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

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CCD photometric observations of six near-Earth asteroids (NEA) were made at the Center for Solar System Studies from 2022 June to October. (54789) 2002 MZ7 appears to be in non-principal axis rotation ("tumbling"), which was reliably established by Pravec et al. (2005). Our analysis found an additional, unexpected short period, low amplitude lightcurve. 398188 Agni also appears to be tumbling. It was not possible to establish the true periods of rotation and precession for either asteroid.

CCD photometric observations of six near-Earth asteroids (NEAs) were made at the Center for Solar System Studies (CS3) in 2022 June to October. Two of the seven, (54789) 2002 MZ7 and 398188 Agni, are in a state of non-principal axis rotation, i.e., "tumbling." Given the limitations of the software used to analyze the data and insufficient data, 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.

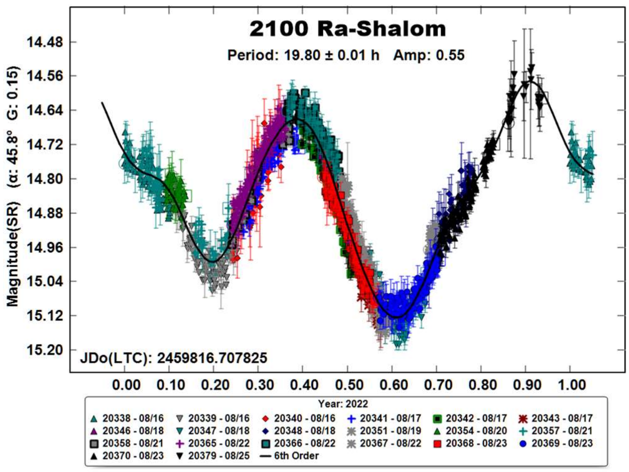
Measurements were made using *MPO Canopus*. The Comp Star Selector utility in *MPO Canopus* found up to five comparison stars of near solar-color for differential photometry. To reduce the number of times and amounts of adjusting nightly zero points, we use the ATLAS catalog r´ (SR) magnitudes (Tonry 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 values in the parentheses give the phase angle(s) (*a*) 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 so that 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.

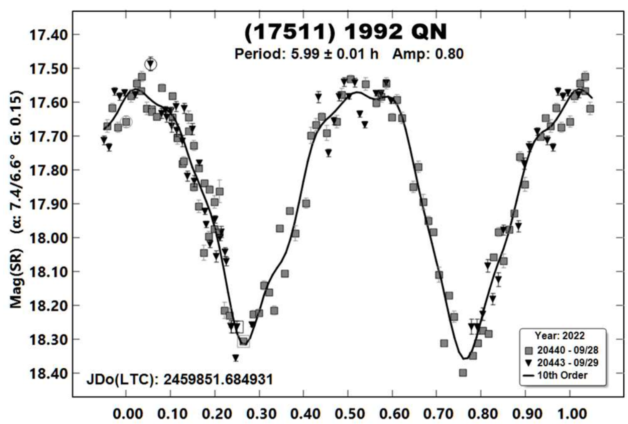
There can be up to three phase angles given. If two, the values are for the first and last night observations. If three, the middle value is the extrema (maximum or minimum) reached between the first and last observing runs. The X-axis shows rotational phase from -0.05 to 1.05. If the plot includes the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

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

2100 Ra-Shalom. Ostro et al. (1984) observed this NEA with radar and optical photometry to find a rotation period of 19.79 h, a period that has often been reproduced to within 0.01 h over the years, e.g., Pravec et al. (2003web; 2016web) and Warner (2017). Our results from the 2022 campaign are consistent with the established period.



(17511) 1992 QN. Pravec et al. (1998) found a period of 5.9902 h. We observed the asteroid twice before: Warner (2014; 5.985h) and Warner (2018; 5.990 h). The 2022 data led to similar results.

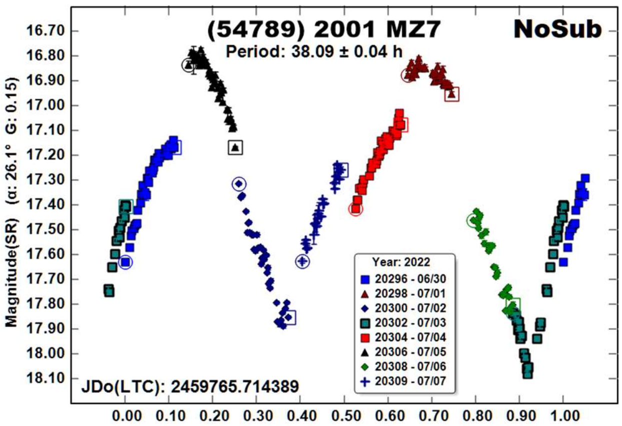


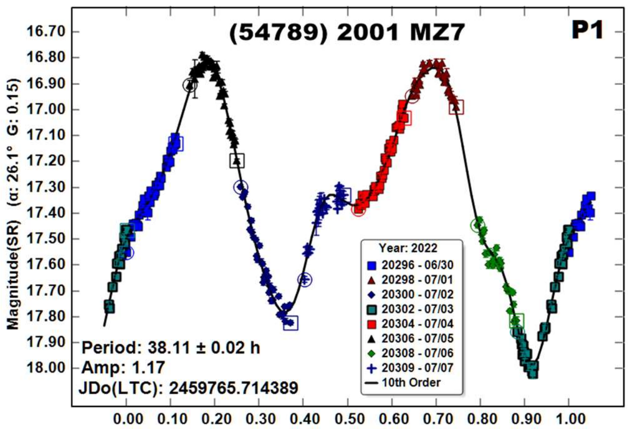
Number	Name	2022 mm/dd	Phase	L_{PAB}	B_{PAB}	Period(h)	P.E.	Amp	A.E.
2100	Ra-Shalom	08/16-08/23	45.6,33.5	347	19	19.80	0.01	0.55	0.03
17511	1992 QN	09/28-09/29	7.3,6.5	12	4	5.99	0.01	0.80	0.03
54789	2002 MZ7	06/30-07/07	26.1,26.8	252	27	^{T}38.11	0.02	1.17	0.03
						7.330	0.003	0.16	0.02
398188	Agni	07/09-07/20	*51.9,51.7	279	29	^{T}22.115	0.003	0.92	0.03
						32.5	0.1	0.68	0.03
						9.48	0.02	0.23	0.03
	2011 TG2	09/28-09/29	53.8,48.0	34	-9	2.562	0.002	0.60	0.05
	2012 PG6	08/24-08/28	41.1,50.5	350	19	10.58	0.02	1.27	0.06

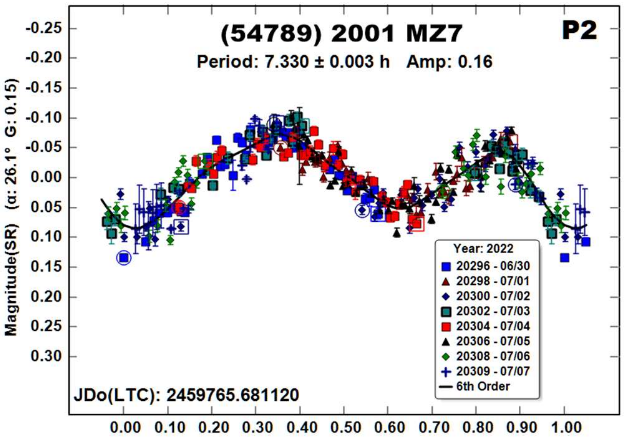
Table II. Observing circumstances. The first line gives the sole period or, if preceded with ^{T}, the dominant period of a tumbler. Any additional lines give the secondary period(s). The phase angle (α) is given at the start and end of each date range. If preceded with an asterisk, the phase angle reaches a minimum or maximum between the first and last date. L_{PAB} and B_{PAB} are, respectively the average phase angle bisector longitude and latitude (see Harris et al.,1984).

(54789) 2002 MZ7. Pravec et al. (2005; see Pravec et al., 2014) established that the asteroid was tumbling and reported periods of 37.57 h and 52.79 h. The solution, however, was not unique, meaning that combinations of four possible periods provided a nearly equal fit. Despite the ambiguities, it was rated PAR = –3, i.e., reliable.

Our data were far too sparse for a definitive solution even with the proper software. Regardless, we found a dominant period (38.11 h; "P1") that is in good agreement with one of the periods found by Pravec et al. (2005). Not expected was, after subtracting the dominant period, finding a short period, low amplitude (7.330 h, 0.16 mag) lightcurve ("P2") with a very good fit that is reminiscent of a "typical" single body in single axis rotation. Likewise, subtracting this secondary period dramatically improved the fit of the data to the dominant period, but the result lightcurve shape is still somewhat unusual.



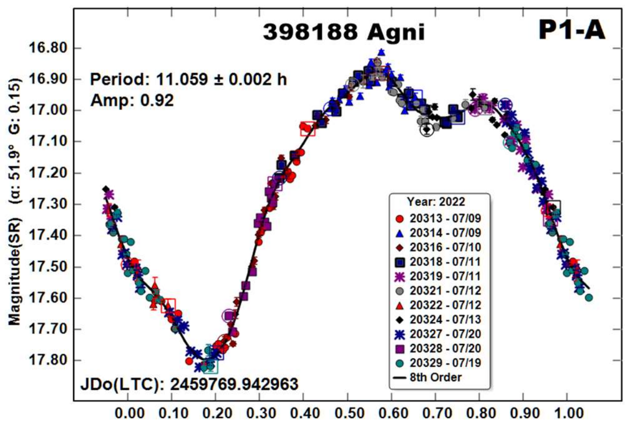


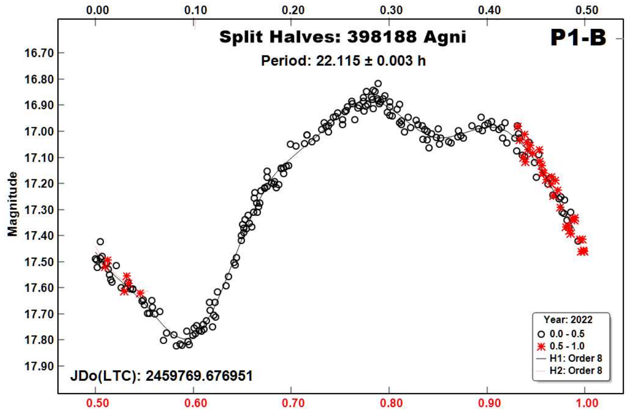


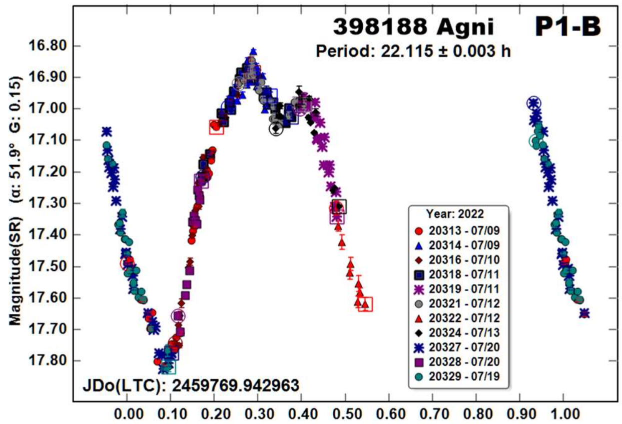
398188 Agni. We observed this asteroid in 2014 (Warner, 2015), finding dominant periods of 22.1 h and 32.6 h for what we believed to be a tumbling asteroid. Neither solution led to even a close fit of the data. We had better luck with the 2022 data.

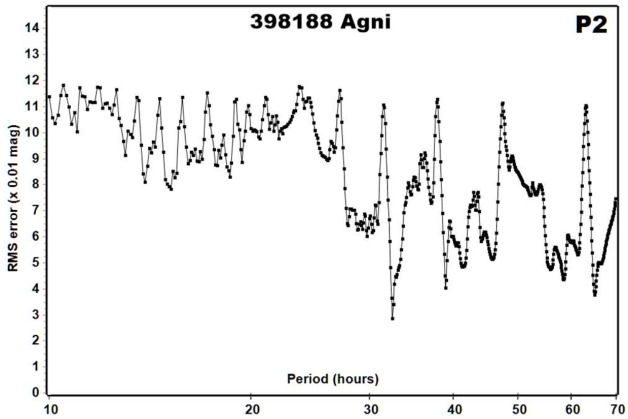
The most dominant period was 22.115 h, in agreement with our previous result. A seemingly good fit at 11.059 h was, essentially, a monomodal lightcurve. The split-halves plot at the doubled period (22.115 h) showed the two halves were identical. However, given the large amplitude, a monomodal solution was considered unlikely (see Harris et al., 2014). More so, the inability of *MPO Canopus* to deal with tumbling asteroids, means both periods are somewhat suspect.

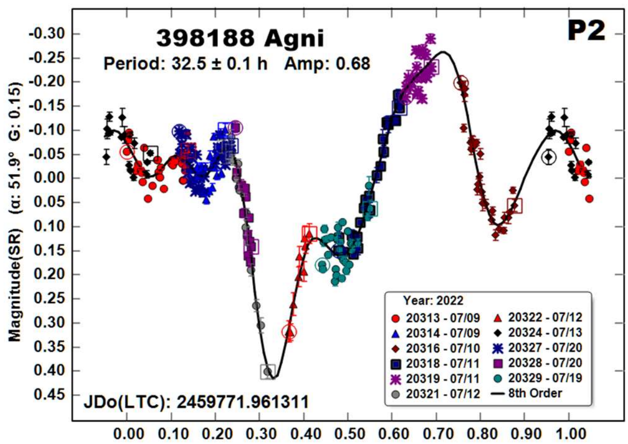
Our search for a secondary period to improve the fit of the primary led to an unusually-shaped bimodal lightcurve with a period of 32.5 h, in good agreement with our result from the 2014 data.



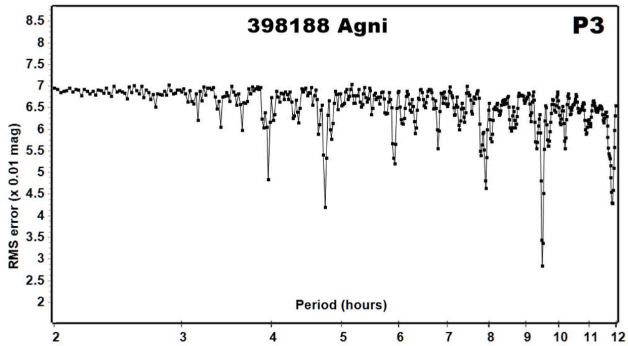


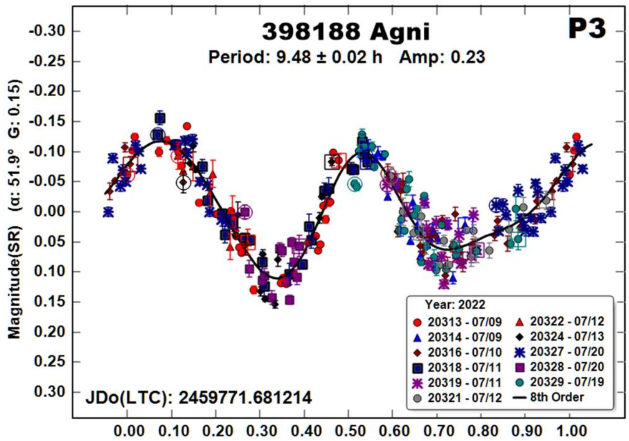






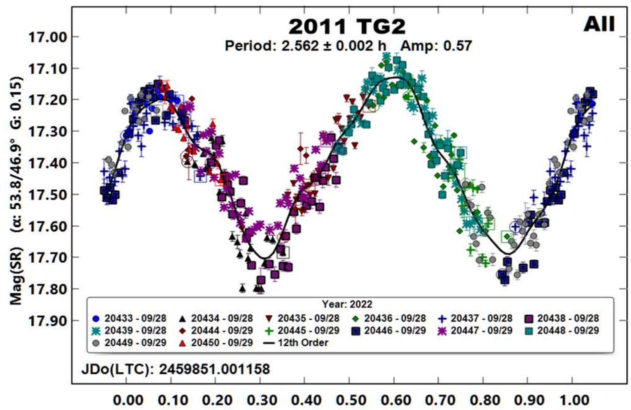
Sometimes, we can find a third period that does not have direct physical origin, i.e., is likely an analysis "artifact," but greatly improves the fit of the two main periods. This was the case with our 2022 data set.

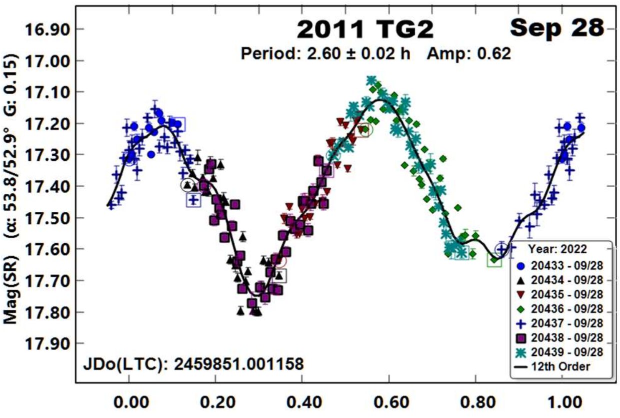


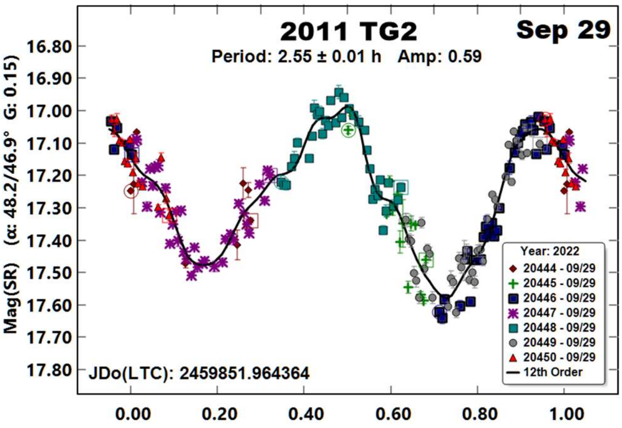


The fit for the third lightcurve to a period of 9.48 h is remarkably "clean" and, on its own, would be a typical for a "normal" asteroid. The lightcurves for P_1 and P_2 are the result of subtracting one from the other *and* this third period. Without the third period, the two other lightcurves have much poorer fits to their adopted periods.

2011 TG2. The estimated size of 2011 TG2 is about 250 m. There were no entries in the LCDB for the asteroid, but the current version of the LCDB is about a year old as of this writing. We observed on 2022 September 28 and 29. Combining the data from the two nights leads to a period of 2.562 h, but the fit of the data is not very good.

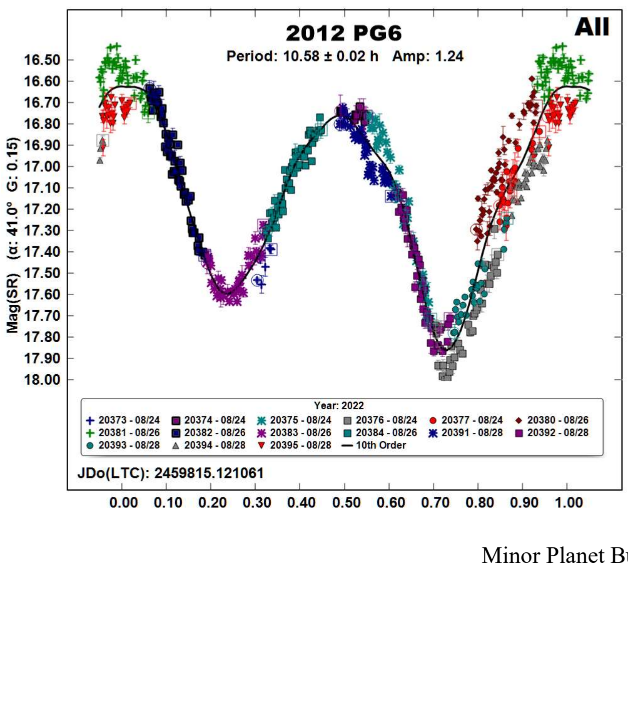


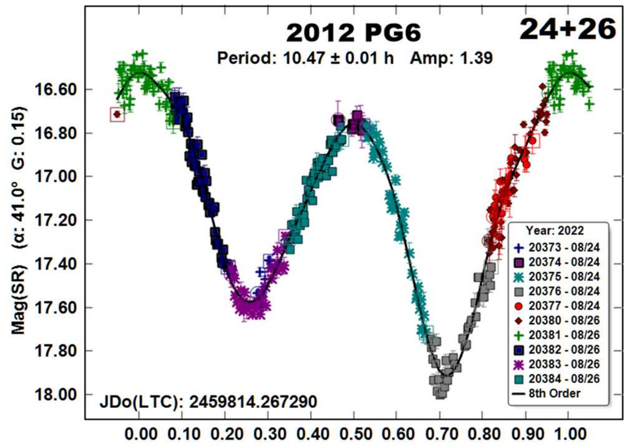


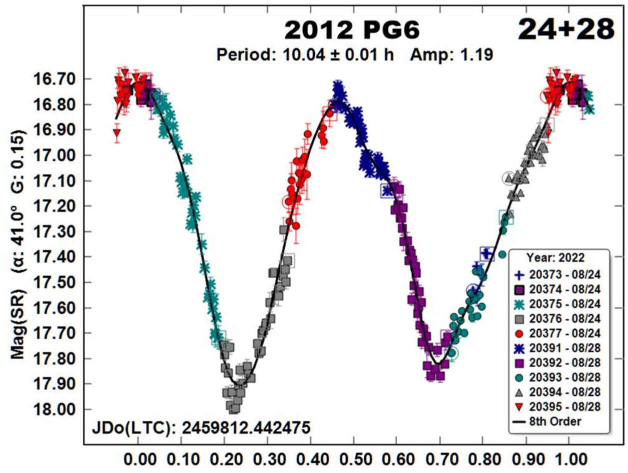


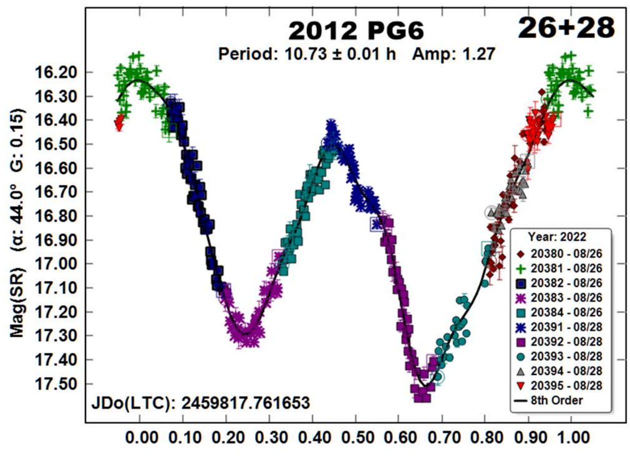
Since the phase angle was significantly different on the two nights, we suspected that the poor fit was due to the changing viewing aspect and not tumbling. This seemed confirmed after finding an independent solution for each night and comparing the lightcurve shapes and amplitude.

2012 PG6. We observed this asteroid on three nights, 2022 August 24, 26, and 28. As seen in the lightcurves, the combined data set has a good fit until the second half. This is due to the evolution of the lightcurve over four nights of observations. Three combinations of two nights of observing runs produced tight fits to the derived period for that combination. The resulting lightcurves show how the shape and, more so, the amplitude evolved.









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