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

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Lightcurves of 12 near-Earth asteroids (NEAs) obtained at the Center for Solar System Studies (CS3) from 2021 July through early October were analyzed for rotation period, peak-to-peak amplitude, and signs of satellites or tumbling. We have good reason to believe that 2019 UD4 is in a tumbling state.

CCD photometric observations of 12 near-Earth asteroids (NEAs) were made at the Center for Solar System Studies (CS3) from 2021 August through early October. 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.

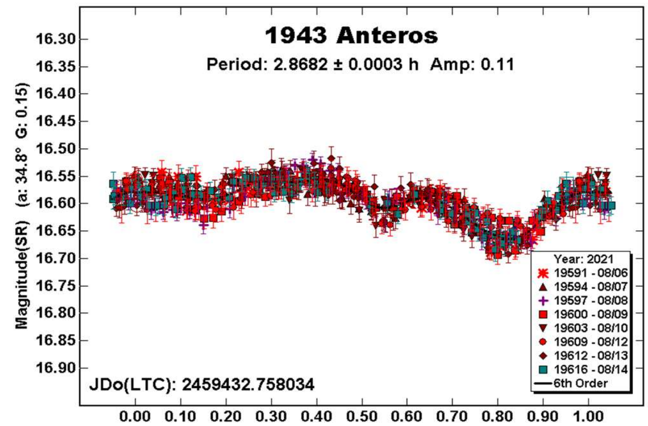
All lightcurve observations were unfiltered since a clear filter can cause a 0.1-0.3 mag loss. The exposure duration varied depending on the asteroid's brightness and sky motion. Guiding on a field star sometimes resulted in a trailed image for the asteroid.

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.

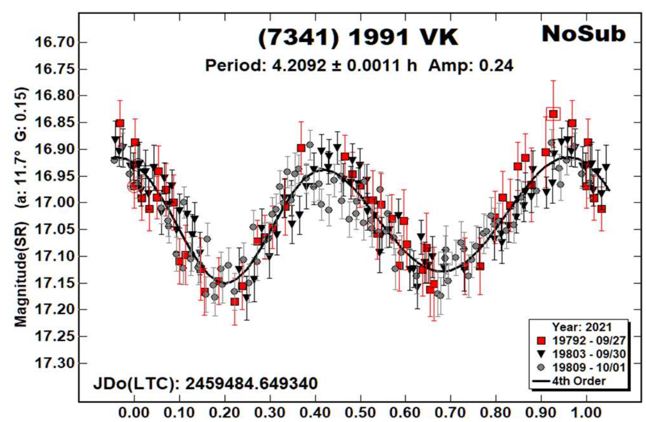
The Y-axis values are ATLAS SR "sky" (catalog) magnitudes. The two values in the parentheses are the phase angle (a) and the value of *G* used to normalize the data to the comparison stars used in the earliest session. This, in effect, corrected all the observations to seem to have been made at a single 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*.

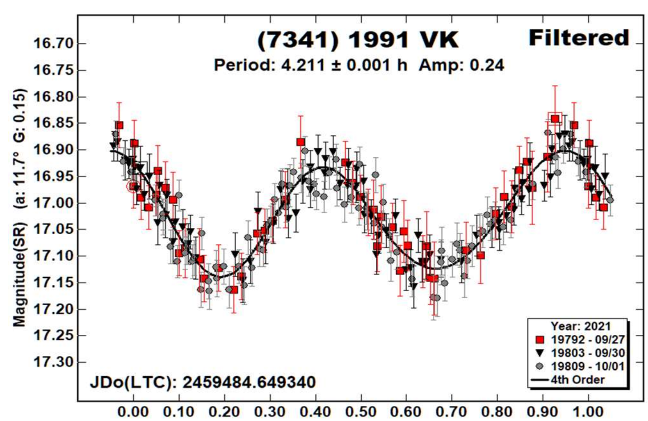
"LCDB" substitutes for "Warner et al. (2009)" from here on.

1943 Anteros. Warner et al. (2017) reported this to be a suspected binary with an orbital period of 23.548 h. We (Warner and Stephens, 2019) found inconclusive results, finding a suspected secondary period of 19.7 h. The 2021 data showed no signs of a satellite. If nothing else, the negative results help constrain the pole solutions for the primary spin axis and satellite orbit.



(7341) 1991 VK. Pravec et al. (1998) found a period of 4.2096 h. Our previous result of 4.211 h (Warner, 2017) is the same found with the most recent observations after applying a noise filter.

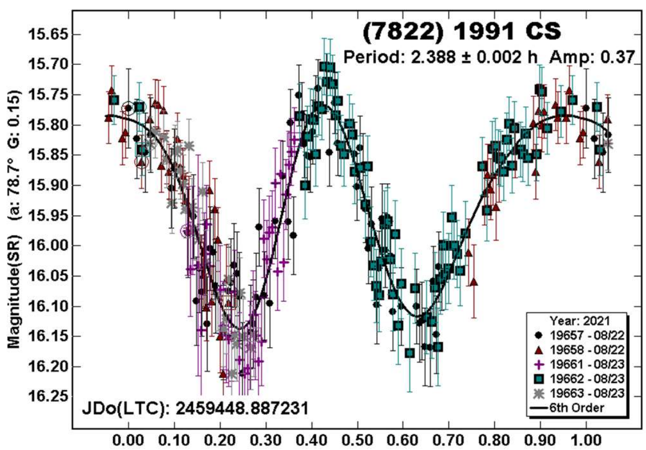




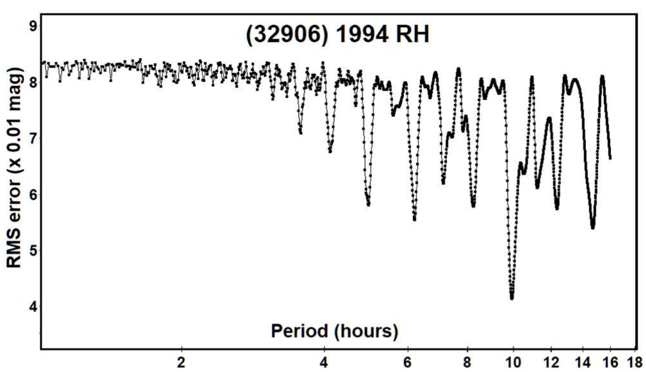
The "NoSub" plot shows the data phase to a single period but the scatter is a bit excessive. A dual-period search found several, low-amplitude possibilities but none of the phased plots showed indications of a satellite. Furthermore, the combination of period and estimated size (1 km), make it very unlikely that any of those secondary periods can be attributed to tumbling (Pravec et al., 2005; 2014). We applied the most dominant secondary solution to the original data to act as a *noise filter*. This produced a curve with less scatter ("Filtered" plot). The unfiltered data were submitted to ALCDEF (*https://alcdef.org*).

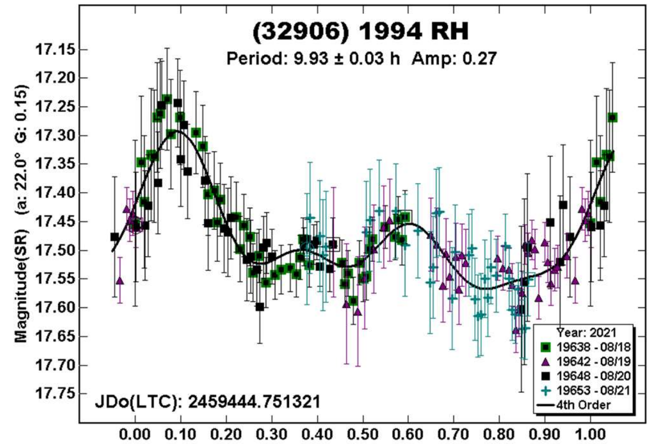
(7822) 1991 CS. The previously reported periods are all very close to 2.39 h, including our two previous results of 2.391 h (Warner, 2016a) and 2.392 h (Warner, 2016b), as well as Pravec et al. (1998; 2.389 h), Behrend (2016web; 2.3896 h), and Klinglesmith et al. (2016; 2.389 h). The amplitude has ranged from 0.26 to 0.46 mag.

It should be noted that the larger amplitudes were observed at more extreme phase angles, α > 45°, which exaggerates the amplitude due to shape alone that is seen at low phase angles (Zappala et al., 1990).



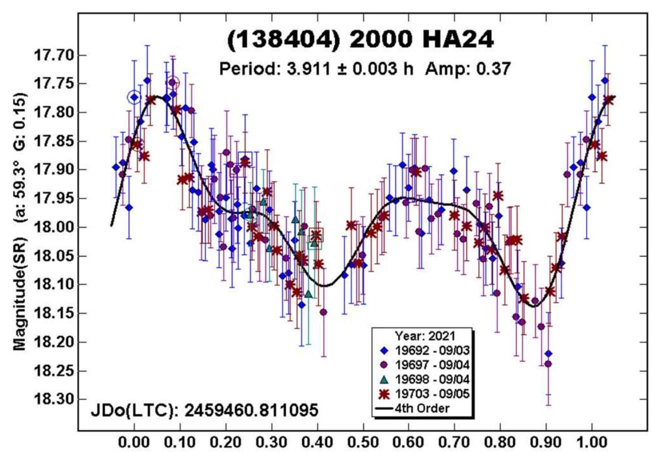
(32906) 1994 RH. Skiff (2012web) reported a period of 2.569 h, but no lightcurve is available. We could not get our data to fit anything close to that period, as seen in the period spectrum.





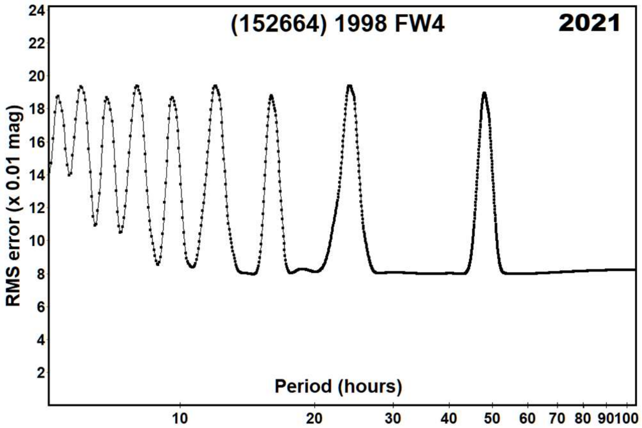
The odd shape of the lightcurve lends doubt to our period of 9.93 h despite its prominence in the period spectrum. Attempts to force a solution near some of the alternates in the period spectrum produced unsatisfactory results.

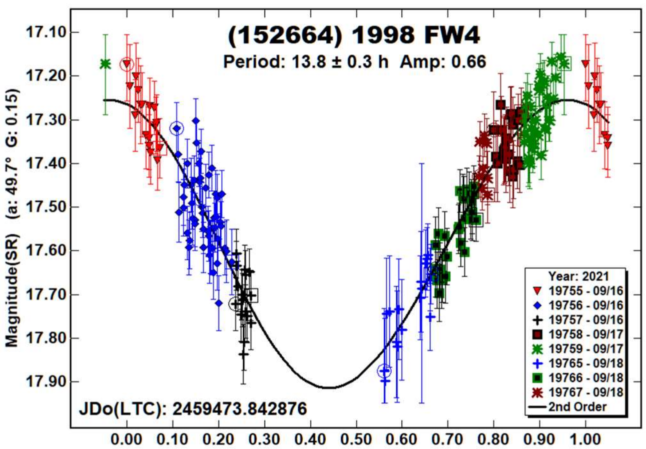
(138404) 2000 HA24. Hayes-Gehrke et al. (2017) reported a period of 3.7768 h but it is rated U = 2– in the LCDB, meaning that there is a good chance that the result is incorrect. It turned out that they were close. Monteiro et al. (2018) found P = 3.908 h and Pravec et al. (2019web) found P = 3.9077 h. Our result of 3.911 h is consistent with the longer periods.

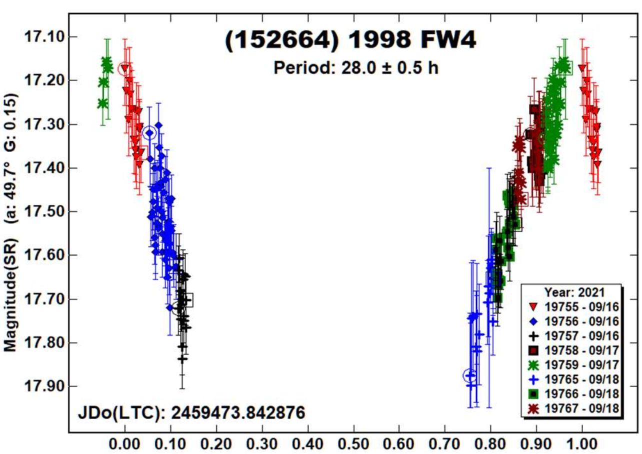


(152664) 1998 FW4. Various circumstances did not allow observing the asteroid to where the lightcurve could be even mostly filled. Despite the high phase angle, which can distort the lightcurve shape (Harris et al., 2014), it's very likely that the asteroid should produce a bimodal lightcurve.

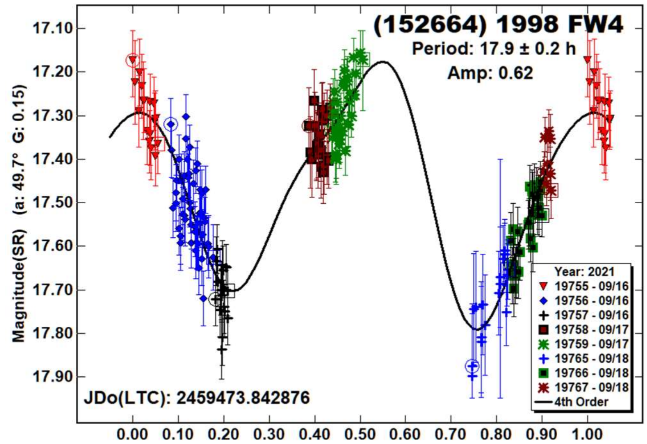
Proceeding on that assumption, we searched for a likely half-period. This would provide more coverage of the lightcurve and allow finding a good estimate for amplitude. That search found P = 13.8 h and amplitude of A = 0.66 mag. Based on this, we tried to find a solution near 28 h. The slopes of the lightcurve were far too steep to consider that possibility.

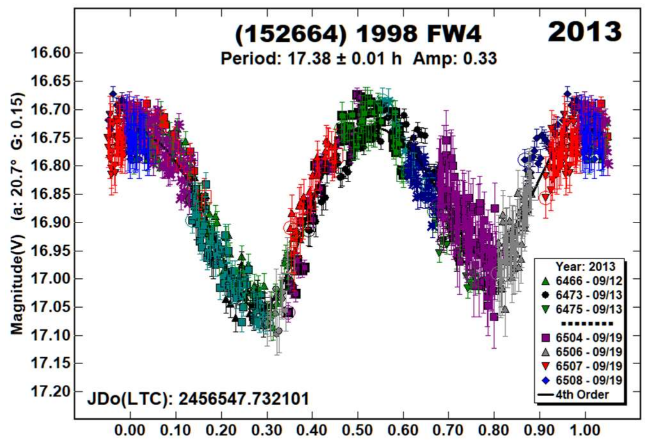






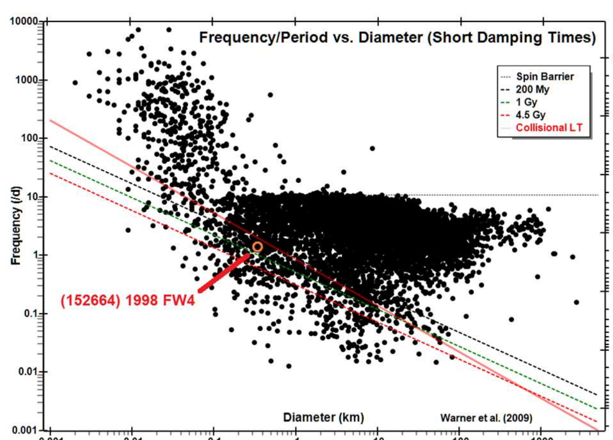
Using data from 2013 (Warner, 2014), we found a reliable solution of 17.38 h, but with an amplitude only half of what was suggested by the 2021 data ("2013" plot). We forced the latest data set to a period between 17-19 h and found one that is reasonably close to the earlier result when taking into account the gaps in the lightcurve.



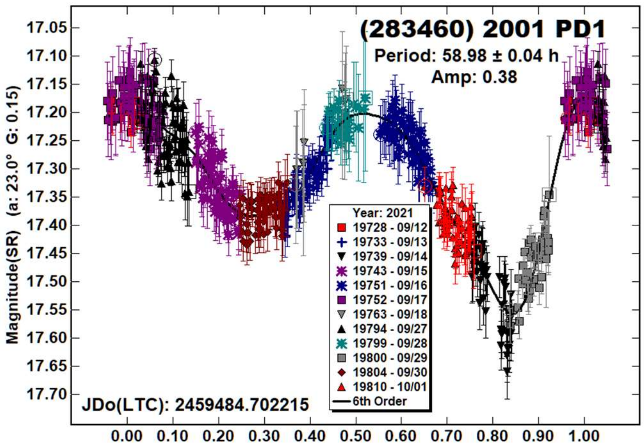


In the frequency-diameter plot from the LCDB, the asteroid is just below the 200 Myr damping and collisional life-time lines. By general rule of thumb (Pravec et al., 2005; 2014), there is a chance that the asteroid could be tumbling. There was no clear sign of such in 2013 nor, within the limits allowed by the sparse data set, in 2021.

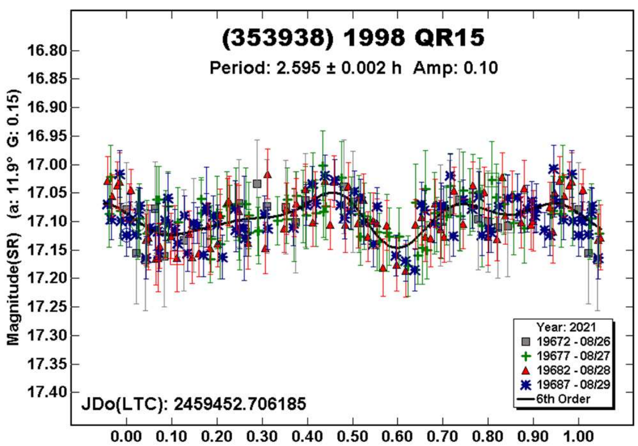
However, "absence of evidence is not evidence of absence," so future observations with low errors are encouraged to help confirm the rotational status of 1998 FW4.



(283460) 2001 PD1. Pravec et al. (2001web) found a period of 14.58 h, which is rated U = 2 in the LCDB. After the first few sessions, it seemed apparent that the correct period was much longer. It took several weeks of fighting weather and the moon to obtain what we consider a reliable period, despite the somewhat odd shape of the lightcurve. The period spectrum showed a very low likelihood that a period of about 14.5 h could be supported by the data.

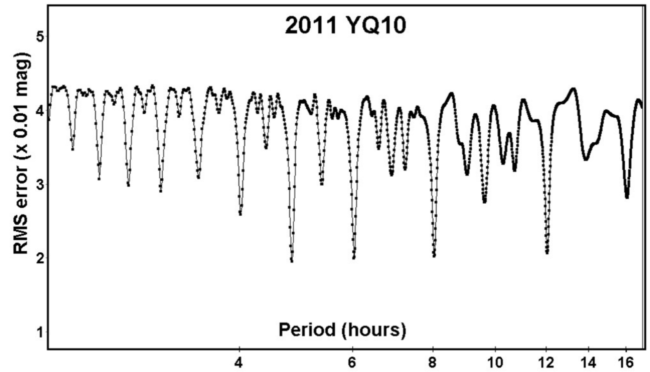


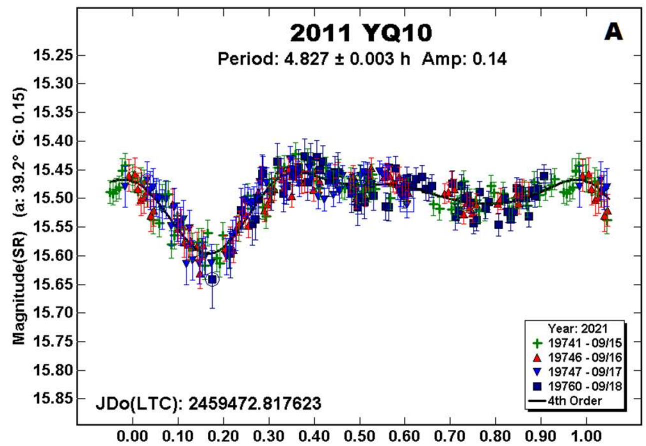
(353938) 1998 QR15. Pravec et al. (1998web) determined a rotation period of 2.454 hours, but this is rated U = 2– in the LCDB. Our data set allowed finding a more reliable period that was not too far removed from Pravec et al.



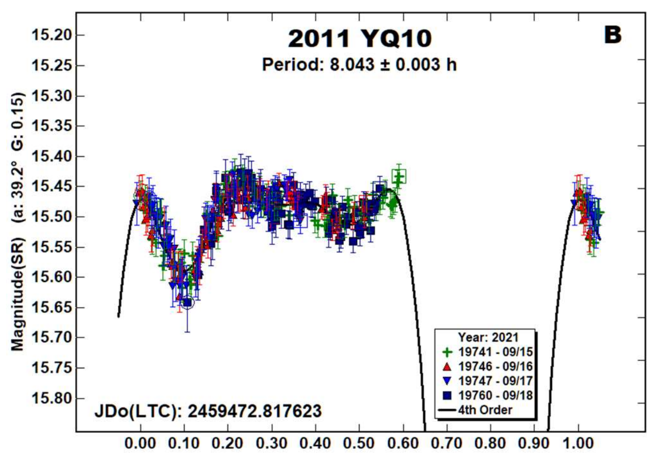
2011 YQ10. There we no previous results of any kind in the LCDB for this 0.5 km NEA. Some guidance from the past would have been helpful since our results are hardly conclusive.

The period spectrum for the 2021 data shows four nearly equal solutions ranging from 5 to 12 h. The strongest one, at 4.827 h, produces an odd shape ("A") but the observations were at phase angles near 40°, so shadowing may have come into play.

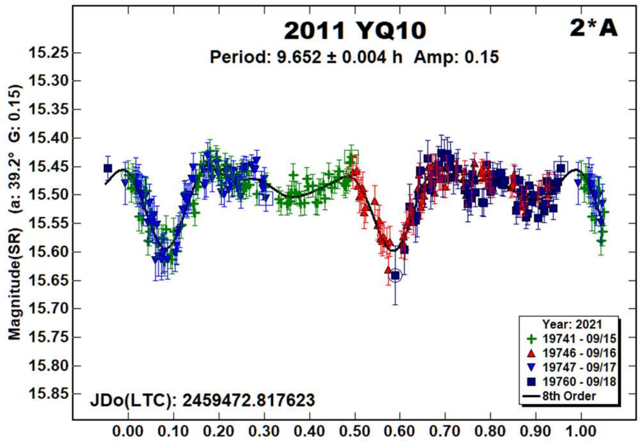




When assuming an alternate solution near 8.0 h, the Fourier curve reached unreasonable values ("B"). We clipped the curve, reduced the magnitude range, so that the data could still be seen to have a shape. For that solution to be given consideration, a minimum should be seen near 0.6 rotation phase. The data don't cover that point, but those just before *suggest but don't confirm* that that minimum would not exist even with more data.

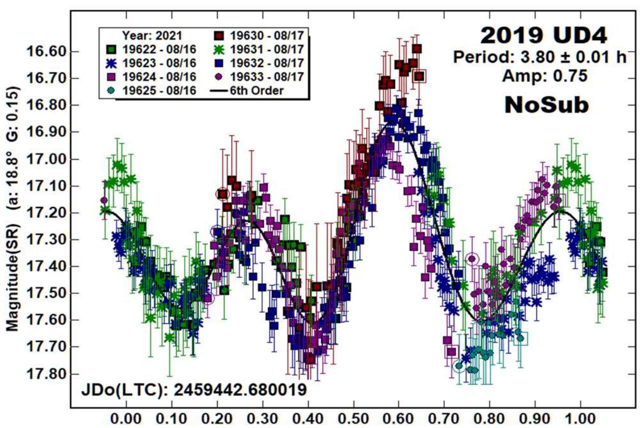


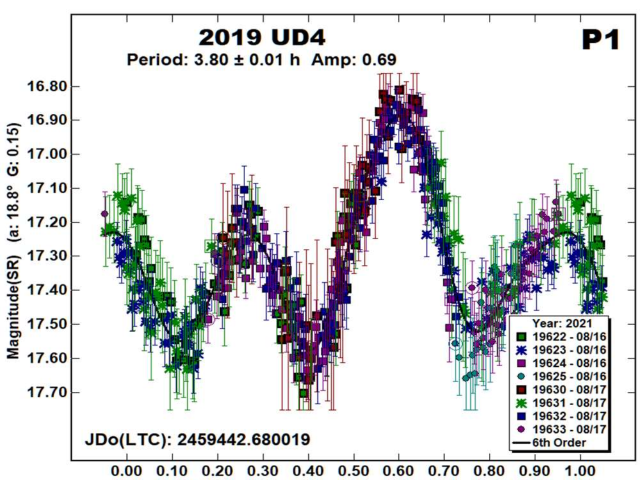
Plotting to the double-period of "A" ("2*A", 9.652 h) produced an intriguing lightcurve suggestive of a short period binary asteroid. However, the halves are identical in a split-halves plot (the second half superimposed on the first half). Such symmetry is unlikely. Even so, a search for a requisite short period due to the rotation of the primary or the satellite found nothing but a low-amplitude (flat) result. This further confirmed the unlikely symmetry.

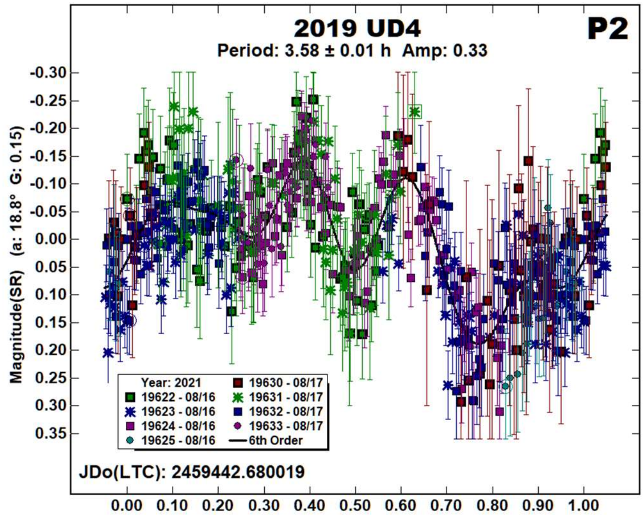


We adopt the period of 4.827 h as the best solution. We would suggest additional observations to confirm or refute that period but the 2021 apparition was the only one from 1995-2050 with V < 16 and the brightest it will be through 2050 is V ~ 19.4 in 2031.

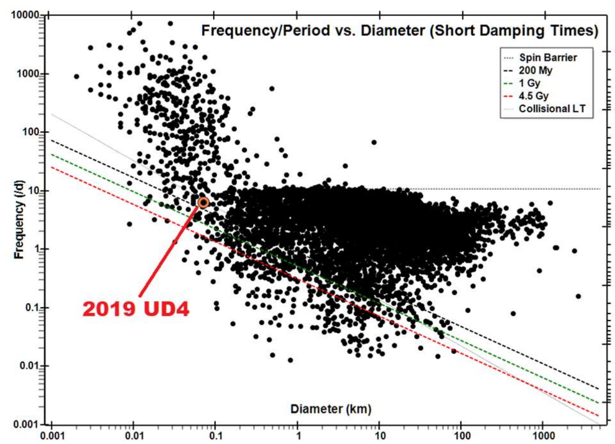
<u>2019 UD4</u>. These appear to be the first results for this 70 m asteroid, which we suspect is in a tumbling state.







The "NoSub" plot, meaning a single-period solution, shows just enough deviations outside the noise to prompt a dual-period search. After several iterations, we found a second period of 3.58 h that, when subtracted from the raw data, produced a clean result of 3.80 h ("P1"). The lightcurve for 3.58 h ("P2") is multimodal and very noisy, which is not unusual given that *MPO Canopus* does not implement an algorithm that properly analyzes tumbling asteroids.



If tumbling, there's a good chance that one of true periods, precession or rotation, matches our 3.80 h, or that our result (taken as a frequency) is an integral fraction/multiple of the true period. The other period remains unresolved.

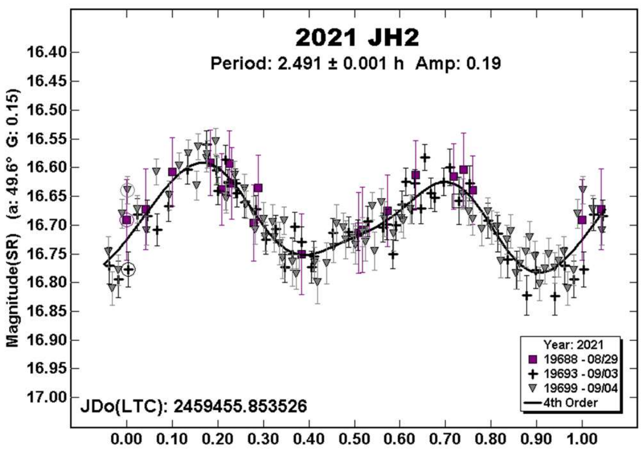
The LCDB frequency-diameter plot shows the asteroid's location. While above the three tumbling damping lines (suggesting no tumbling), such small asteroids are much more likely to be involved in collisions that have a significant impact on their rotational characteristics.

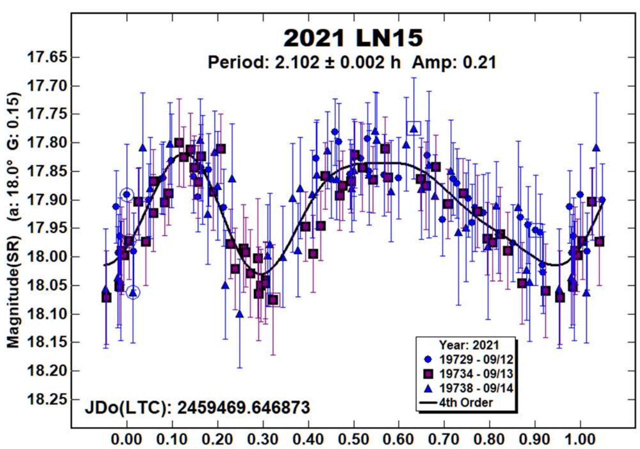
<u>2021 JH2, 2021 LN15</u>. There were no previous results in the LCDB for either of these NEAs. 2021 JH2 has an estimated diameter of 400 m while the estimated diameter for 2021 LN15 is about 300 m. Referring to the frequency-diameter plot under 2019 UD4, they are both near that asteroid's location. Despite that, there were no signs of tumbling in either data set, or at least none that came close to or above the noise level.

Number	Name	2021 mm/dd	Phase	L_{PAB}	B_{PAB}	Period(h)	P.E.	Amp	A.E.
1943	Anteros	08/06-08/14	34.8,30.0	348	16	2.8682	0.0003	0.11	0.01
7341	1991 VK	09/27-10/01	11.7,11.0	11	10	4.211	0.001	0.24	0.02
7822	1991 CS	08/22-08/23	78.6,79.4	17	-4	2.388	0.002	0.37	0.04
32906	1994 RH	08/18-08/21	22.0,20.9	353	6	9.93	0.03	0.27	0.03
138404	2000 HA24	09/03-09/05	59.2,61.5	21	6	3.911	0.003	0.37	0.03
152664	1998 FW4	09/16-09/18	49.6,56.2	27	2	17.9	0.2	0.62	0.05
283460	2001 PD1	09/12-10/01	23.1,32.3	344	16	58.98	0.04	0.38	0.04
353938	1998 QR15	08/26-08/29	*11.9,11.9	341	7	2.595	0.002	0.10	0.02
	2011 YQ10	09/15-09/18	39.1,42.2	14	-13	4.827	0.002	0.14	0.01
	2019 UD4	08/16-08/17	19.0,21.9	326	11	^{T}3.80	0.01	0.69	0.01
						3.58	0.01	0.33	0.04
	2021 JH2	08/29-09/04	49.7,42.2	6	-7	2.491	0.001	0.19	0.02
	2021 LN15	09/12-09/14	18.0,18.9	354	12	2.102	0.002	0.21	0.03

Table II. Observing circumstances and analysis results. ^{T}Tumbling asteroid. 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).

Our calculations show that 2021 JH2 will be V ~ 19 in 2037 and 2021 LN15 will be V ~ 19.4 in 2038. Other than those apparitions, the two will be well below V = 20 through 2050.





Acknowledgements

Funding work on the asteroid lightcurve database (Warner et al., 2009) and ALCDEF database (*alcdef.org*) were supported in part by NASA grant 80NSSC18K0851. 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. 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. This paper made use of the services provided by the SAO/NASA Astrophysics Data System, which is operated by the Smithsonian Astrophysical Observatory under NASA Cooperative Agreement 80NSSC211M0056.

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ON CONFIRMED AND SUSPECTED BINARY ASTEROIDS OBSERVED AT THE CENTER FOR SOLAR SYSTEM STUDIES

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Analysis of CCD photometric observations made at the Center for Solar System Studies from 2021 August through September suggested or confirmed that several asteroids were binary. The candidates are 5715 Ables, 7087 Lewotsky, 7173 Sepkoski, (16960) 1998 QS52, (68063) 2000 YJ66, (143649) 2003 QQ47, (159857) 2004 LJ1, and (326732) 2003 HB6,

Data from CCD photometric observations made at the Center for Solar System Studies in 2021 August through September were used to look for indications of an asteroid being binary. Confirmed binaries are those that show mutual events (occultations/eclipses) while suspected binaries include those with two periods, no obvious mutual events, and periods consistent with binary asteroids (Pravec et al., 2018, Figure 14).

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
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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 adjusted nightly zero points and their amounts, the analysis of the 2021 data used the ATLAS catalog r´ (SR) magnitudes (Tonry et al., 2018). The rare zero-point adjustments ≥ ±0.03 mag may be related in part to using unfiltered observations, poor centroiding of the reference stars, not correcting for second-order extinction, or selecting a star that is 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