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

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(Received: 2021 October 12)

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
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.

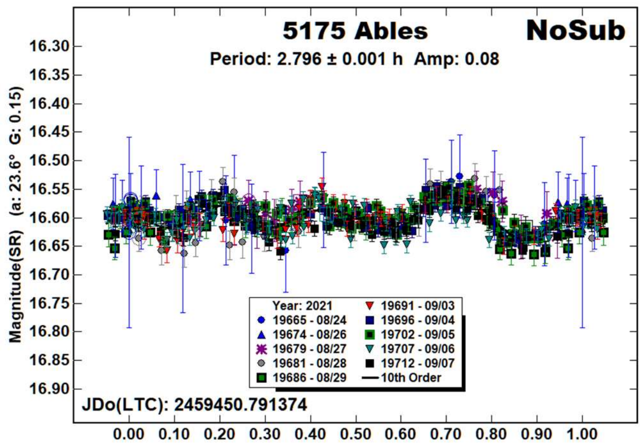
All lightcurve observations were unfiltered since a clear filter can cause a 0.1-0.3 mag loss. The exposure duration varied depending on the asteroid’s brightness and sky motion. Guiding on a field star sometimes resulted in a trailed image for the asteroid.

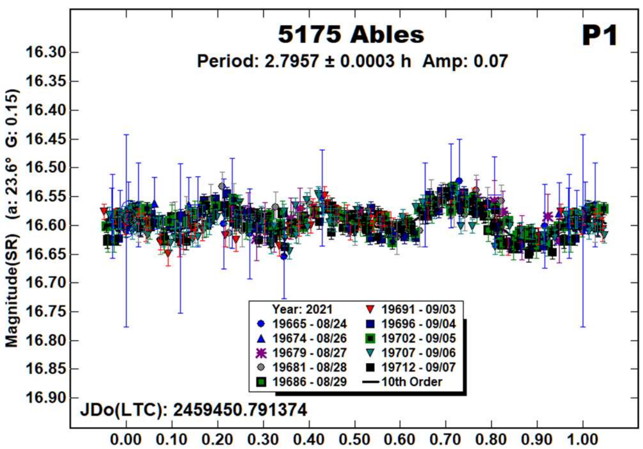
Measurements were made using *MPO Canopus*. The Comp Star Selector utility in *MPO Canopus* found up to five comparison stars of near solar-color for differential photometry. To reduce the number of adjusted nightly zero points and their amounts, the analysis of the 2021 data used the ATLAS catalog r´ (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.

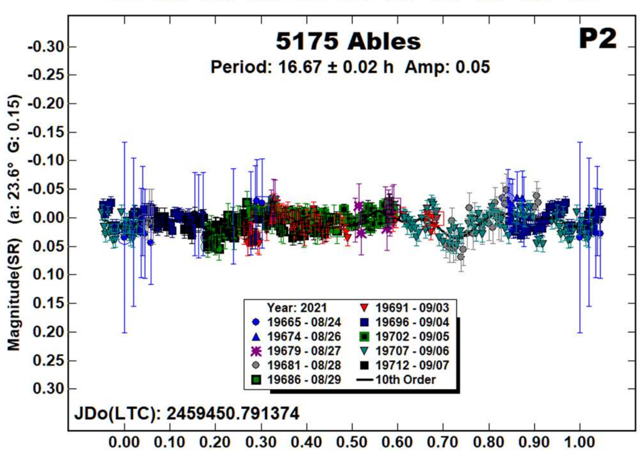
The Y-axis values are ATLAS SR “sky” (catalog) magnitudes. The two values in the parentheses are the phase angle (a) and the value of *G* used to normalize the data to the comparison stars used in the earliest session. This, in effect, corrected all the observations to seem to have been made at a single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

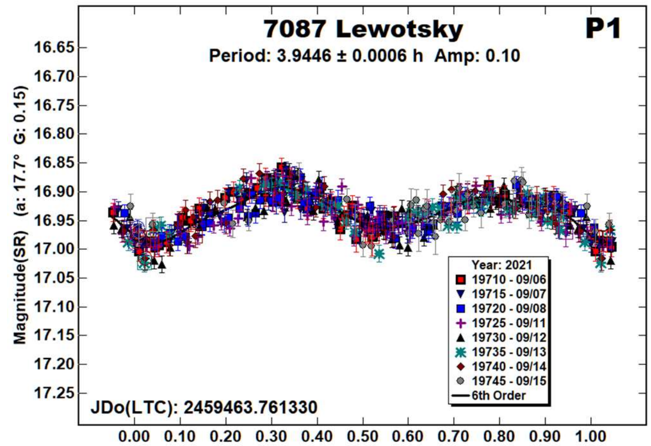
5175 Ables. Warner (2014b) reported this as a suspected binary with a secondary period of 10.4 h but no mutual events to confirm a satellite. That solution was rejected in a follow-up analysis (Warner, 2019). The data from 2021 show some signs of mutual events and period of 16.67 h, but the events are near the noise level. Assuming there is a satellite, the estimated primary-to-satellite diameter ratio is $Ds/Dp \geq 0.16 \pm 0.03$.





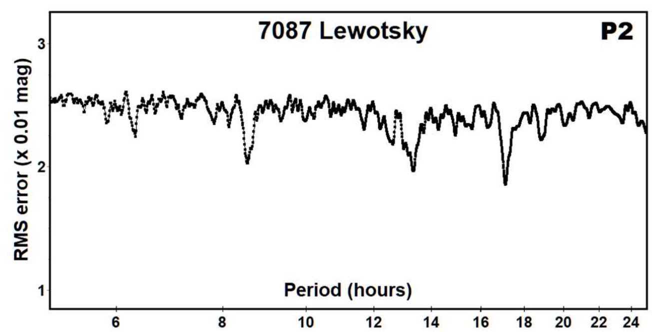


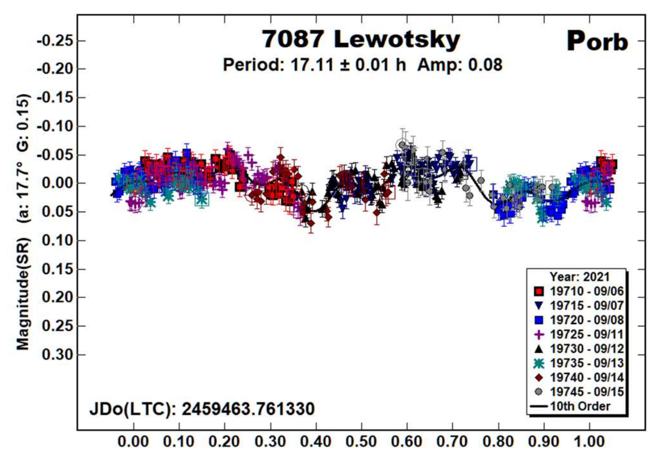
7087 Lewotsky. Being a Hungaria asteroid, which were targets of interest for many years at CS3, we've observed Lewotsky several times in the past (see Warner, 2014a, and references therein), all with final results of $P = 3.941 \pm 0.005$ h, i.e., without indications of a satellite. The 2021 data finally showed what appear to be mutual events but with unusual shapes, not the typical smooth up/down change in the overall lightcurve.



The period spectrum for the secondary period shows the adopted solution to be among a small group of candidates, all being nearly commensurate with an Earth day. Trying to fit the data to those other solutions produced unlikely lightcurves.

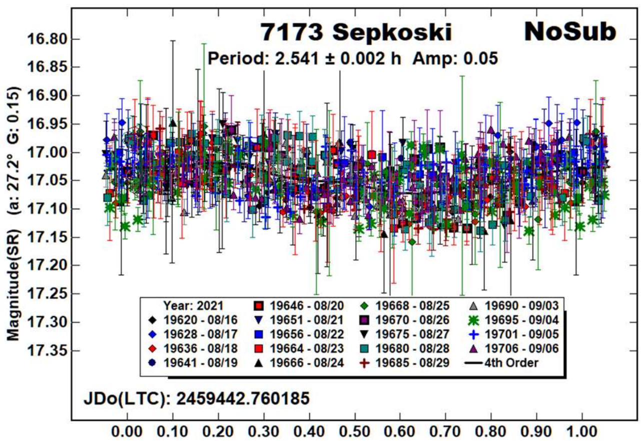
Given the odd-shape of the presumed events, it is difficult to give more than a rough estimate of the diameter ratio *Ds/Dp*. Assuming the shallower event is 0.06 mag deep, this gives Ds/Dp 0.23 ± 0.04.

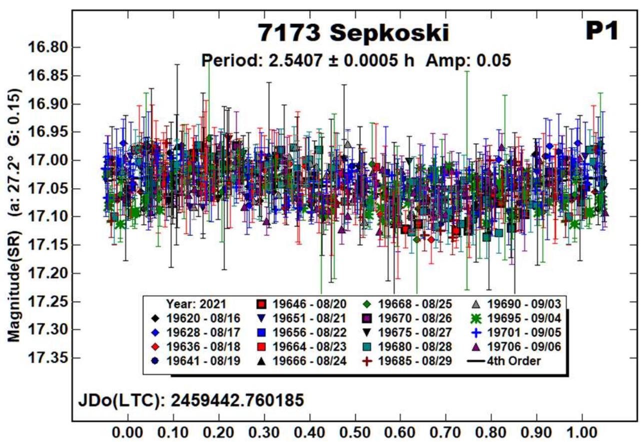


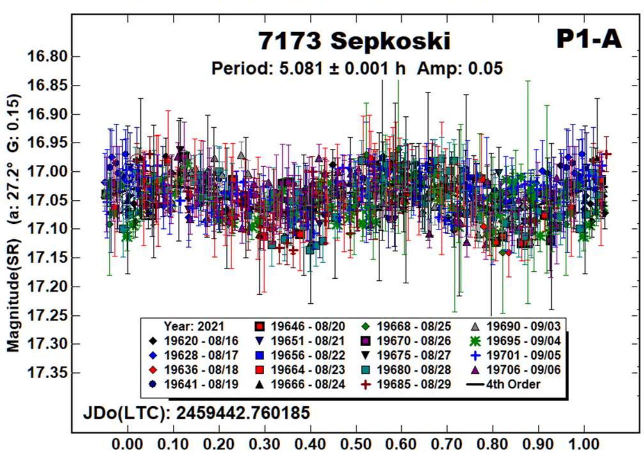


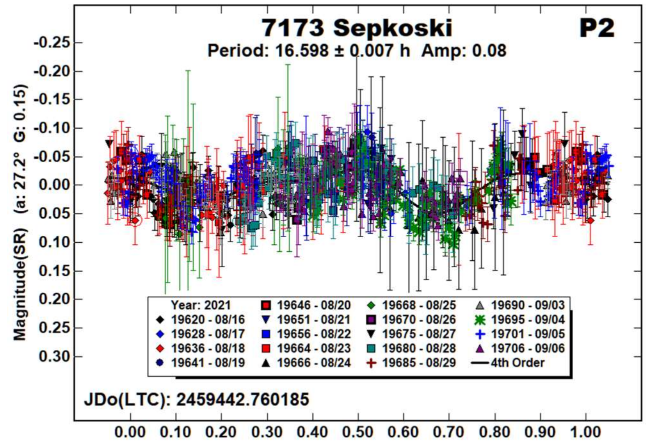
7173 Sepkoski. This asteroid was suspected of being binary using observations from 2013 (Warner, 2014a) but a secondary period could not be established. The 2021 data, hampered by a high noise level, provided a slightly better picture.

The earlier results had a primary period of about 2.5 h. Forcing to near that solution produced a monomodal lightcurve, which is not unexpected (see Harris et al., 2014). The bimodal lightcurve at the doubled-period of 5.081 h is very symmetrical but, because of the noise, cannot be formally excluded. It is worth noting that the 2021 result of 2.5407 h is 0.04 h longer than previous results, the difference being well beyond the reported errors. It may be that including a better secondary period altered the primary solution. The estimated satellite-to-primary diameter ratio is 0.19 ± 0.03.

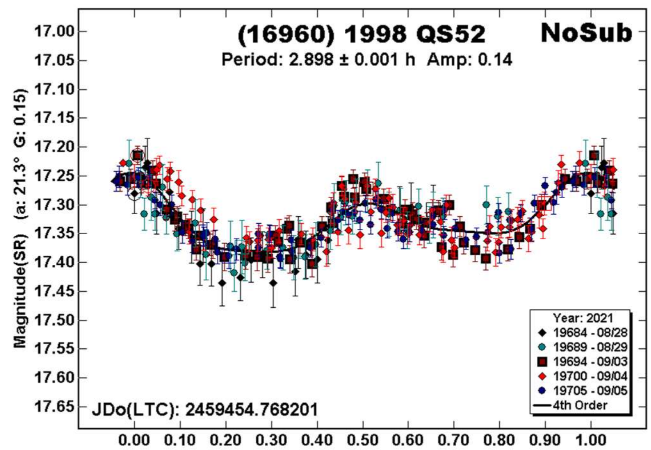




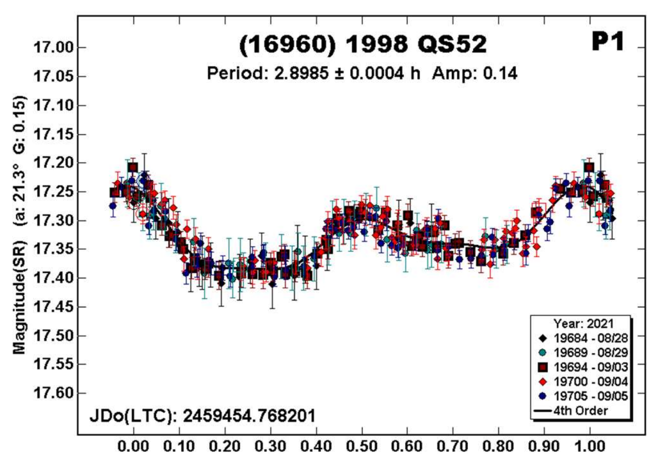


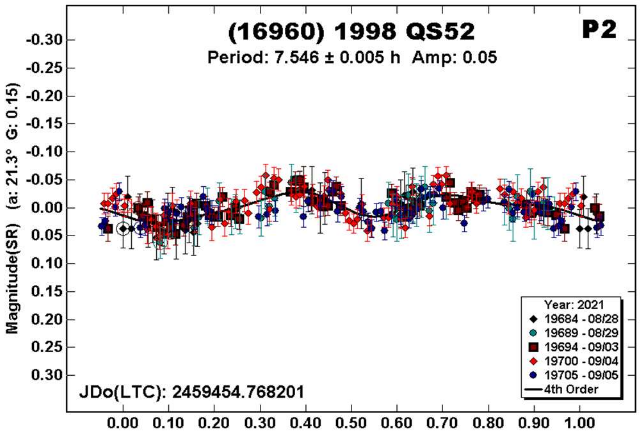


(16960) 1998 QS52. Warner (2009) found a period of 5.789 h for this near-Earth asteroid. Skiff (2019) reported 5.8 h and, more notable, an amplitude of 1.5 ± 0.2 mag. Our data from 2021 showed a lightcurve amplitude that matched the results found by Warner.



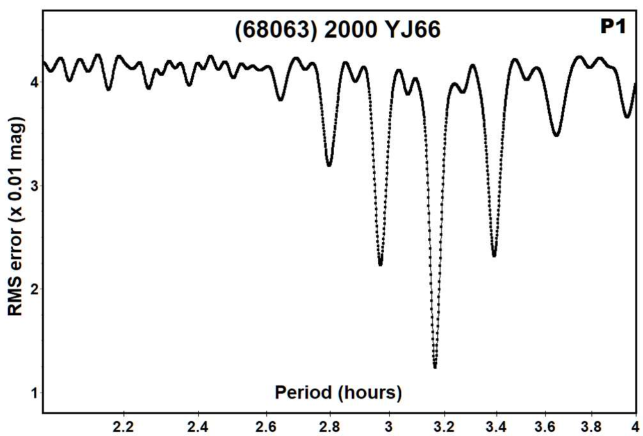
Neither observer reported signs of a satellite in those original results. Our 2021 data indicated a secondary period (NoSub plot) and so we ran a dual-period search in *MPO Canopus*. The end result was a secondary period of 7.548 h. If the true orbital period of a satellite, it would be among the shorter periods found in the LCDB for a typical small binary asteroid. Forcing the data to a more typical solution of the double-period (15.08 h) produced what appeared to be four evenly spaced mutual events. This was rejected.



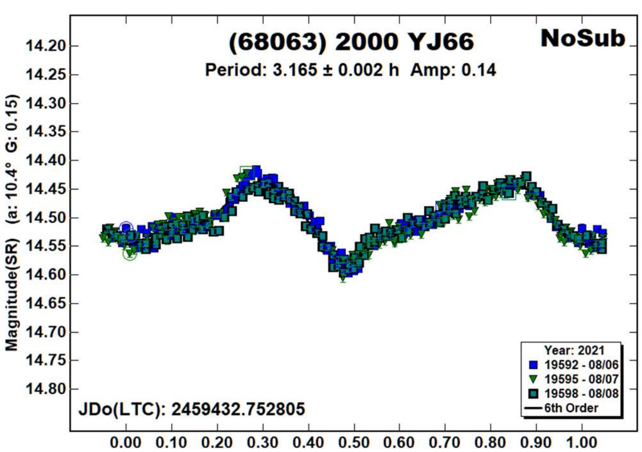


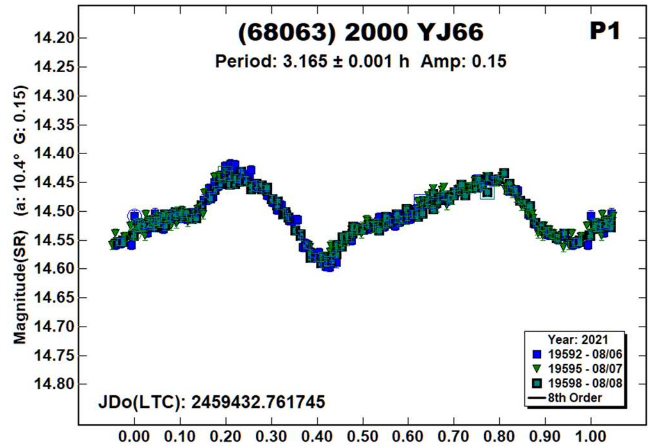
(68063) 2000 YJ66. Warner et al. (2015) reported this to be a binary asteroid with a primary period of 2.11 h and orbital period of 15.69 h. The secondary lightcurve had an overall amplitude of 0.13 mag. Our most recent data gave much different results.

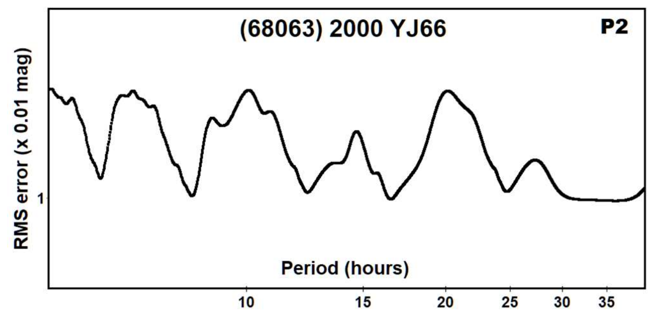
First was that a period of 2.11 h was not possible. The period spectrum shows only the slightest hint of a period near that value and is dominated by one of about 3.15 h.

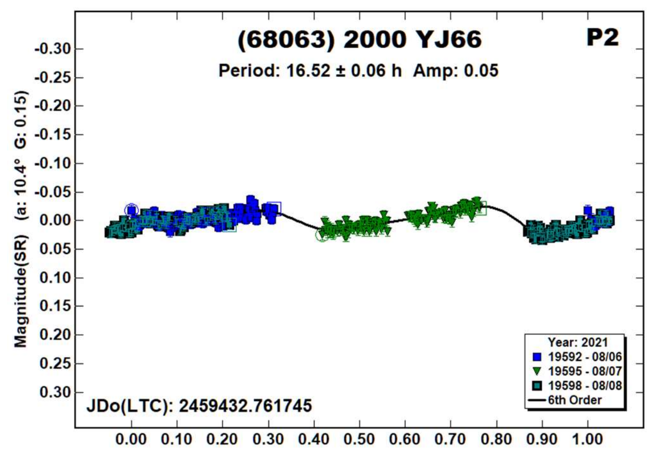


Looking at the single period solution lightcurve (NoSub), there seems little evidence of a secondary period. Since this was reported to be a binary, we ran the dual-period search of *MPO Canopus* to confirm whether or not there might be a second period present. The result is a highly-ambiguous set of solutions, all nearly commensurate with an Earth day. The one closest to that from Warner et al. (2015) was the only bimodal solution.



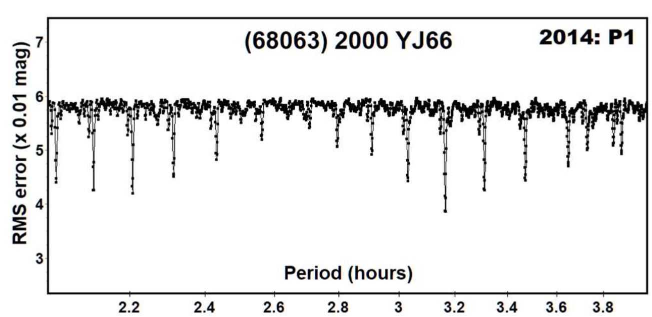




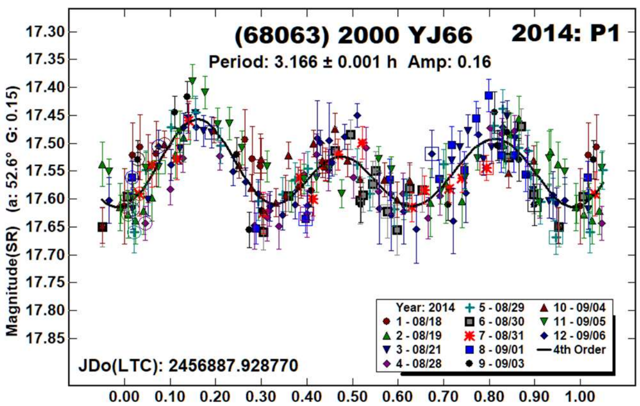


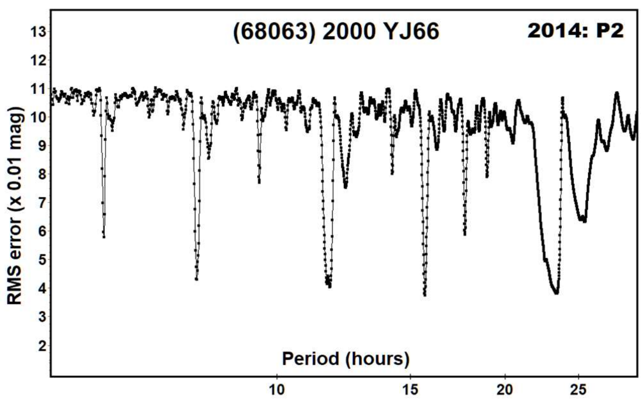
2014 Revisited

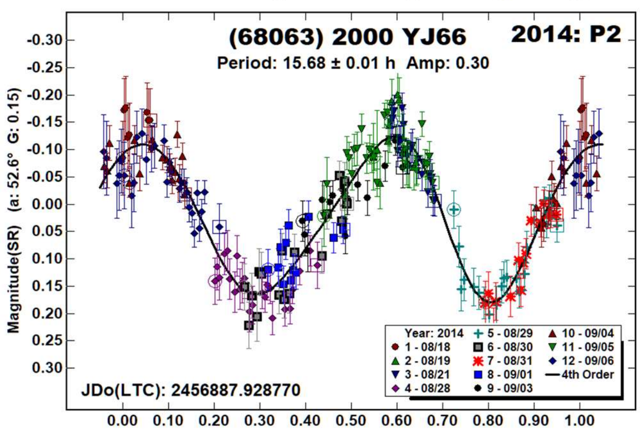
Given the new results, we returned to the data from 2014. Part of the revised analysis was to change the comparison star magnitudes to the SR (Sloan r′) from the ATLAS catalog (Tonry et al, 2018). This removed almost all zero-point adjustments that might have altered the solution.



The period spectrum still shows a solution near 2.11 h being viable but one at 3.166 h a little more likely (the two periods have an almost integral ratio of 3:2). The trimodal lightcurve for the longer period is not unexpected (Harris et al., 2014) given the low amplitude. On the other hand, the large phase angle may have had an effect on the lightcurve shape.

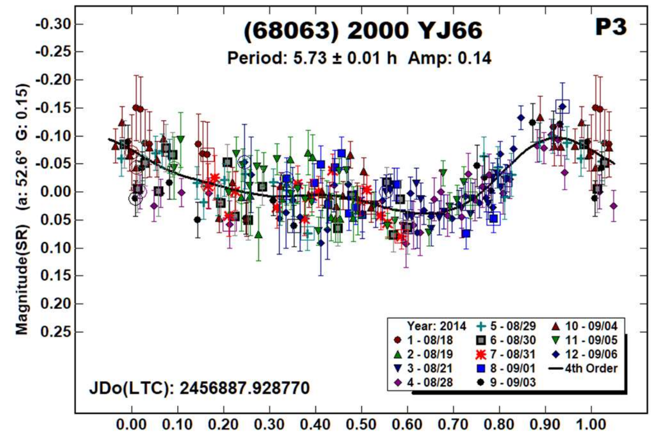






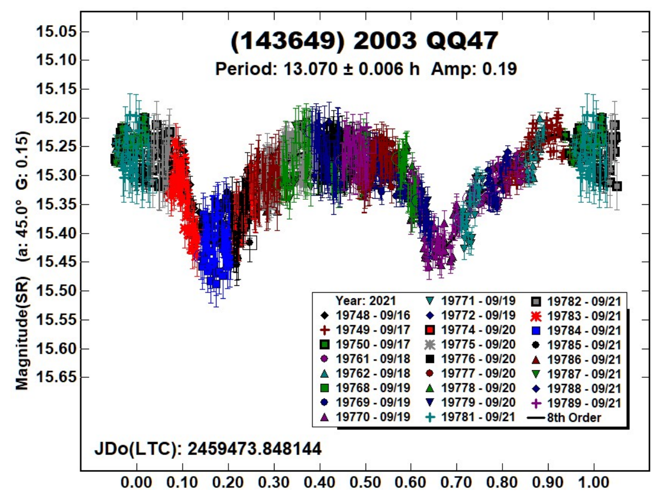
Subtracting the revised primary period from the data found a large amplitude (0.30 mag) secondary period of 15.68 h, which is close to the one derived from the 2021 data. Given the large amplitude of the 2014 solution, we consider it to be the more likely.

There remains no small amount of uncertainty. The P1 and P2 plots from 2014 are not the result of subtracting a single period from the data. Instead, a third period of about 5.7 h with an amplitude of 0.14 mag was found and factored into the analysis.



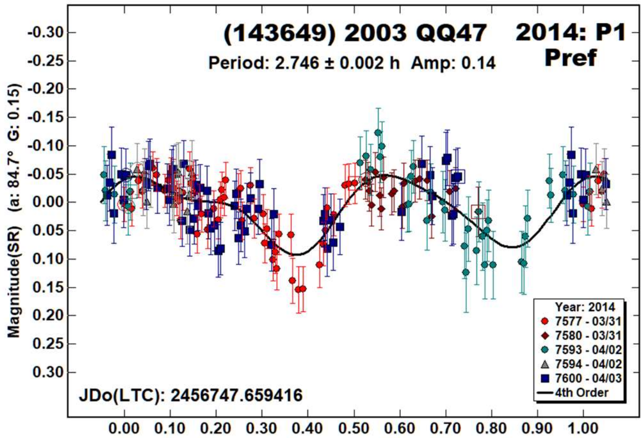
This period is close to being harmonically-related to the others and so may be an artifact of the Fourier analysis. We cannot give a plausible physical cause for the third period.

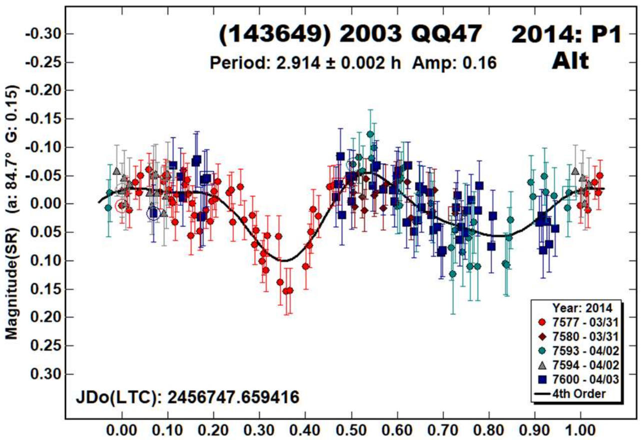
(143649) 2003 QQ47. The results from the data from 2021 thoroughly contradict our earlier findings (Warner, 2014c). The most recent data set produces a lightcurve that has all the signs of a highly-bifurcated body or, possibly, a binary with two similarly-sized bodies in a tight mutual orbit. There is no secondary period in this circumstance.

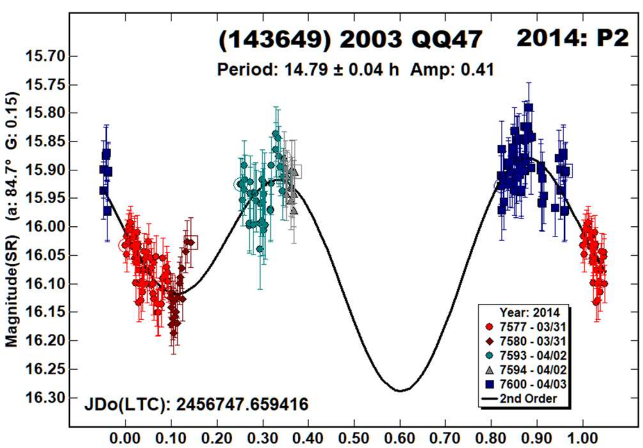


With such a definitive result, we returned to the data set obtained in 2014, which was considerably less dense and didn't cover as long a period. The best solution that could be obtained was a short period superimposed over a longer on. This is reminiscent of the *very wide binary* class (see Warner, 2016) but the 2021 data set dispels that possibility.

The raw data from 2014 clearly (or seemingly so) showed a long period. We could do only a second-order Fourier analysis because of the sparse data set and to avoid Fourier curves with amplitudes of hundreds to thousands of magnitudes. Once settling on a long period of 14.79 h, a search for the short primary period produced ambiguous results. The preference is for P_1 = 2.746 h since it is more symmetrically shaped and is less of a *fit by exclusion*.

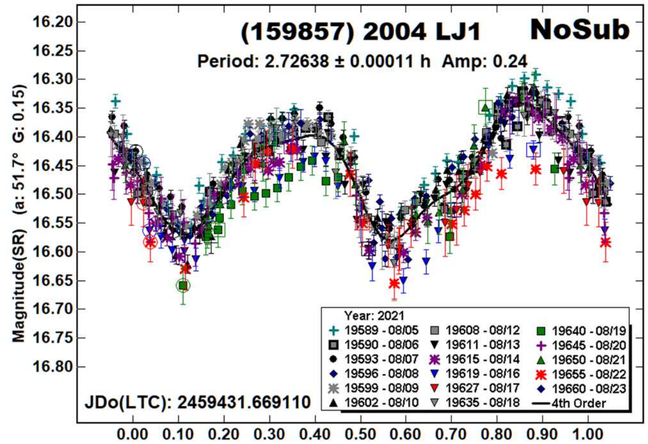


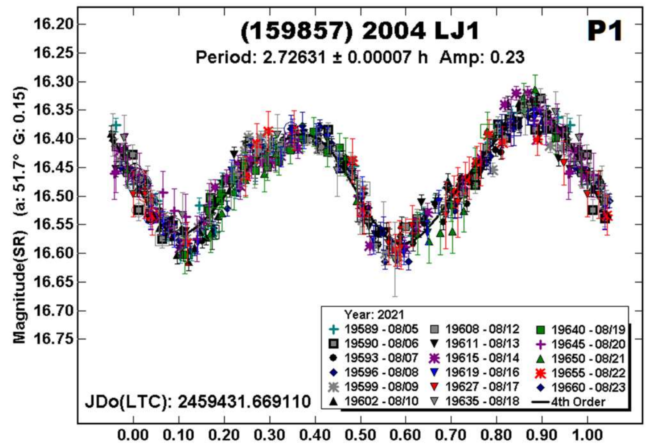


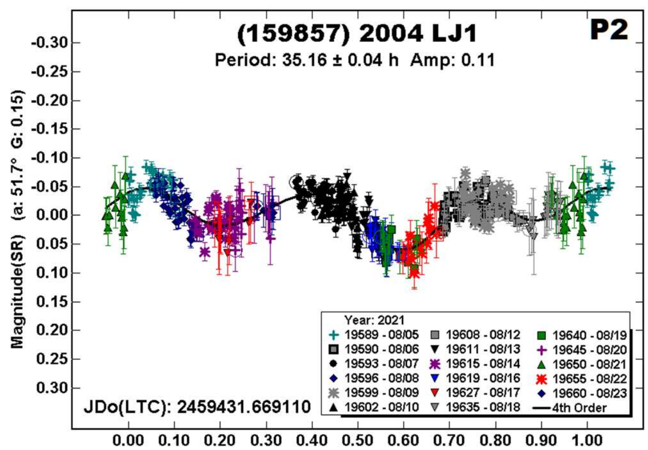


(159857) 2004 LJ1. Previous work on this NEA (Pravec et al., 2004web; Galad et al., 2005; and Warner (2015) produced periods between 2.661 and 2.7247 h. Those previous results did not include signs of the asteroid being a binary. Our 2021 data set seems to indicate otherwise.

The NoSub plot clearly shows deviations from a single period solution that are consistent with a satellite being present. The final dual-period search using *MPO Canopus* found a clean primary lightcurve with a period P_1 = 2.72631 h. The secondary lightcurve ($P2$ = 35.16 h) is not ideal, but still leads to $Ds/Dp \geq 0.22 \pm 0.02$.



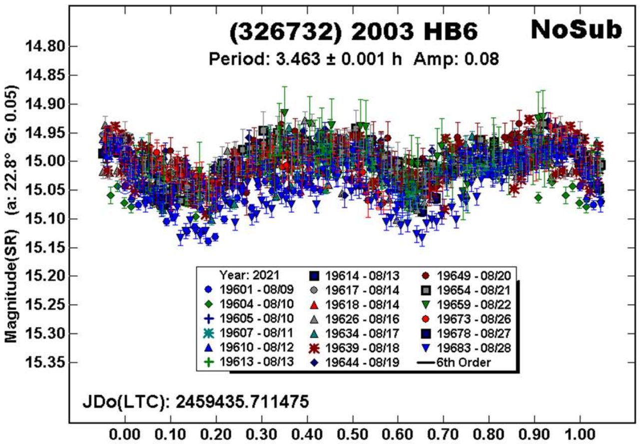


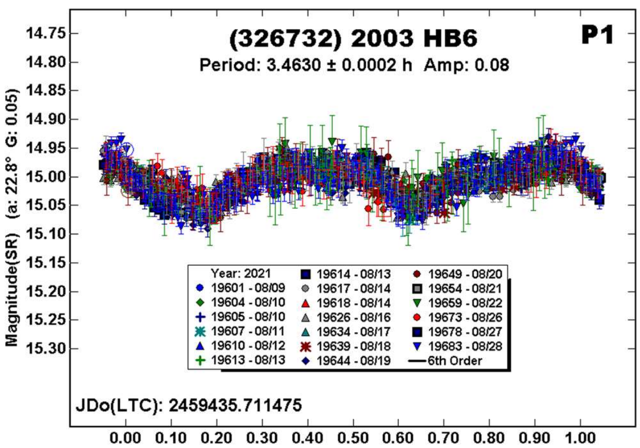


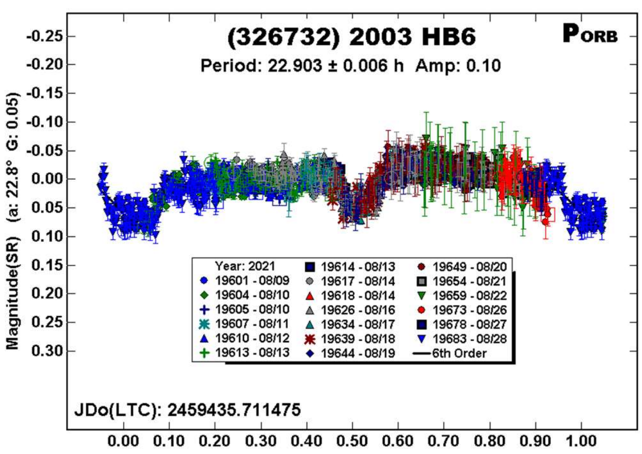
(326732) 2003 HB6. Our result from observations in 2012 (Warner, 2012) was P = 9.436 h. This now seems highly unlikely even though Monteiro et al. (2018b) found a similar period.

The most recent data set, covering nearly 20 days in 2021 August, showed the usual signs of a secondary period. Dual-period analysis in *MPO Canopus* found P_1 = 3.4630 h and P_{ORB} = 22.903 h. Among all the targets in this work, this is the most secure solution.

The mutual events are about the same depth, 0.06 mag, with the one near orbital phase 0.0 coming close to being flat, which would imply a total eclipse/occultation. The estimated diameter ratio is *Ds/Dp* ≥ 0.24 ± 0.02. The secondary lightcurve shows a slight *bowing.* This indicates a modestly elongated satellite with its rotation period tidally-locked to its orbital period.







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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Number	Name	20yy mm/dd	Phase	L_{PAB}	B_{PAB}	Period(h)	P.E.	Amp	A.E.	Grp/Dr
5175	Ables	08/24-09/07	23.6,19.2	10	19	2.7957	0.0003	0.07	0.01	H
						16.67	0.02	0.05	0.01	
7087	Lewotsky	09/06-09/15	17.8,14.5	8	18	3.9446	0.0006	0.10	0.01	H
						17.11	0.01	0.08	0.01	
7173	Sepkoski	08/16-09/06	27.2,22.1	6	26	[P]2.5407	0.0005	0.05	0.01	H
						5.081	0.001	0.05	0.01	
						16.598	0.007	0.08	0.02	
16960	1998 QS52	08/28-09/05	21.4,20.2	5	24	2.8985	0.0004	0.14	0.01	NEA
						7.546	0.005	0.05	0.01	
68063	2000 YJ66	08/06-08/08	10.4,9.4	323	2	3.165	0.002	0.14	0.01	NEA
						16.52	0.06	0.05	0.01	
68063	2000 YJ66	2014 08/18-09/06				3.166	0.001	0.16	0.02	
						15.68	0.01	0.30	0.03	
143649	2003 QQ47	09/16-09/21	45.2,25.9	17	-8	13.070	0.006	0.19	0.03	NEA
143649	2003 QQ47	2014 03/31-04/03				[P]2.746	0.002	0.14	0.02	
						2.914	0.002	0.16	0.03	
						14.79	0.04	0.41	0.05	
159857	2004 LJ1	08/05-08/23	51.8,64.9	286	45	2.72631	0.00007	0.23	0.02	NEA
						35.16	0.04	0.11	0.01	
326732	2003 HB6	08/09-08/28	22.8,10.9	335	6	3.4630	0.0002	0.08	0.01	NEA
						22.903	0.006	0.10	0.01	

Table II. Observing circumstances. [P]Preferred period of ambiguous solution for the primary. 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; HIL Hilda; MB-I Inner main-belt; NEA: Near-Earth asteroid. The Dr column on the second line indicates a confirmed binary and is the estimated diameter ratio of the secondary to primary (Ds/Dp).