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

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The analysis of observations made at the Center for Solar System Studies from 2020 September to 2021 January led to the discovery that the Vestoid asteroid 3865 Lindbloom is a fully synchronous binary. The orbital period is 26.016 h and the ratio of the effective diameters is 0.65 ≤ Ds/Dp ≤ 1.0. Assuming a bulk density of 2 g/cm, *Dp* ≤ 7.2 km, *Ds* ≥ 4.6 km, and the center-to-center separation is 20 km. Other objects presented here were found to have secondary periods: 4503 Cleobulus, (22056) 2000 AU31, 25465 Rajagopalan, (46818) 1998 MZ24, (48205) 2012 TQ78, 2013 PY6, and 2020 PD1. Of those, only 1998 MZ24 and 2013 PY6 might be said to show mutual events due to a satellite.

CCD photometric observations at the Center for Solar System Studies in 2020 September to early 2021 January led to discovery at least one confirmed binary asteroid, 3865 Lindbloom. Several other asteroids that were observed could not be adequately defined with a single period solution. Two of those additional objects, (46818) 1998 MZ24 and 2013 PY6, came closest to showing the requisite mutual events (occultations/eclipses) due to a satellite.

Table I lists the telescopes and CCD cameras that were combined to make the observations. 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*/6.3 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	

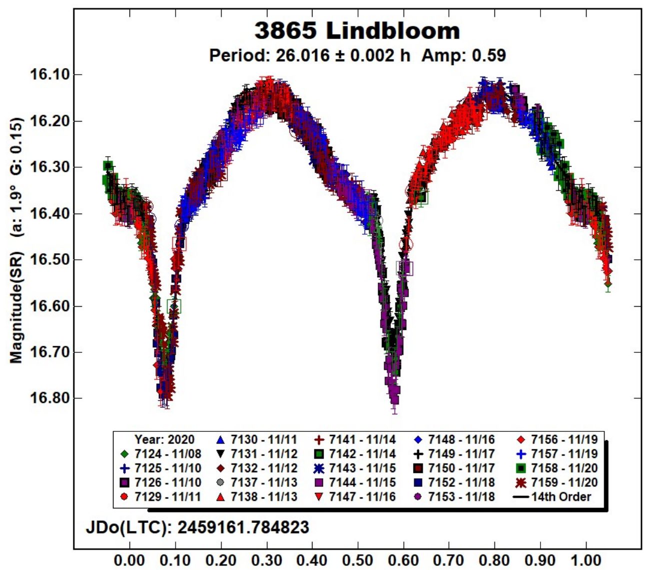
Table I. List of available telescopes and CCD cameras at CS3. The exact combination for each telescope/camera pair can vary due to maintenance or specific needs.

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 adjusted nightly zero points and their amounts, we use the ATLAS catalog r´ (SR) magnitudes (Tonry et al., 2018). This makes most zero-point adjustments ≤ ±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 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, had all the observations 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*.

<u>3865 Lindbloom</u>. There was only one previously reported rotation period found in the LCDB for this 8-km Vestoid: Pravec et al. (2018web), who found P = 5.42 h, A = 0.03 mag. Our extensive data set, obtained 2020 Nov 8-20, led to a much different solution.



The final lightcurve has a period of 26.016 h and clearly shows the *shoulders* (sudden changes in slope in the descending/ascending sections) associated with a fully synchronous binary with the two bodies separated by a small distance.

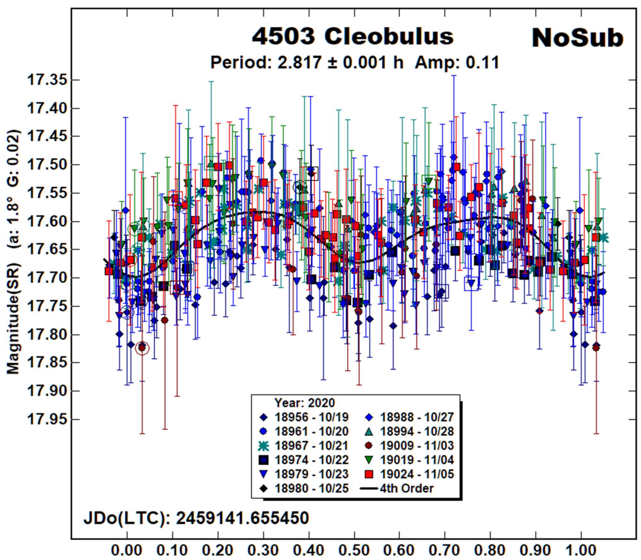
The depth of the lightcurve outside the mutual events is 0.27 mag. If both bodies have the same elongation, and assuming a smoothed ellipsoid, this would imply an *a/b* ratio of 1.27:1. The mutual events themselves are 0.38 mag and, since they present sharp minimums, the events are not total. From this, the estimated effective diameter ratio is 0.65 ≤ Ds/Dp ≤ 1.0.

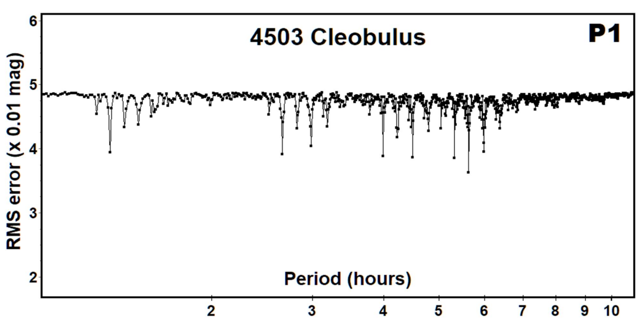
Mainzer et al. (2016) give an effective diameter 8 km for the system. Assuming a bulk density of 2 g/cc for both bodies sets $D_1 \leq 7.2$ km, $D_2 \geq 4.6$ km, and the center-to-center separation of 20 km. These numbers are consistent with the narrow events that are <0.1 rotation phase wide.

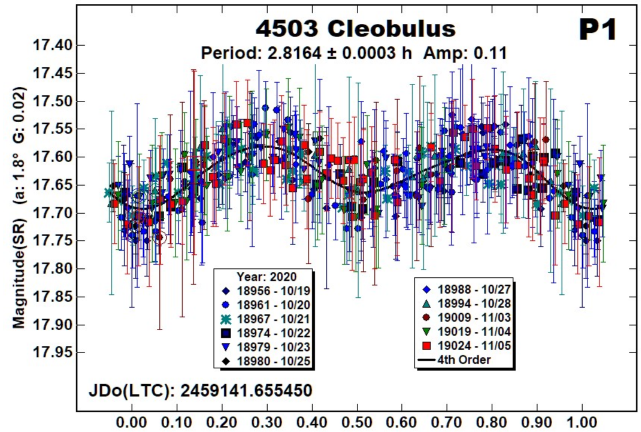
4503 Cleobulus. This NEA has an estimated effective diameter of 1.9 km (LCDB; Warner et al., 2009). The LCDB lists only one previous rotation period, that being 3.13 h from Wisniewski et al. (1997).

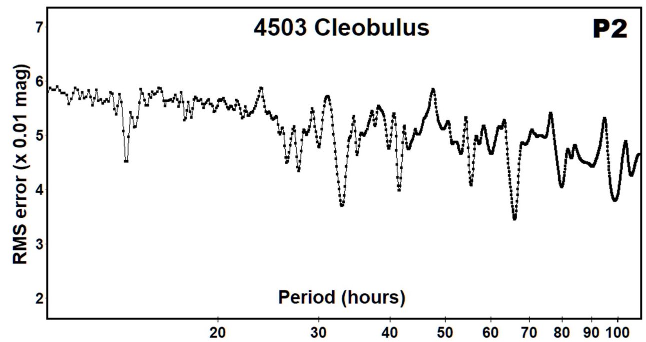
The data set appeared to be excessively noisy, even though the errors for individual data points were on the order of 0.2-0.3 mag. We've found that the excessive noise can be due to the presence of a second period and so we tried a dual-period search using *MPO Canopus*. The P_1 period spectrum shows that several solutions stood out, some in addition to our adopted period of about 2.82 h, which we used as the basis in the search for the second period.

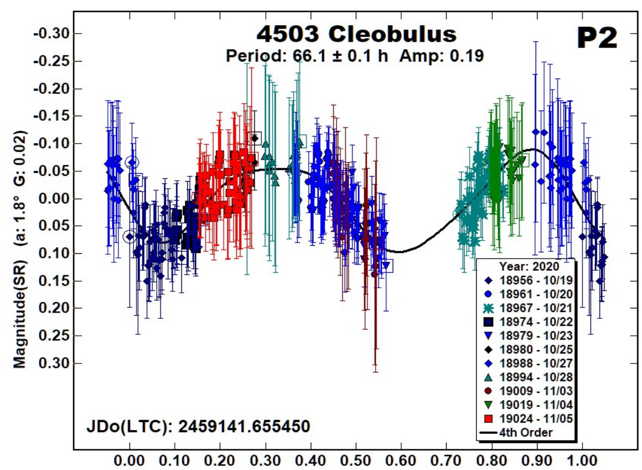
The P_2 period spectrum showed potential solutions near 35 h and 65 h. After several iterations of finding one period, subtracting it to find a second period, and subtracting that to find a revised first period, our final result was P_1 = 2.8164 h and P_2 = 66.1 h. The P_2 lightcurve does not show evidence of mutual events (occultations/eclipses), which are required to elevate the asteroid to a confirmed binary. It is also sufficiently asymmetrical to raise at least some doubt about the validity of the solution. However, as seen in the P_1 lightcurve, subtracting P_2 removes a large portion of the noise from a single period lightcurve.







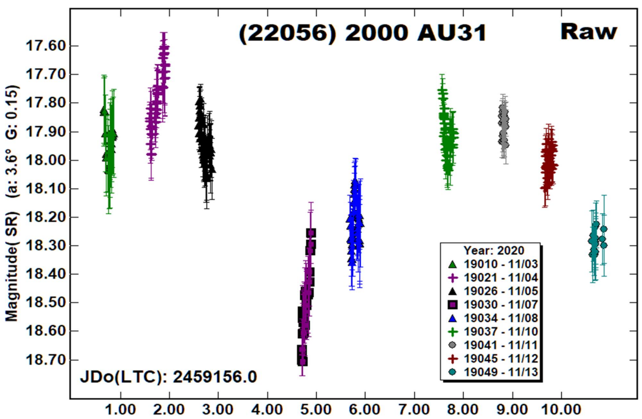


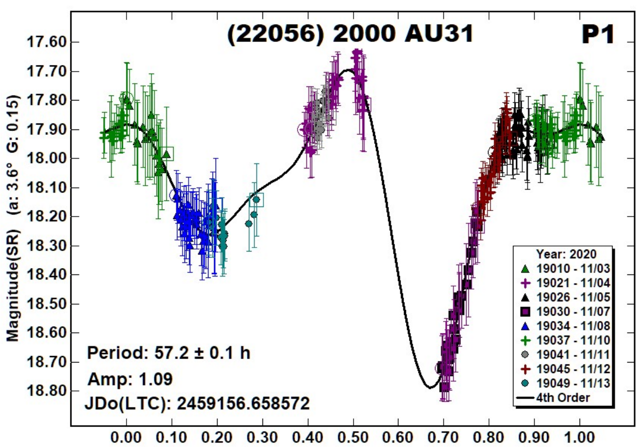


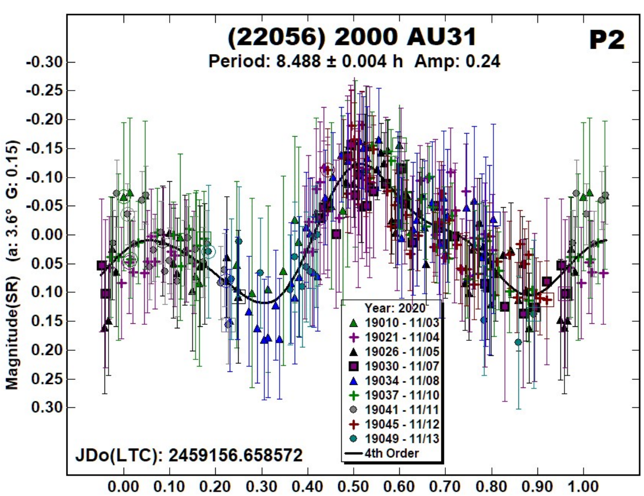
Unfortunately, the NEA remains well below V ~ 18.5 for some time. The next best chance for follow-up observations is not until 2029 November when it will be about 1.5 mag brighter (15.7) at +21° declination.

(22056) 2000 AU31. This is a Jupiter trojan with an estimated diameter of 25 km (Mainzer et al., 2016). Ryan et al. (2017) and Szabó et al. (2017) observed the asteroid in 2015 August, finding periods of 356 h and 358 h, respectively. Our data set, even though sparse in coverage, led to a significantly different result.

The “Raw” plot shows the data set as magnitude versus JD, with the magnitudes being normalized to the Nov 3 observations using $G = 0.15$. Taken at face value, it implies a period on the order of about 12 days, or 288 hours. However, it can happen that the 24-hour sampling interval is actually catching slightly different portions of a lightcurve with a much shorter period. Keeping this mind, a period search beyond 400 h found a more likely solution to be under 100 hours.







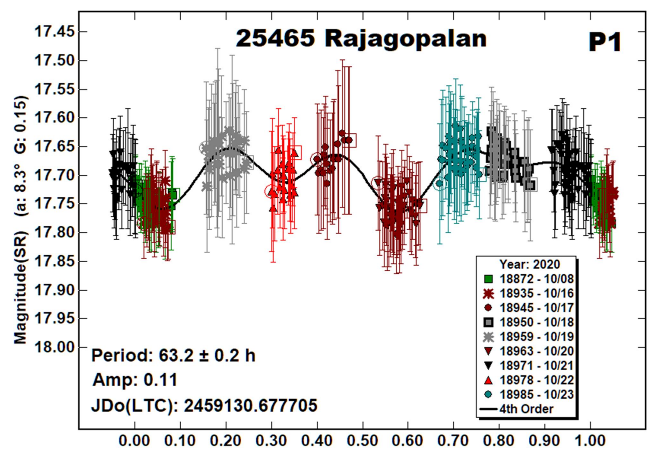
The eventual P_1 lightcurve, found using the dual-period search feature of MPO Canopus, has a highly asymmetrical shape due exclusively to the data from Nov 7. Removing those from the analysis found a similar period and a more symmetrical shape. After reviewing the Nov 7 data, the zero-point adjustment required to bring them “into line” with the rest of the data was deemed too excessive and with no apparent systematic cause. Its physical cause is a matter of speculation.

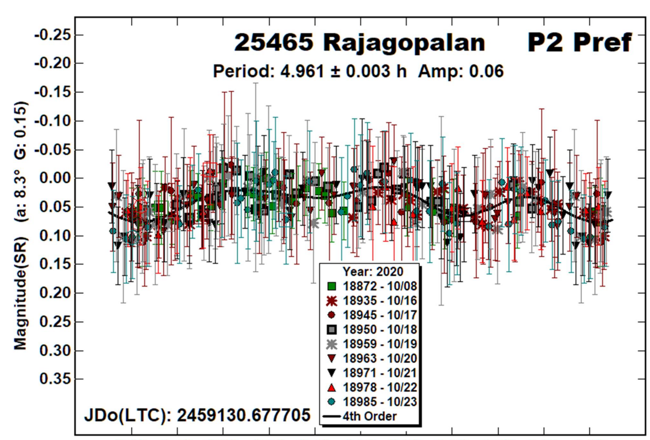
Removing the P_1 result from the data found two very strong solutions of about 8.5 h and 17 h. We have adopted $P_2 = 8.488$ h, which produces a symmetrical lightcurve along the X-axis. One *suggested* model of the system is a wide binary with an elongated secondary and an orbital inclination that may allow seeing mutual events. This, of course, requires validation with higher quality data.

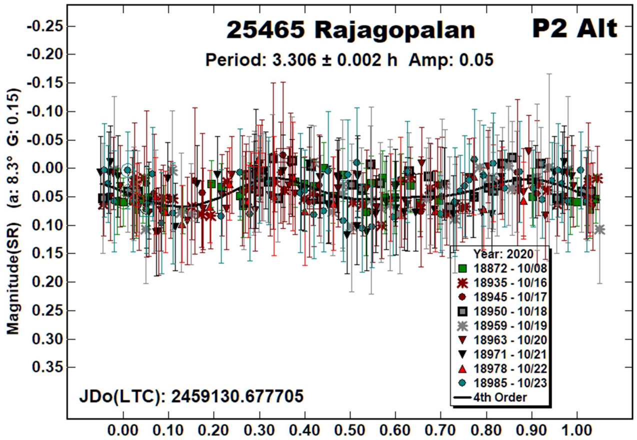
25465 Rajagopalan, a member of the Flora family/group, had no previous entries of any kind in the LCDB. The estimated diameter is 2.3 km. The data set was noisy but, here again, a single-period solution did not provide an acceptable fit, or at least could be considerably improved by removing a secondary period.

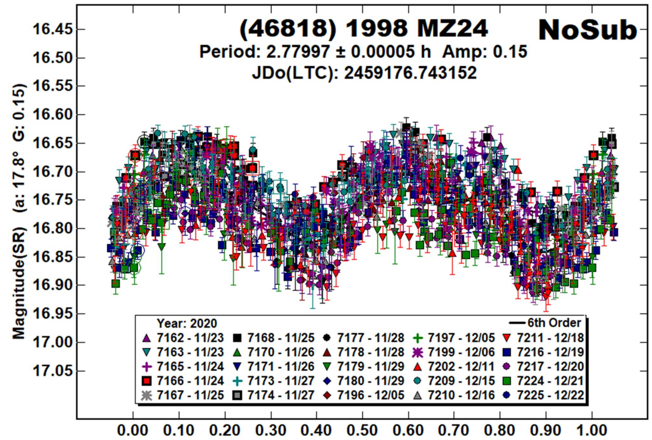
The initial period search found $P \sim 65$ h that was further refined to 63.2 h. The lightcurve has some hints of mutual events near 0.05 and 0.55 rotation phase (P_1 plot). The additional attenuation near 0.35 phase is most likely an artifact of the Fourier analysis since it has no counterpart near 0.85 phase. Subtracting P_1 lead to an ambiguous solution for a weak secondary period of either 4.961 h or 3.303 h, the former being the preferred solution even though it results in a trimodal lightcurve.

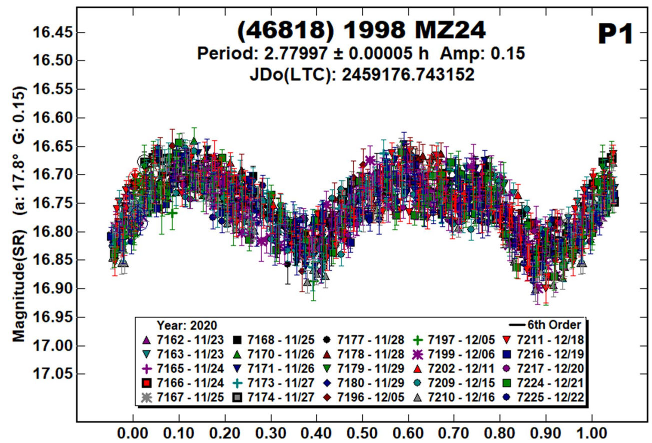
The purported events in P_1 are about 0.07 mag deep, leading to $Ds/Dp \geq 0.25 \pm 0.04$. Given the quality of the limited data set, the results presented here should be considered to be no more than an alert to future observers of the possibility, admittedly a small one, that the asteroid is binary.







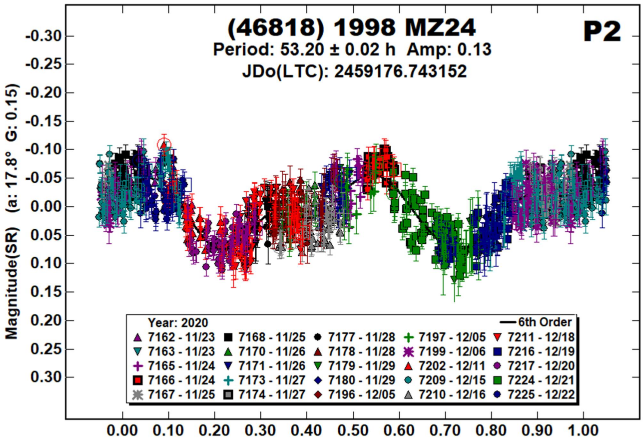




<u>(46818) 1998 MZ24</u>. Warner (2010) observed this 4-km Mars-crosser in 2009 August and fond a period of 2.779 h. There were no indications of a satellite at that time. Stephens (2017) observed it in 2016, finding a rotation period of 2.78 h and, again, no signs of a satellite. Our observations in 2020 were close to being diametrically opposed in ecliptic longitude from the 2016 observations, 90° versus 293°. On the other hand, the ecliptic latitude of the phase angle bisector differed by about 20°. This, along with a longer observing campaign, may be why signs of a satellite were found in 2020.

Number	Name	2020 mm/dd	Phase	L_{PAB}	B_{PAB}	Period(h)	P.E.	Amp	A.E.	Grp/Dr
3865	Lindbloom	11/08-11/20	1.9,7.4	42	-1	[FS]26.016	0.002	0.64	0.02	V
										0.65-1.0
4503	Cleobulus	10/19-11/05	*1.8,9.5	29	-1	2.8164	0.0003	0.11	0.03	NEA
						66.1	0.1	0.19	0.03	
22056	2000 AU31	11/03-11/13	3.6,6.0	27	-1	57.2	0.1	1.09	0.06	TR-J
						8.488	0.004	0.24	0.04	
25465	Rajagopalan	10/08-10/22	8.3,15.0	4	-6	63.2	0.1	0.11	0.02	FLOR
						[A1]4.961	0.003	0.06	0.02	
						[A2]3.306	0.002	0.05	0.02	
46818	1998 MZ24	11/23-12/22	*17.8,3.3	90	-3	2.77997	0.00005	0.15	0.01	MC
						53.20	0.02	0.13	0.02	
482505	2012 TQ78	11/23-12/02	*28.2,38.0	105	13	11.418	0.005	0.25	0.03	NEA
						12.35	0.03	0.09	0.03	
	2013 PY6	09/20-10/13	14.0,2.7	15	1	3.9210	0.0004	0.05	0.01	NEA
						19.130	0.004	0.11	0.02	
	2020 PD1	10/08-10/18	*7.1,9.7	20	-5	2.8367	0.0004	0.15	0.02	NEA
						37.8	0.1	0.13	0.02	

Table II. Observing circumstances. [FS]Period is orbital and rotation for each body. [A1,2]Preferred and alternate period of an ambiguous solution. The first line gives the primary period for the system. The second line gives the secondary period. The phase angle (α) is given at the start and end of each date range. An asterisk indicates that 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). For the Grp/Dr column, the first line gives the group/family based on Warner et al. (2009). FLOR Flora; MC Mars-crosser; NEA: Near-Earth asteroid; TR-J Jupiter trojan; V

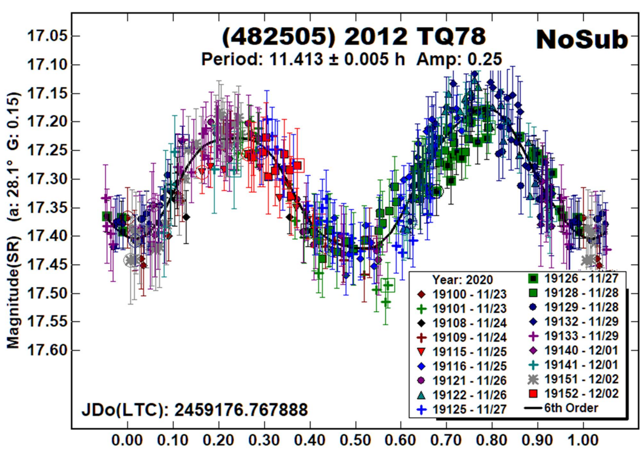


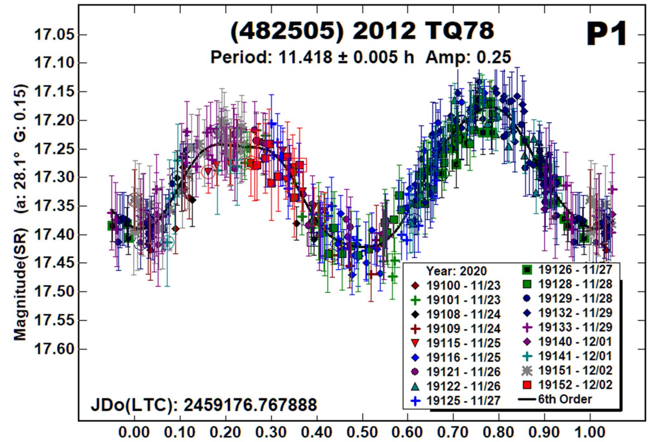
The single-period lightcurve (P1) scatter is considerably in excess of the individual errors of the observations, which prompted a dual period search using *MPO Canopus*. After several iterations, we found P_1 = 2.77997 h and P_2 = 53.2 h.

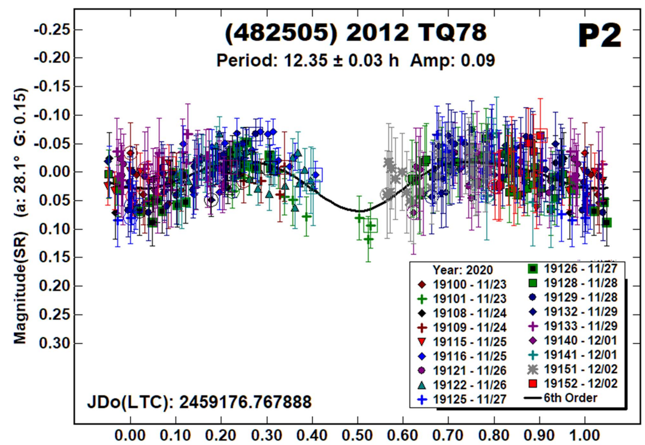
A “simple” lightcurve showing mutual events is mostly flat save the events themselves. In this case, the continually changing amplitude implies an elongated secondary that is likely tidally-locked to the orbital period, i.e., its rotation and orbital periods are the same.

For southern observers, the next opportunity for confirmation comes in 2023 June with V = 16.3 and –20° declination. Northern observers need to wait until 2027 November when the asteroid reaches V = 15.6 at +37° declination.

<u>(482505) 2012 TQ78</u>. There were no previously reported rotation periods in the LCDB for 2012 TQ78, which has an estimated diameter of 370 m. The signs of a secondary period in the NoSub plot are weak but were sufficient to try searching for a better fit than one to a single-period solution. We eventually adopted P_2 = 12.35 h with a significant amplitude of 0.09 mag. This is somewhat surprising since subtracting the second period produces very little change in the fit of the P_1 lightcurve and its period.



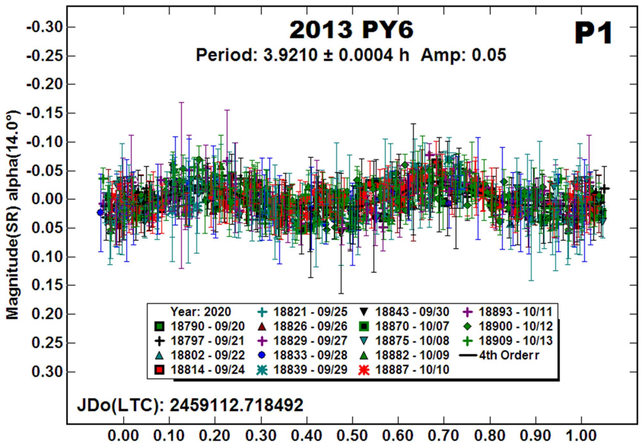


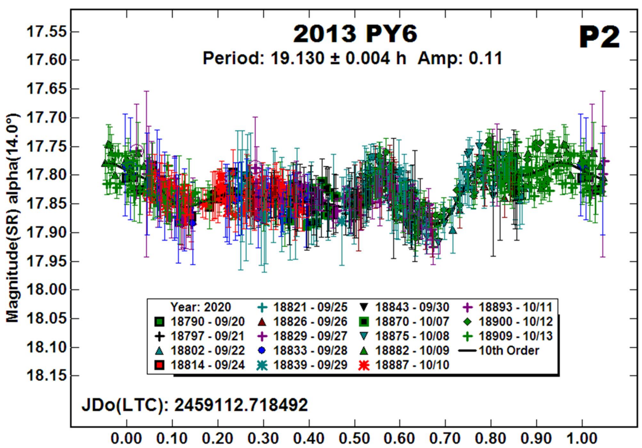


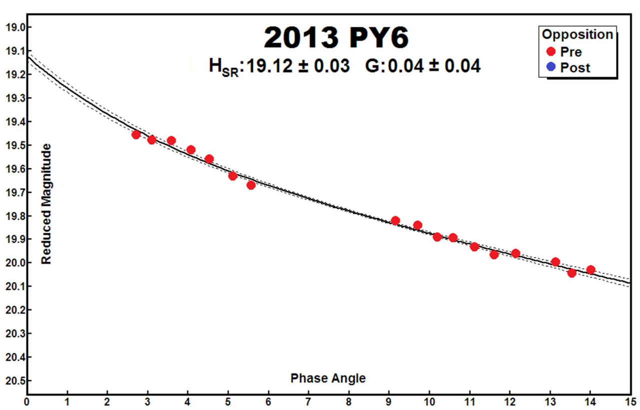
It’s possible that P_2 is some sort of systematic artifact of the data set and the 24-hour sampling intervals. Assuming it’s not, the two periods don’t fit the usual models for a binary asteroid. In that case, the possibility falls to the two being the periods of rotation and precession of a tumbling asteroid, or their frequencies (1/*P*) being integral multiples of the true periods. The rule of thumb for damping time given in Pravec et al. (2014) is about 2.5 Ga, so tumbling is not unexpected.

<u>2013 PY6</u>. There were no previous entries of any kind the LCDB for this 400-m NEA. The initial data showed indications of a second period, became more certain as additional data were obtained. Our final analysis found P_1 = 3.9210 h, A_1 = 0.05 mag for the primary of the assumed binary asteroid. The lightcurve for the secondary period, P_2 = 19.130 h, shows signs of mutual events at about 0.15 and 0.65 rotation phase. Using the shallower event, we derived an effective diameter ratio of Ds/Dp ≥ 0.19 ± 0.02.

The data set covered a sufficient range of phase angles to find preliminary values of H_{SR} = 19.12 ± 0.03 and G = 0.04 ± 0.04. Based on Warner et al. (2009), the value for G implies a low albedo object, which is not entirely uncommon with the NEA population.







To transform from H_{SR} to H requires using known values of

$$(SG\text{-}SR)_{Sun} = 0.44 \text{ (Rodgers et al., 2006)}$$

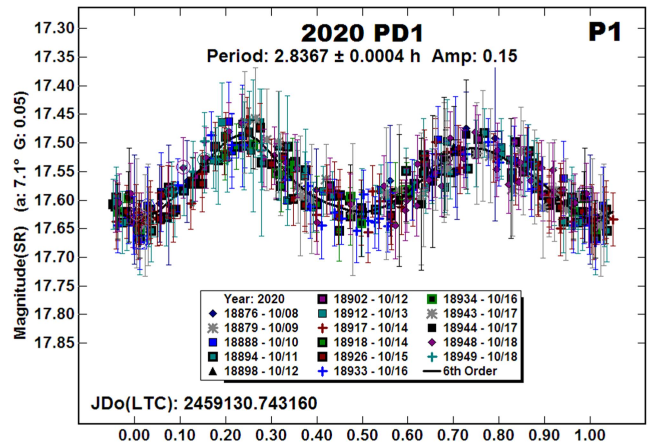
$$V = SR + 0.44(SG\text{-}SR) \text{ (Fukugita et al., 1996)}$$

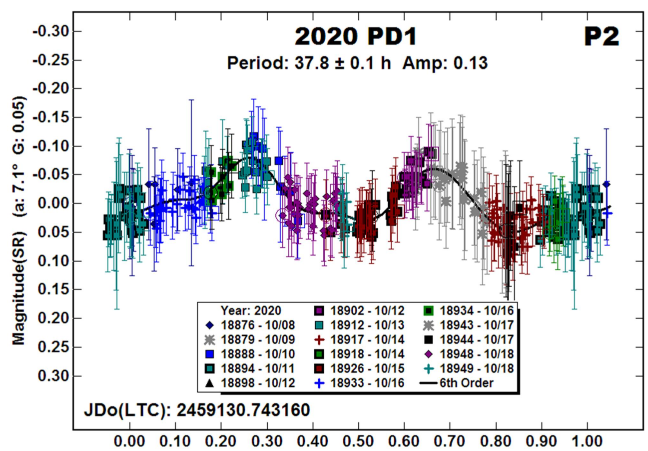
and assuming that $(SG\text{-}SR)_{Asteroid} = (SG\text{-}SR)_{Sun}$ because its presumed low albedo is consistent with type D asteroid (Warner et al., 2009) and a type D asteroid is similar in color to the Sun (Dandy et al., 2003). Substituting values

$$V = 19.12 + 0.44(0.44) = 19.31$$

The MPCOrb file (MPC, 2021) gives H = 19.3. We caution that deriving a result from several "ifs" (assumptions) makes the result less than fully-reliable. Furthermore, it should be not be used as the foundation for another series of assumptions.

2020 PD1. The single-period solution for this 400-m NEA showed the typical signs of a secondary period. Using the dual-period search feature of *MPO Canopus*, we found P_1 = 2.8367 h and P_2 = 37.8 h.





The P_2 lightcurve doesn't show signs of mutual events but it is consistent with a slightly-elongated satellite that is tidally locked to its orbit. Confirmation will be a long-time coming. The brightest the asteroid gets through 2050 is V ~ 20.3 in 2029 Nov. Otherwise, it ranges from about 21.5 to 25.0.

Acknowledgements

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