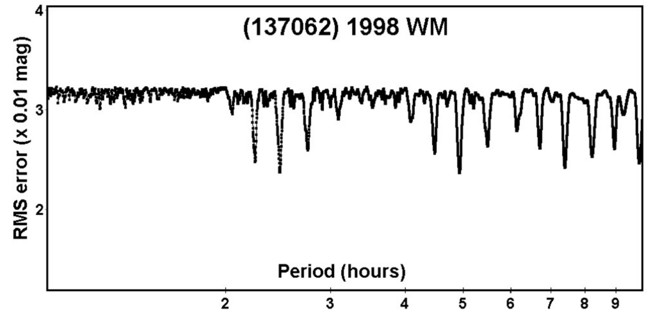


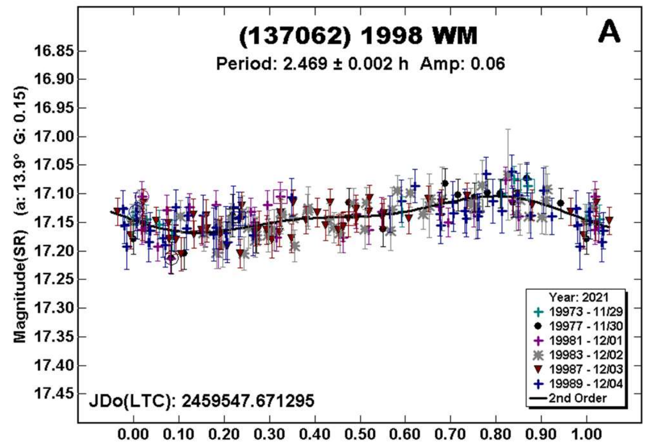


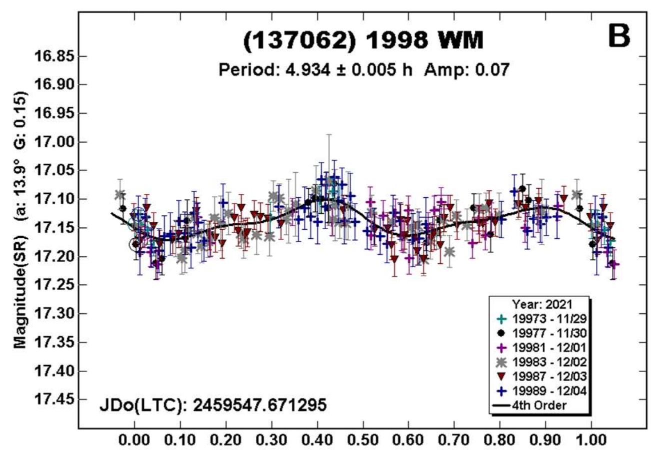


(137062) 1998 WM. The only previously reported period in the LCDB is 2.58 h (Vaduvescu et al., 2017). The period spectrum shows several possible solutions, which is not unexpected for a low amplitude lightcurve at moderate phase angles (Harris et al., 2014).

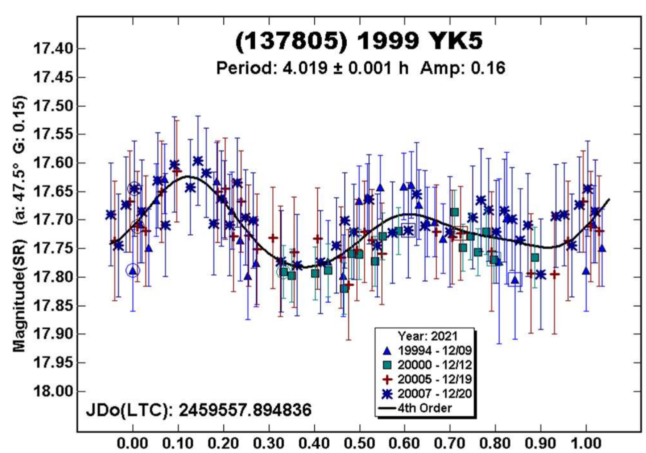
The more common solutions, shown below, correspond to a monomodal lightcurve, $P = 2.469$ h, and a bimodal lightcurve at the doubled period of $P = 4.934$ h. The shorter period is adopted for this work since it and the estimated diameter make the asteroid fall just below the so-called "spin barrier," a more typical location for many small NEAs.





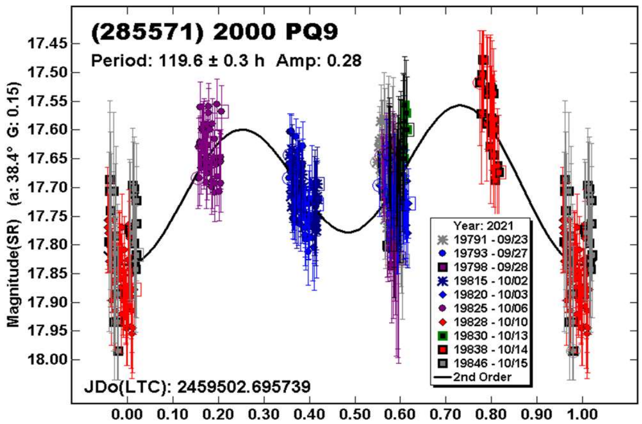


(137805) 1999 YK5. The latest solution is in fairly good agreement with a previous result of 3.930 h (Warner, 2016a). It was not possible to get a satisfactory fit to 3.468 h (Aznar et al., 2018).

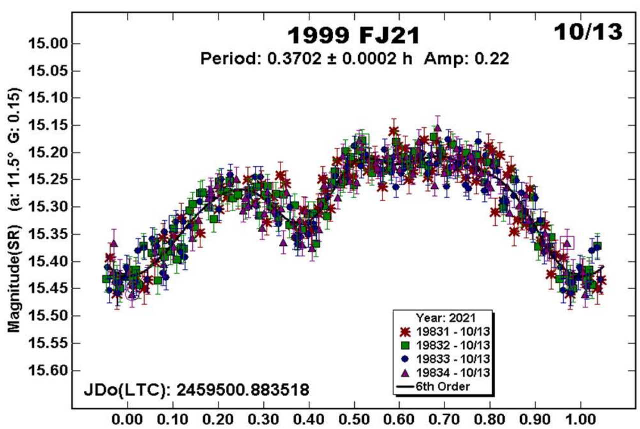


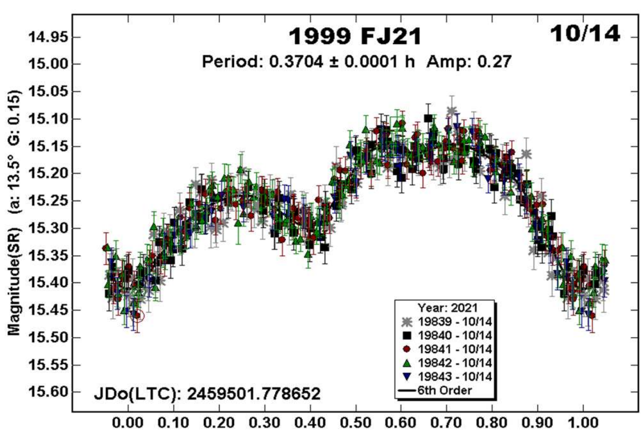
(285571) 2000 PQ9. Colazo et al. (2022) and Behrend (2021web) both reported periods near 3.74 h. Assuming the ATLAS catalog magnitudes allowed near-zero zero-point adjustments, a long-period solution of 119.6 h was found using the CS3 data.

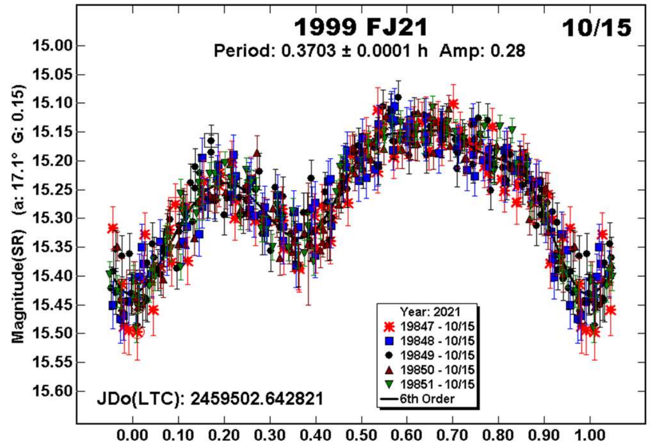
A shorter period superimposed on the long-period curve, if it exists, could not be extracted from the noise. A dual-period solution with $P_{Shorter} < 10$ h, might fit with the suspected class of very wide binary asteroids (e.g., see Warner, 2016b).

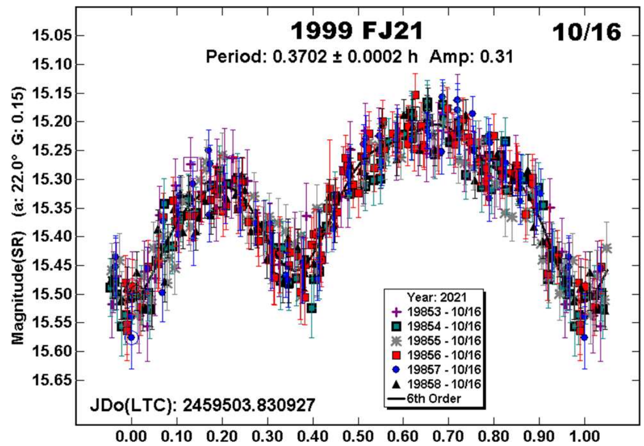


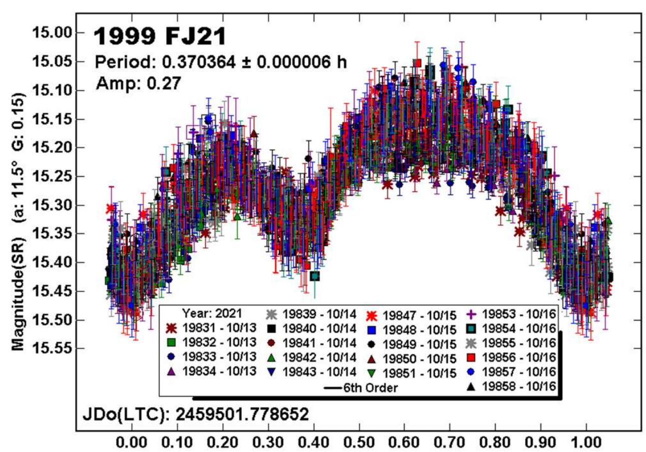
1999 FJ21. This NEA was followed for four consecutive nights in 2021 October. This provided a good demonstration of the evolution of a lightcurve over a relatively short number of days. As the phase angle increased from 11.5° on Oct 13 to 22° on Oct 16, the depth of the first minimum (about 0.35 rotation phase) increased as did the overall amplitude of the lightcurve. The latter is an expected trait (Zappala et al., 1990).







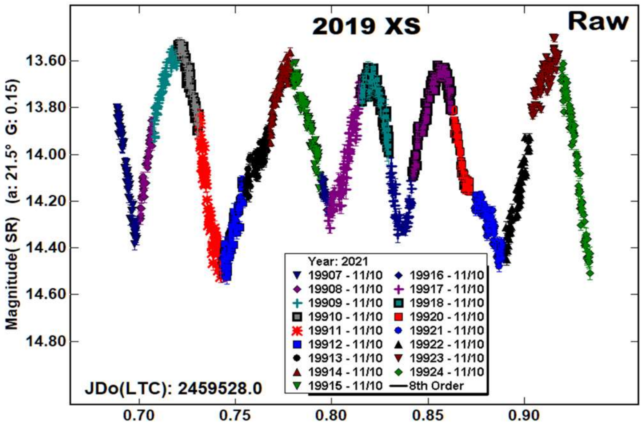


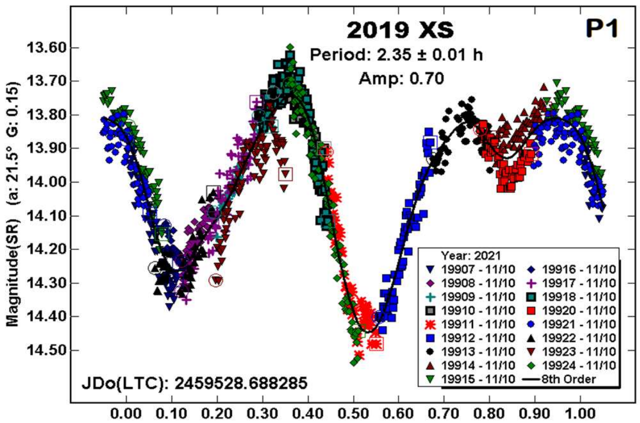


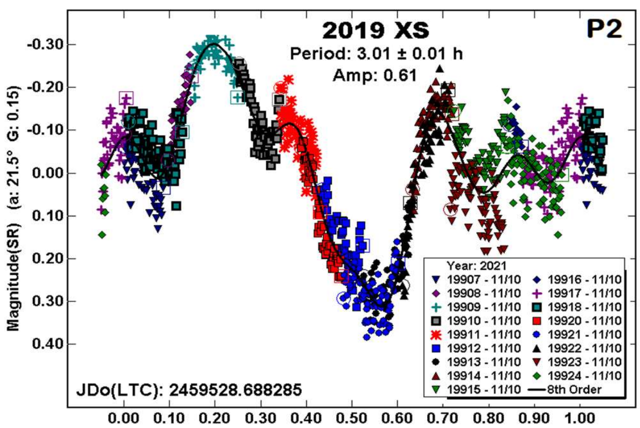
While combing the four nights into a single set covered up the changes in the lightcurve, it did provide a longer baseline to establish a more precise synodic period of 0.370364 h, or – with a 5-sigma error bar – 1333 ± 0.1 s.

2019 XS. The raw plot was reminiscent of previous examples of tumbling where two periods could be combined to what appeared a single period but with an unlikely lightcurve shape (see Harris et al., 2014). However, no single period provided a reasonable fit to the CS3 data obtained on the night of 2021 November 10.

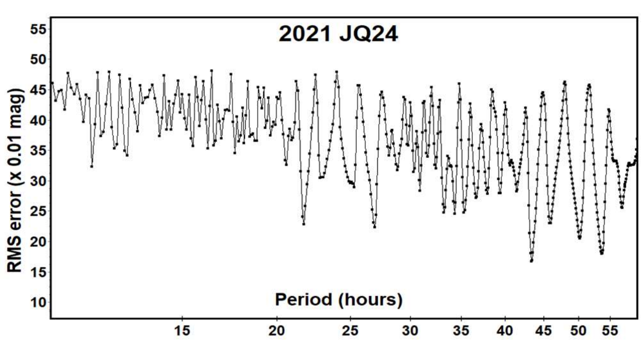
Knowing the limitations of *MPO Canopus* for analyzing tumbling asteroids, an attempt was made to find a dual-period solution. This led to a dominant period of 2.35 h and a secondary period of 3.01 h. The two periods should not be taken as the actual periods of rotation and precession (Pravec et al., 2005; 2014).

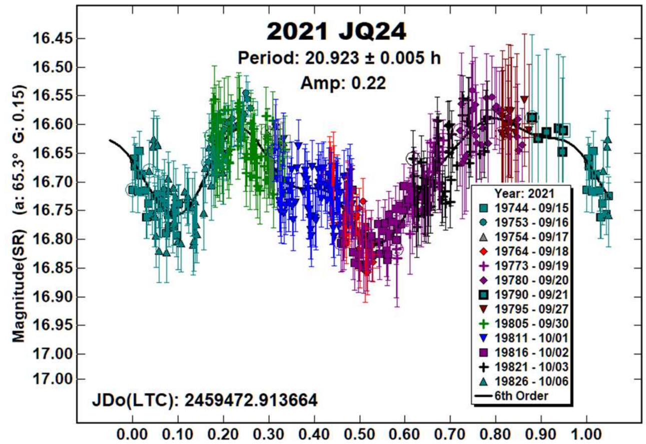




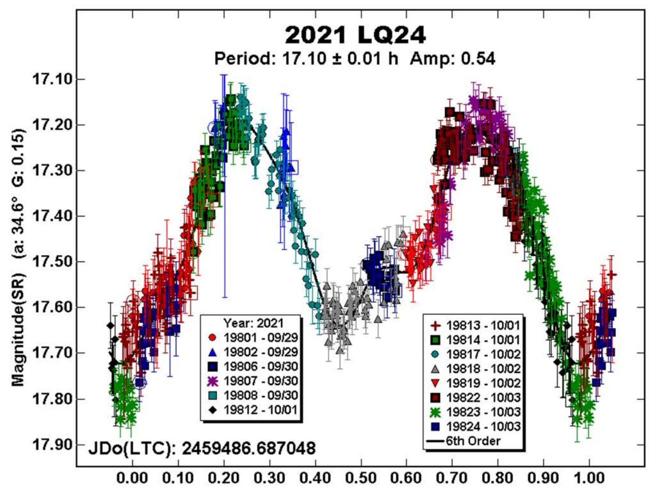


2021 JQ24. There were no previous entries of any kind in the LCDB for this NEA with an estimated diameter of 0.8 km. Given the noise in the data and the almost three-week span of the data set, it is possible that the actual period is an integral (or 0.5) multiple or divisor of the period reported here.





2021 LQ24. Pravec et al. (2021web) reported this to be a tumbling asteroid with periods of 25.39 h and 15.6 h. The data set was insufficient to duplicate those results but a dominant period of 17.1 h was found.



Acknowledgements

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References from web sites should be considered transitory, unless from an agency with a long lifetime expectancy. Sites run by private individuals, even if on an institutional web site, do not necessarily fall into this category.

Number	Name	2021 mm/dd	Phase	L_{PAB}	B_{PAB}	Period(h)	P.E.	Amp	A.E.
1862	Apollo	12/11-12/12	51.8,50.9	39	8	3.066	0.002	0.61	0.03
3200	Phaethon	12/04-12/06	13.2,14.3	53	14	3.589	0.003	0.19	0.02
3361	Orpheus	10/13-10/15	20.7,19.3	35	-2	3.547	0.003	0.19	0.02
4660	Nereus	10/26-11/03	16.0,12.7	45	5	15.172	0.002	0.75	0.03
7358	Oze	10/17-11/13	48.0,35.4	91	2	125.8	0.2	0.11	0.01
12711	Tukmit	11/29-11/30	39.6,39.4	119	18	3.483	0.001	0.72	0.04
18882	1999 YN4	12/09-12/12	28.2,26.8	105	22	2.346	0.001	0.10	0.02
20460	Robwhiteley	11/30-12/03	27.3,26.5	110	3	2.751	0.001	0.12	0.02
87024	2000 JS66	11/10-11/27	*3.8,21.5	49	-3	56.532	0.005	1.08	0.05
						53.347	0.007	0.43	0.03
						39.46	0.01	0.13	0.02
137062	1998 WM	11/29-12/04	14.0,18.1	58	13	2.469	0.002	0.06	0.01
137805	1999 YK5	12/09-12/20	47.5,44.4	123	28	4.019	0.001	0.16	0.03
285571	2000 PQ9	09/23-10/15	38.3,32.4	123	29	119.6	0.6	0.30	0.05
	1999 FJ21	10/13-10/16	11.7,23.1	13	3	0.370364	0.000006	0.27	0.03
	2019 XS	11/10-11/10	18.7	43	-8	[T]2.35	0.01	0.70	0.03
						3.01	0.01	0.61	0.03
	2021 JQ24	09/15-10/06	65.3,63.8	43	-17	20.923	0.005	0.22	0.03
	2021 LQ24	09/28-10/03	34.7,34.2	21	17	17.10	0.01	0.54	0.03

Table II. Observing circumstances and analysis results. [T]Dominant period of a likely 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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