

NEAR-EARTH ASTEROID LIGHTCURVE ANALYSIS AT THE CENTER FOR SOLAR SYSTEM STUDIES: 2022 MARCH-JUNE

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CCD photometry of 11 near-Earth asteroids (NEAs) obtained at the Center for Solar System Studies (CS3) in 2022 March to June were analyzed for rotation period, peak-to-peak amplitude, and signs of satellites or tumbling. While there were no signs of any of the asteroids being binary, seven of them are suspected tumblers: (10302) 1989 ML, (100756) 1998 FM5, (163692) 2003 CY18, (388945) 2008 TZ3, (464798) 2004 JX20, and 2018 XV5.

CCD photometric observations of 11 near-Earth asteroids (NEAs) were made at the Center for Solar System Studies (CS3) in 2022 March to June. Seven of the set were found to be tumbling, though the true periods of rotation and precession could not be determined.

Table I lists the telescopes and CCD cameras that were available to make observations. All the cameras use a KAF-1001E blue-enhanced CCD 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 telescopes and CCD cameras at CS3 used for this paper. The exact combination for each telescope/camera pair is chosen to meet specific needs.

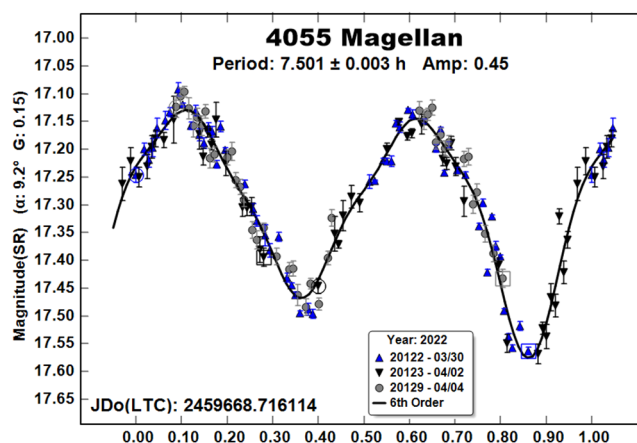
All lightcurve observations were unfiltered or with a clear filter, even though the latter can cause a 0.1-0.3 mag loss. The exposure duration varied depending on the asteroid's brightness and sky motion. Not all images were guided. Regardless, sometimes the asteroid was trailed on the image. In those cases, elliptical apertures were used to increase the target's SNR during measuring.

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 $|\Delta mag| \leq 0.03$. The rare larger corrections may have been due in part to using unfiltered observations, poor centroiding of the target and stars, not correcting for second-order extinction, and/or selecting what appears to be a single star but is actually an unresolved pair.

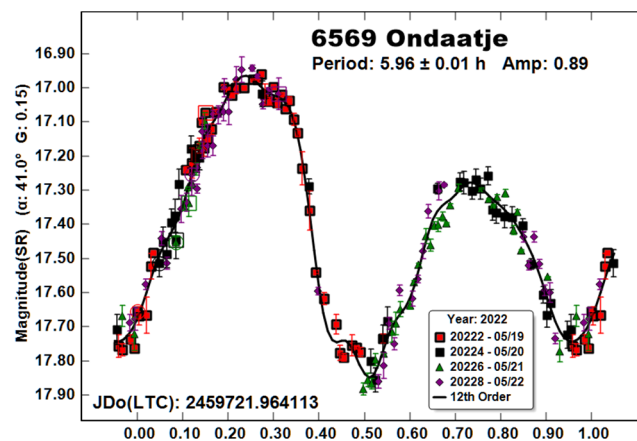
The Y-axis values are ATLAS SR “sky” (catalog) magnitudes. The two values in the parentheses are the phase angle (α) and the value of G used to normalize the data to the comparison stars used in the earliest session. This, in effect, corrects all the observations to seem to have been made at a single fixed date/time and phase angle, presumably 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.

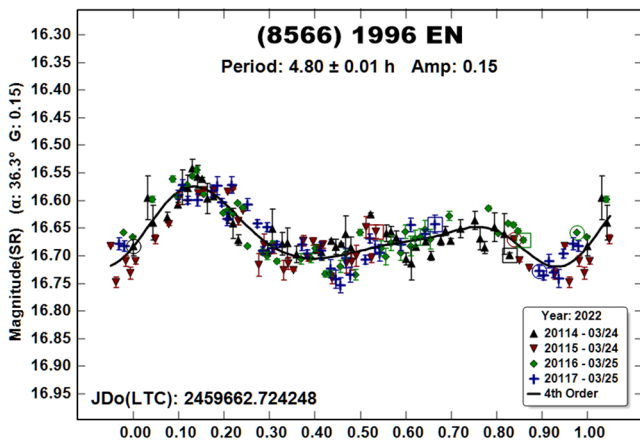
4055 Magellan. Pravec et al. (2000web) first reported a period of 7.475 h based on observations made in 2000. Several other results were obtained over the years and listed in the LCDB, including two of our previous efforts (Warner, 2015b; 2017). All entries had periods close to 7.50 h, save Warner (2014), who reported 6.384 h.



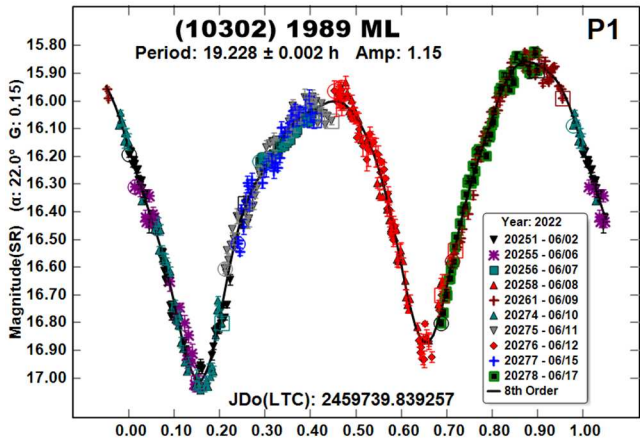
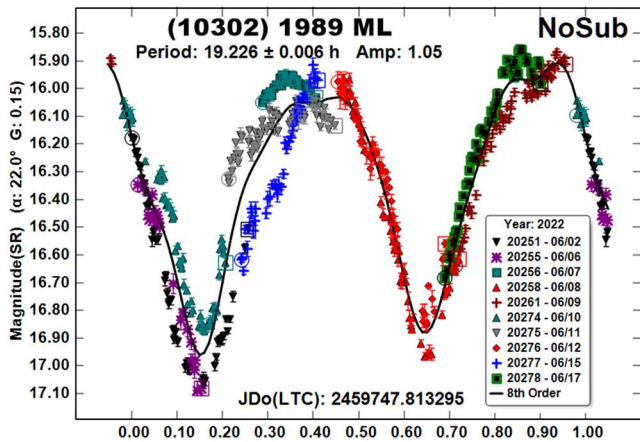
6569 Ondaatje. Pravec et al. (1996) found a period of 5.959 h and amplitude of 0.98 mag. We (Warner and Stephens, 2020b) faced a highly symmetrical lightcurve with 0.92 mag amplitude based on our 2020 observations that had one of two periods: 5.295 h or 5.956 h, which happened to be 0.5 rotations difference per 24 hours. We adopted the shorter period for its slightly lower RMS, but that now seems to be incorrect. Our latest results reinforce a period near 5.96 h with no ambiguity because of the asymmetrical lightcurve.



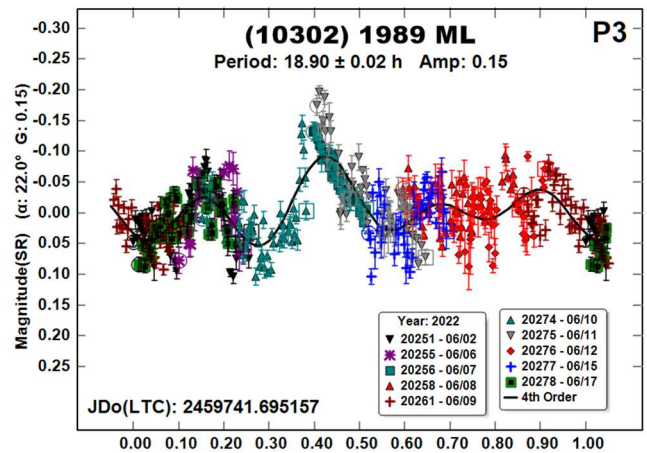
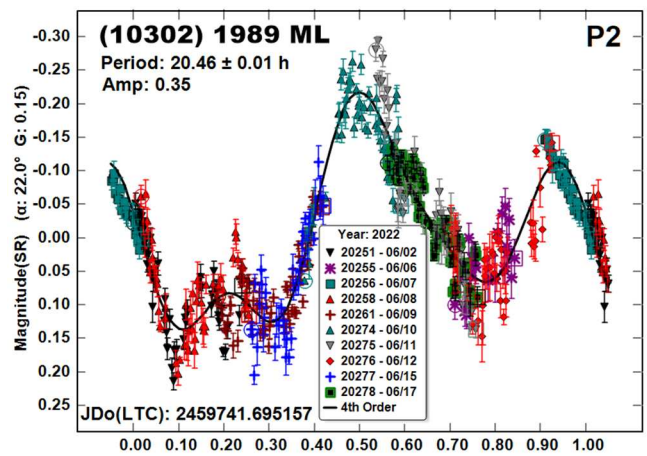
(8566) 1996 EN. The only previously reported period in the LCDB was ours of 4.849 h (Warner and Stephens, 2020a) based on data from 2020. The analysis of the 2022 data gave a similar value, $P = 4.80$ h. The slight difference is probably due to the lower amplitude (0.15 vs. 0.20 mag) and amount of available data.



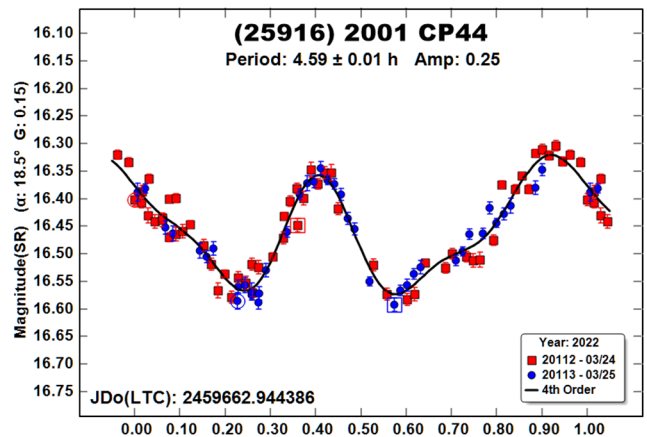
(10302) 1989 ML. Pravec et al. (2019web) found a period of 19.164 h and indications that the asteroid is tumbling. Our 2022 observations support both conclusions.



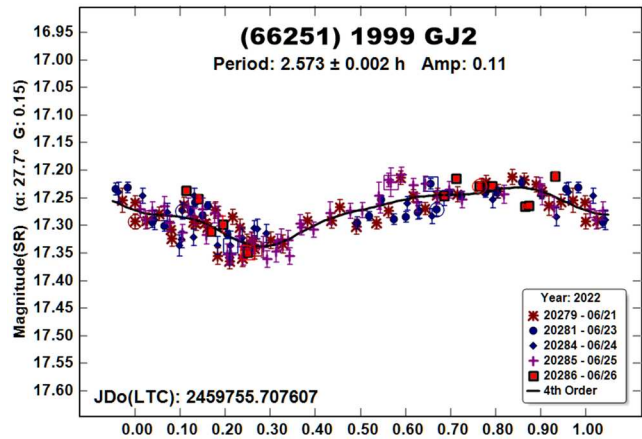
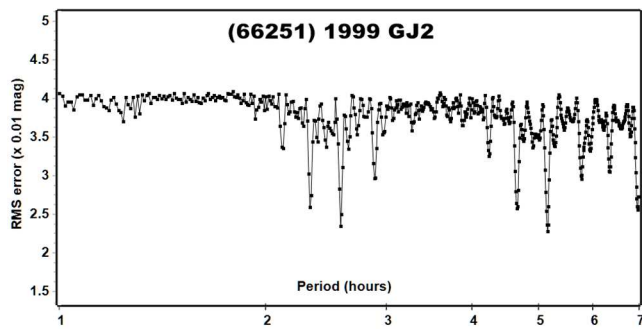
Pravec et al. (2019web) can analyze tumbling asteroids properly (Pravec et al., 2005; 2014). *MPO Canopus* cannot. Even so, we used it to extract the dominant period and two others that, when subtracted from the full data set, allowed a good fit to a bimodal lightcurve with $P_1 = 19.228$ h. The other periods, $P_2 = 20.46$ h and $P_3 = 18.90$ h, are unlikely to have a direct physical cause but are, instead, artifacts of holding two periods constant while searching for a third. Proper analysis would have two periods solved simultaneously.



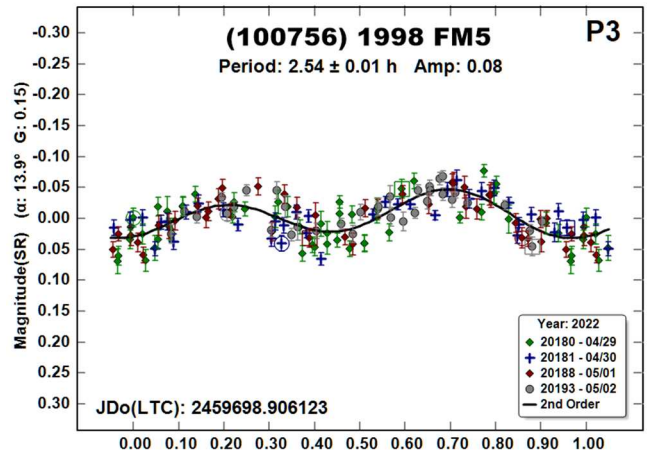
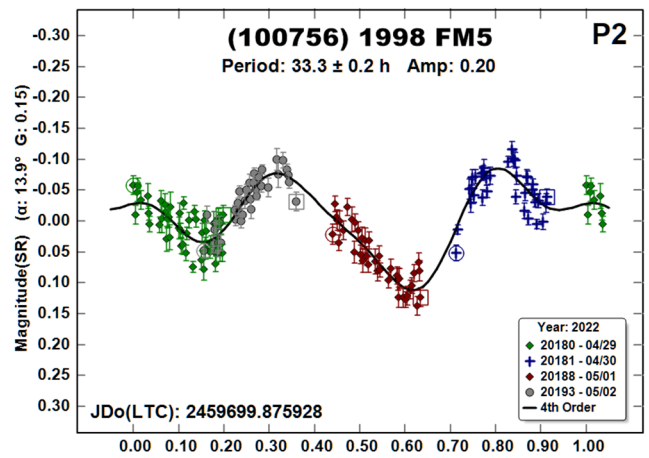
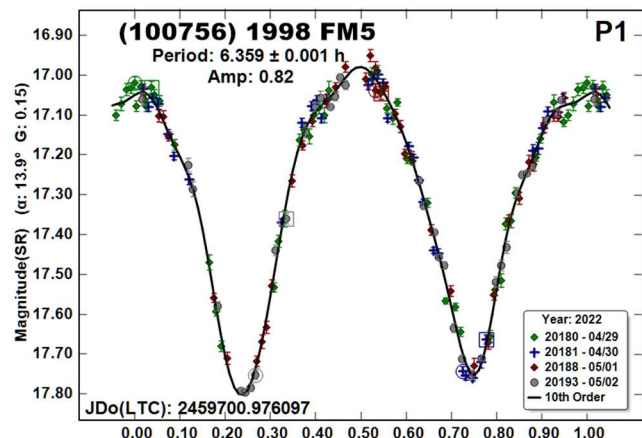
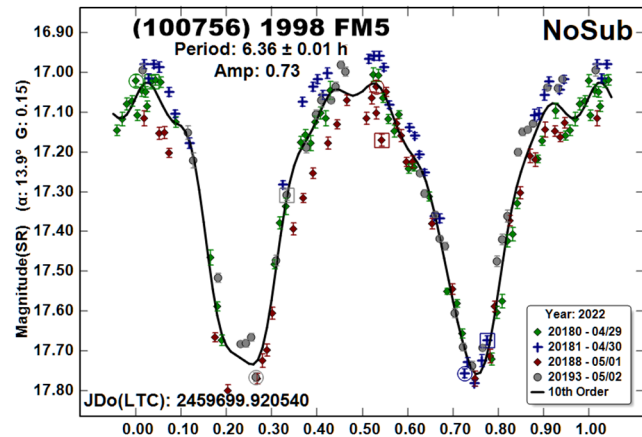
(25916) 2001 CP44. Rare within this work is found a simple lightcurve with easily determined period. This NEA was one of those rare occurrences. There are numerous entries in the LCDB with a period near 4.6 h. Our latest results are in good agreement.



(66251) 1999 GJ2. Pravec et al. (2005web) first reported a period of 2.4621 h. Polishook (2012) found a somewhat reliable solution of 2.50 h. In 2020 (Warner and Stephens, 2020b) determined a period of 50.9 h, but this was based on a data set where the error bars were comparable to the amplitude (0.14 mag) of the lightcurve. Our result from 2022, $P = 2.573$ h, is in alignment with previous results, but not perfectly so since it's 0.07 to 0.11 h longer. What's more is that the doubled period (~5.14 h; bimodal lightcurve), cannot be formally excluded (Harris et al., 2014).

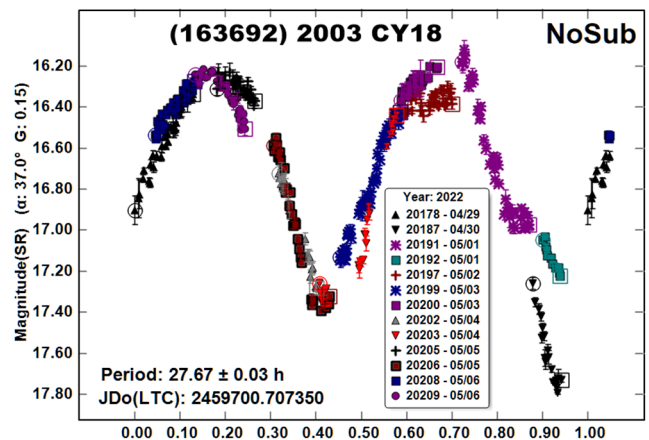


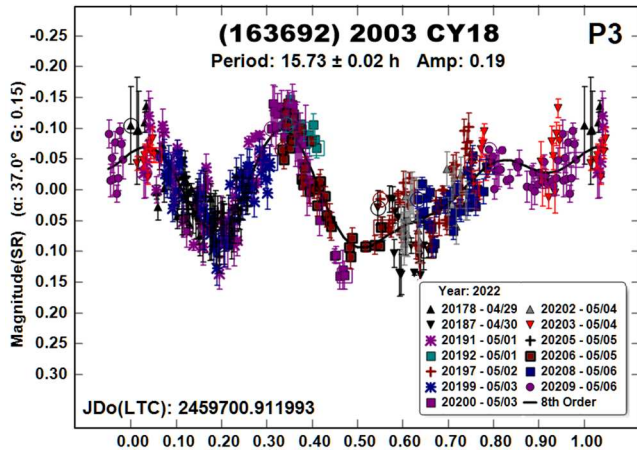
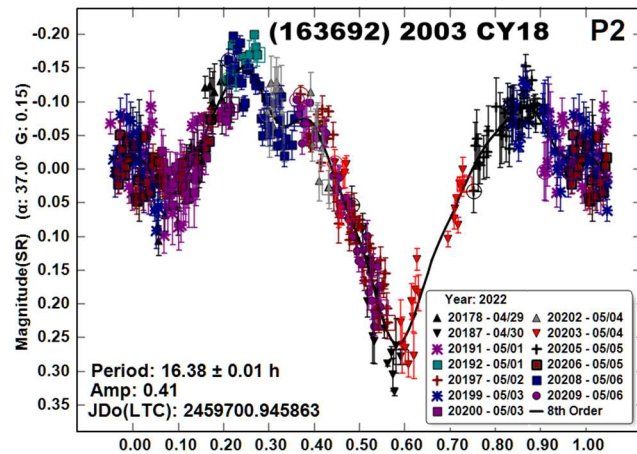
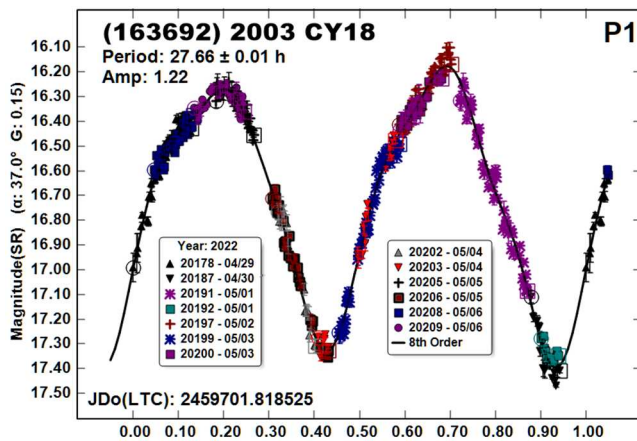
(100756) 1998 FM5. Pravec et al. (1998web) reported a period of 6.35 h based on data obtained in 1998. We observed the asteroid in 2014 (Warner, 2015a) and found a similar result of 6.369 h.



The 2022 data set led to a dominant period of about 6.36 h, but as with many others in this work, would not resolve to a single period. In the end, periods of $P_2 = 33.6$ h and $P_3 = 2.54$ h were required to get a clear dominant period of $P_1 = 6.359$ h. As mentioned before, these are probably the artifacts of an improperly executed dual-period search on a tumbling asteroid.

(163692) 2003 CY18. This appears to be the first reported rotation period for 2003 CY18. We were again faced with a data set that could not be properly analyzed because the asteroid appears to be tumbling. The “NoSub” plot clearly shows that a single-period solution does not work. After many trial solutions and iterations of holding two periods constant to find a third, we found a good fit to a dominant period of $P_1 = 27.66$ h.

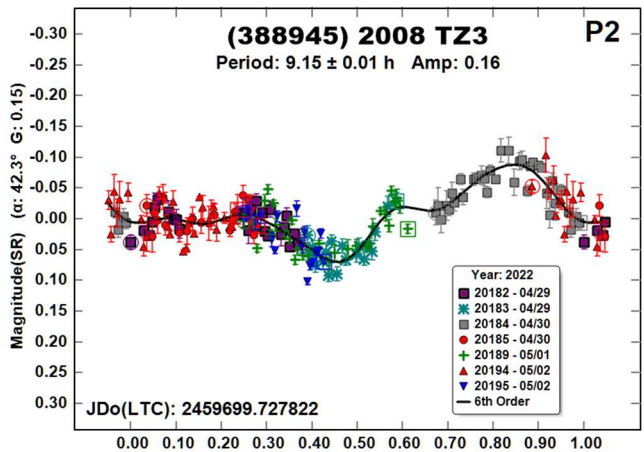
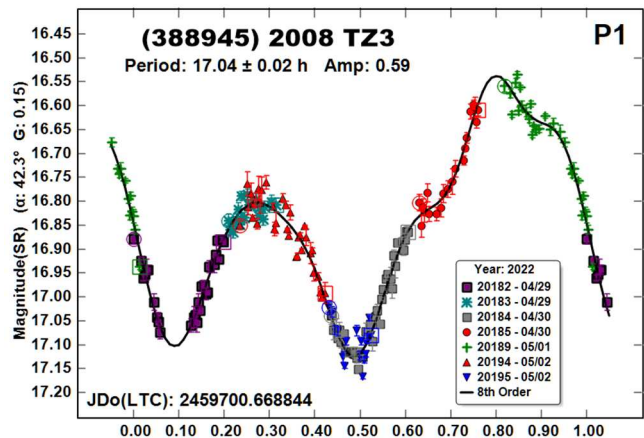
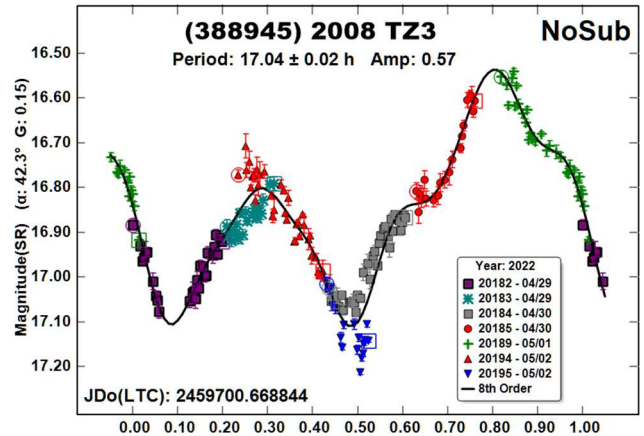




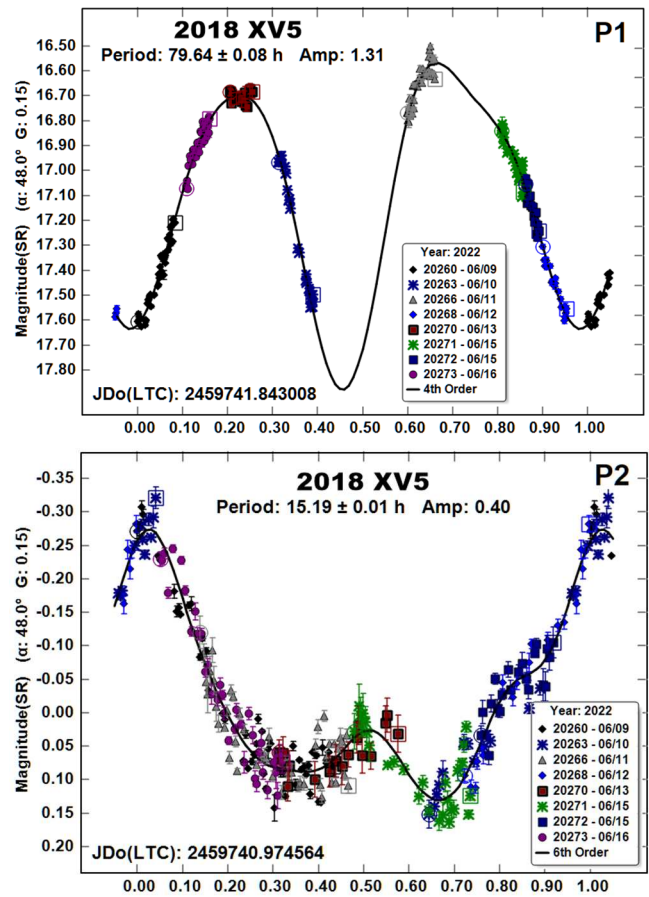
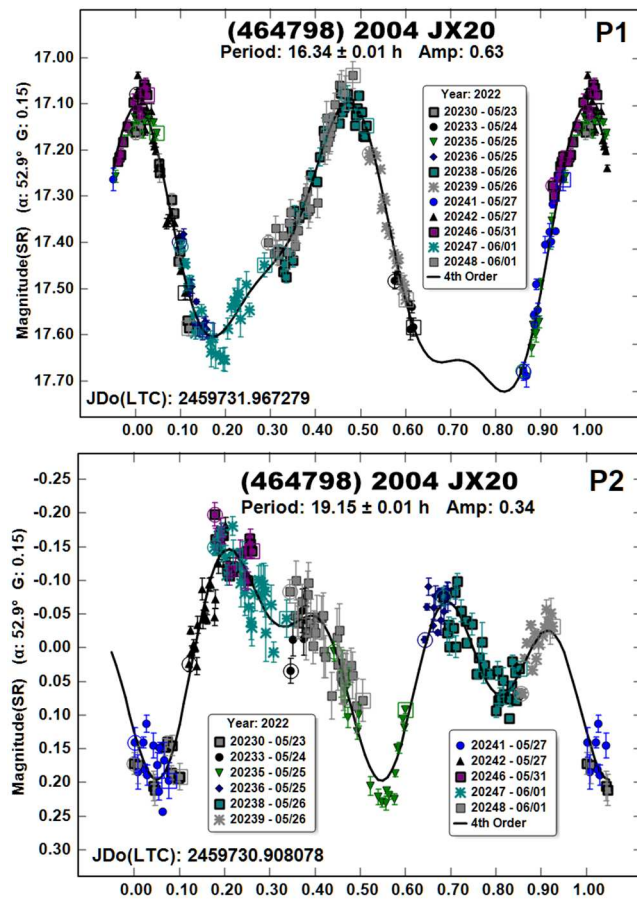
(388945) 2008 TZ3. Pravec et al. (2019web; 2020web) determined that this is a tumbling asteroid with a dominant period of 39.15 h in both cases and a second period of 34.11 h (2019) or 34.16 h (2020). It's rated -3 on the tumbling scale (Pravec et al., 2005), meaning that the solution is considered secure.

In 2016 (Warner, 2016), we suspected that the asteroid was tumbling when we found periods of 44.2 h and 52.4 h. These have no simple relation to the periods from Pravec et al. (2019web; 2020web). The results from our 2022 observations are even more divergent. The "NoSub" lightcurve shows some deviations from a single period solution, but not so much that the final result would

be about half the second period found by Pravec et al. (2019web; 2020web). Our final periods, 17.04 h and 9.15 h, are the best we could find but they are far from being in agreement with earlier results.

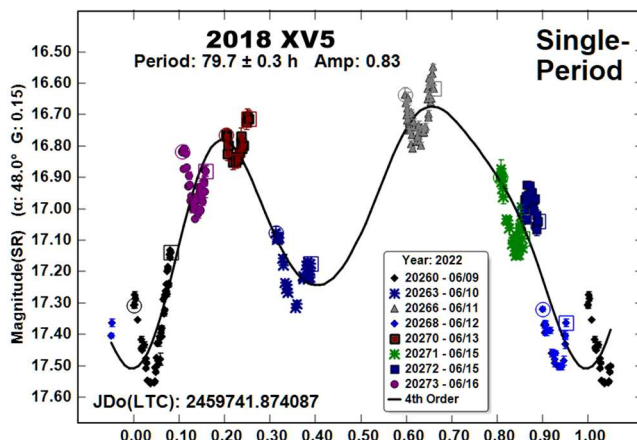
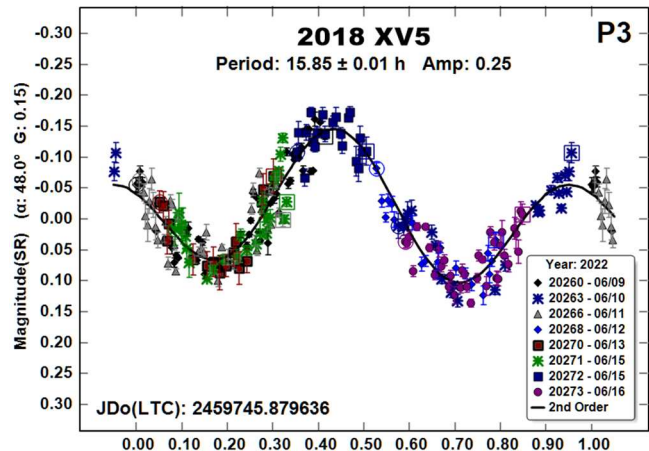


(464798) 2004 JX20. We observed this asteroid in 2016 (Warner, 2016) and found a single period of 36 ± 1 h. There was reasonable reason to believe that it was tumbling but a second period could not be found. Skiff (2019web) also had sufficient reason to suspect tumbling and reported periods of 10.758 h and 9.24 h. Then came our 2022 observations. These also indicate tumbling but with periods dissimilar to those reported before.



2018 XV5. There were no previously reported rotation periods for this NEA. We had a relatively sparse data set on which to do analysis, so our results have more than the usual uncertainty.

The “Single-Period” lightcurve clearly shows that trying to find one, even with more data, would probably be to no avail. As described previously, we attempted to extract one or two periods that, when subtracted from the data set, would at least give a good fit to a dominant period. We were able to do this. However, once again, the two additional periods are more likely due to the inability of *MPO Canopus* to properly handle a dual-period search on a tumbling asteroid. Regardless, it’s intriguing that P_2 and P_3 are close to one another and that the P_3 lightcurve would be a welcome single-period solution under other circumstances.



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Number	Name	2022/mm/dd	Phase	L _{PAB}	B _{PAB}	Period(h)	P.E.	Amp	A.E.
4055	Magellan	03/30-04/04	9.3, 12.0	177	10	7.501	0.003	0.45	0.03
6569	Ondaatje	05/19-05/22	41.0, 41.3	230	39	5.96	0.01	0.89	0.03
8566	1996 EN	03/24-03/25	36.4, 37.4	187	34	4.80	0.01	0.15	0.02
10302	1989 ML	06/02-06/15	22.0, 24.6	250	11	^T 19.228	0.002	1.15	0.03
						20.46	0.01	0.35	0.04
						18.90	0.02	0.15	0.04
25916	2001 CP44	03/24-03/25	18.5, 18.3	206	21	4.59	0.01	0.25	0.02
66251	1999 GJ2	06/21-06/26	27.8, 30.5	267	21	2.573	0.002	0.11	0.02
100756	1998 FM5	04/29-05/02	13.8, 13.0	225	15	^T 6.359	0.001	0.82	0.03
						33.3	0.2	0.20	0.03
						2.54	0.01	0.08	0.01
163692	2003 CY18	04/29-05/05	37.1, 44.2	219	27	^T 27.66	0.01	1.22	0.05
						16.38	0.01	0.41	0.04
						15.73	0.02	0.19	0.03
388945	2008 TZ3	04/29-05/02	42.6, 47.4	196	8	^T 17.04	0.02	0.59	0.03
						9.15	0.01	0.16	0.02
464798	2004 JX20	05/23-05/31	52.9, 43.8	252	30	^T 16.34	0.01	0.63	0.03
						19.15	0.01	0.34	0.05
	2018 XV5	06/09-06/16	48.2, 57.3	256	37	^T 79.64	0.08	1.25	0.10
						15.19	0.01	0.40	0.03
						15.85	0.01	0.25	0.03

Table II. Observing circumstances and results. The phase angle (α) is given at the start and end of each date range. L_{PAB} and B_{PAB} are the average phase angle bisector longitude and latitude (see Harris et al., 1984). If more than one line for an asteroid, the first line gives the dominant solution and has a ^T superscript. Subsequent lines are additional, not alternate, periods. See the text for more details.