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

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Using data from observations made at the Center for Solar System Studies from 2021 January through March along with recovered legacy data, we report on the analysis of confirmed and suspected binary asteroids 2419 Moldavia, 2873 Binzel, 3561 Devine, 4383 Suruga, 4666 Dietz, 16525 Shumarinaiko, (88188) 2000 XH44, (416694) 2004 YR32, and 1999 RM45.

Data from CCD photometric observations made at the Center for Solar System Studies in 2021 January through March along with legacy data recovered following a hard drive failure 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).

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	SBIG STL-1001E
0.35-m *f*/9.1 Schmidt-Cass	FLI Microline 1001E
0.35-m *f*/9.1 Schmidt-Cass	FLI Microline 1001E
0.35-m *f*/9.1 Schmidt-Cass	FLI Microline 1001E
0.35-m *f*/10 Schmidt-Cass	SBIG STL-1001E
0.35-m *f*/10 Schmidt-Cass	FLI Proline 1001E
0.40-m *f*/10 Schmidt-Cass	FLI Proline 1001E
0.40-m *f*/10 Schmidt-Cass	FLI Proline 1001E
0.50-m *f*/8.1 Ritchey-Chrétien	FLI Proline 1001E

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.

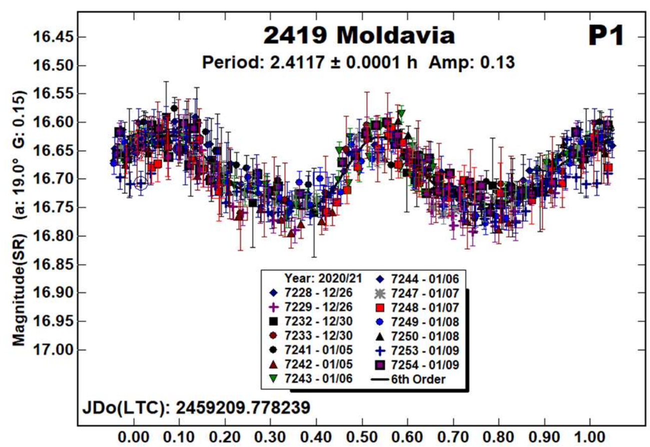
Measurements were made using *MPO Canopus*. The Comp Star Selector utility in *MPO Canopus* found up to five comparison stars of near solar-color for differential photometry. To reduce the number of adjusted nightly zero points and their amounts, the analysis of the 2021 data used the ATLAS catalog r´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

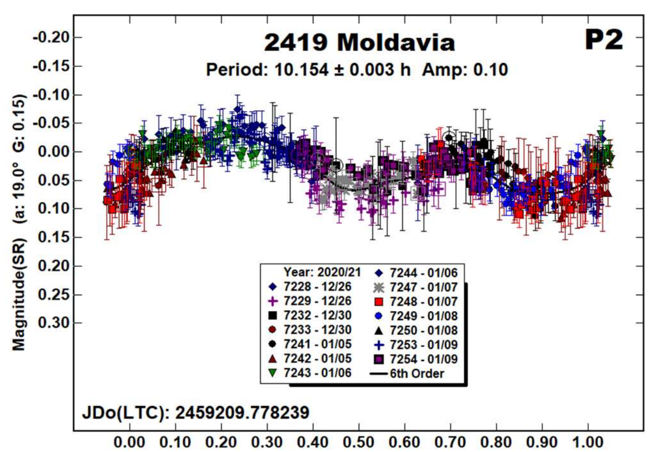
The Y-axis shows the catalog ("sky") magnitudes for the "primary" period (P_1) while the "secondary" (P_2) plots give the differential from the average magnitude in the P_1 plot. "SR" indicates that the ATLAS catalog was used. "V" or "R" came from other catalogs, e.g., APASS (Henden et al., 2009) or MPOSC3 that converted 2MASS J-K to BVRI (Warner, 2007).

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 as well as the mid-date/time of that session. Ideally, this leaves 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*.

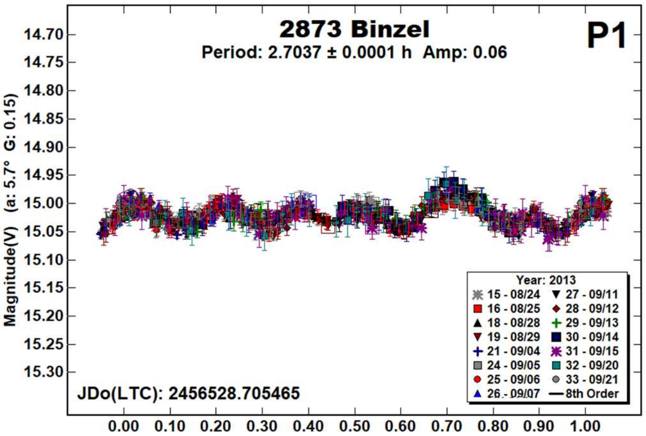
From here on, "LCDB" refers to the asteroid lightcurve database (Warner et al., 2009).

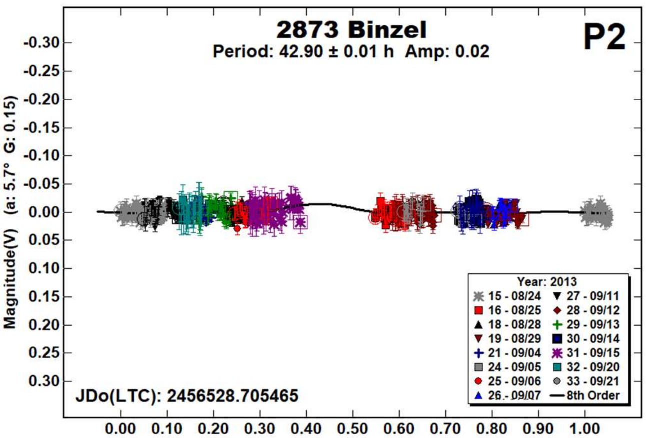
2419 Moldavia (Flora). Birlan et al. (1996) found a period of 2.412 h. Our data from 2020/21 found a very similar period for a primary period derived from a dual-period search in *MPO Canopus*. We also found a secondary period of 10.154 h. The LCDB includes three confirmed binaries with $10.5 \le P_{ORB} \le 11$ h. If confirmed, this would be the shortest orbital period and, to be consistent with Pravec et al. (2018), have the satellite diameter be $D_s < 0.3D_p$.



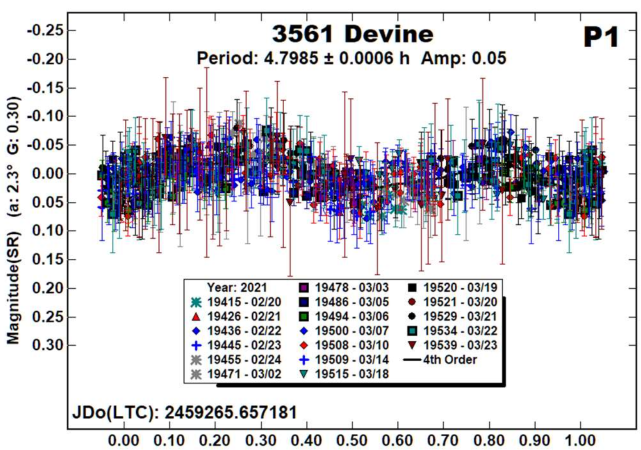


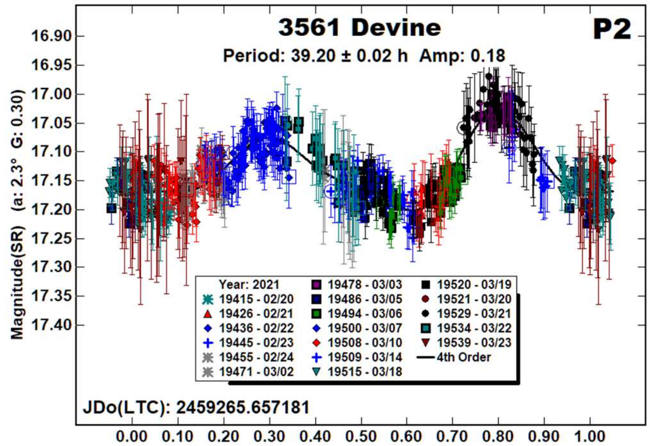
2873 Binzel. Vachier et al. (2019) discovered this Flora asteroid to be binary, finding P_1 = 2.70371 h and P_{ORB} = 44.58 h. The estimated the effective diameters ratio to be $Ds/Dp \geq 0.25$. We were able to recover data obtained in 2013. There dataset was insufficient to confirm the Vachier et al. results. The two plots show the data forced to those earlier results. From the nearly flat P_2 plot, it appears that the asteroid was out of *eclipse season*.



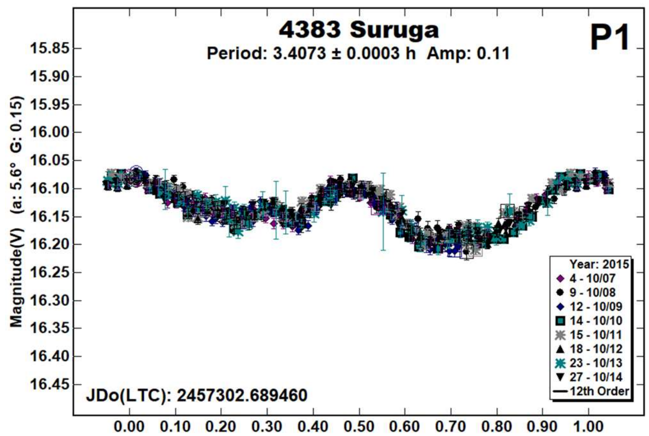


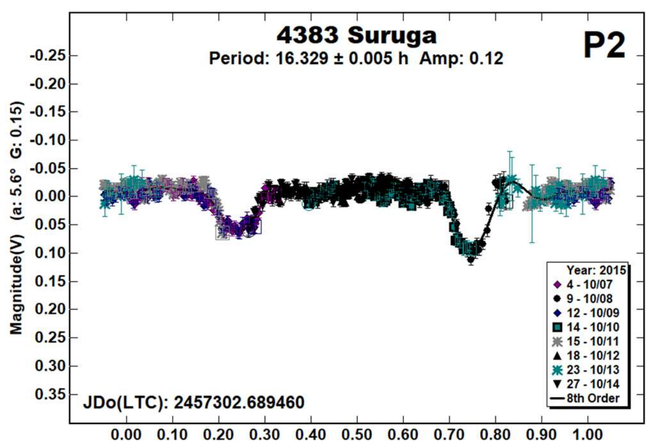
3561 Devine. Binzel et al. (1992) reported a period of 2.81 h for this Hilda asteroid. Analysis of our 2021 data initially found a period near 40 h. Using this as the initial value in a dual-period search, we eventually found a somewhat weak, but obvious, shorter period component with a lightcurve amplitude of 0.05 mag. Given the absence of mutual events, our conclusion is that P_2 = 39.20 h is most likely the orbital period of an elongated satellite (a/b ~ 1.18:1).





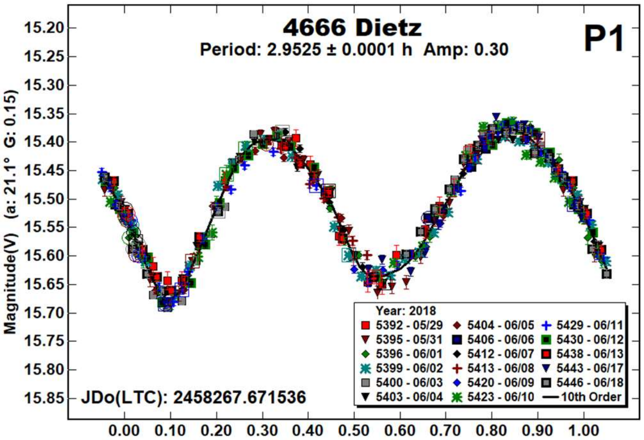
4383 Suruga. Warner (2013) first reported the binary status of this asteroid, finding P_1 = 3.4069 h and P_{ORB} = 16.386 h. The diameters ratio was $Ds/Dp \geq 0.22$. The extracted legacy data from 2015 confirms the initial results, including the size ratio.

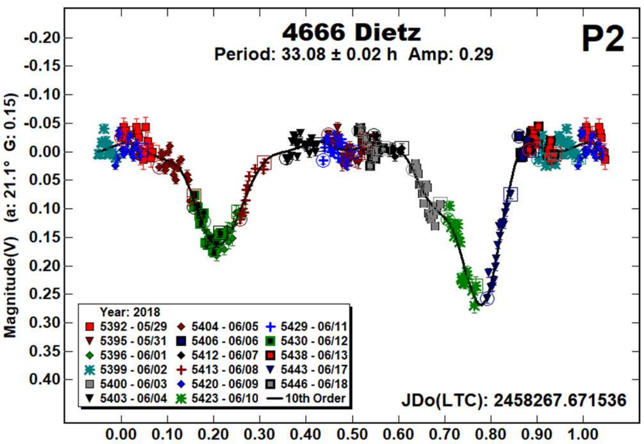




4666 Dietz. There are several entries in the LCDB giving a primary (or sole period if not said to be binary) close to 2.95 h (e.g., Behrend, 2011web, 2.9528 h; Pravec et al., 2011web, 2.95184 h). From observations in 2015, Pravec et al. (2015web) suspected the asteroid to be binary, finding a tentative P_{ORB} = 16.64 h. Adding the Pravec et al. data from 2011 and 2015, Oey et al. (2018) found P_{ORB} = 33.2 h and $Ds/Dp \geq 0.34$. There was also a possibility for a third period.

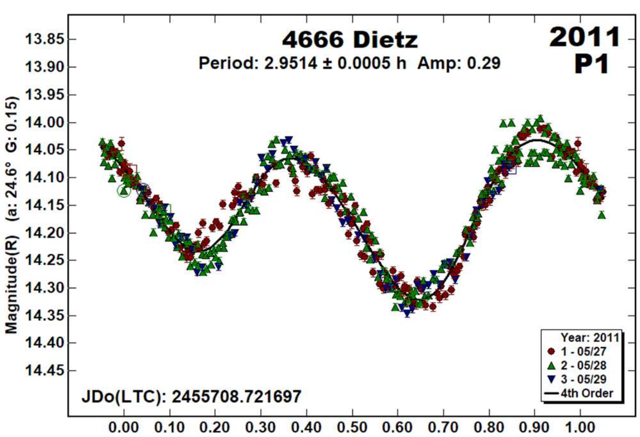
Stephens (this work) observed at the same time in 2018. His data yield essentially the same results: P_1 = 2.9525 h, P_{ORB} = 33.08 h, and $Ds/Dp \geq 0.38$.

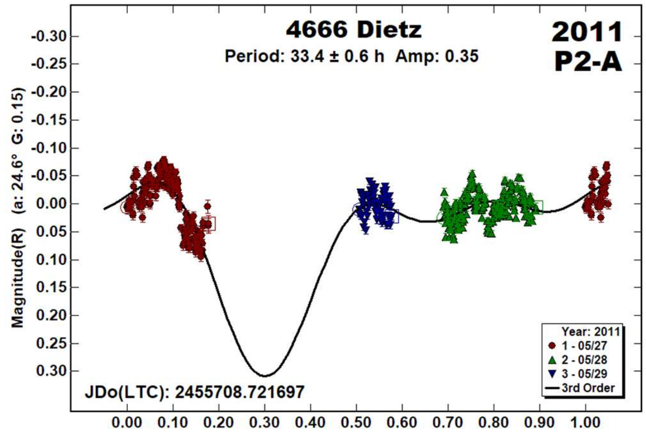


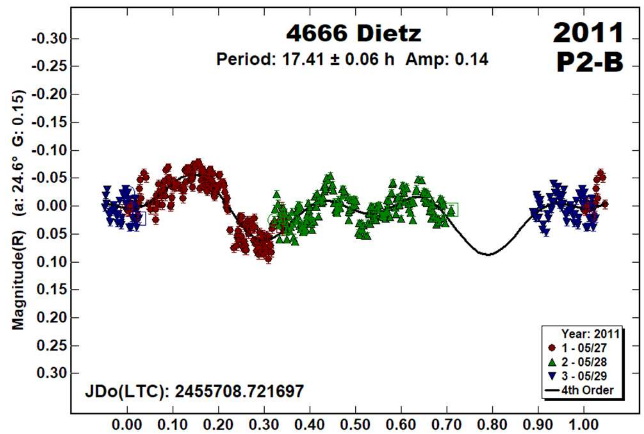


The extracted legacy data from 2011 showed that the binary discovery might have been possible in 2011. The "2011 P1" plot shows the final result of a dual-period search on the dataset that spanned only three days. Note that even after refining P_{ORB} to 16 h or 33 h, there are signs of a third period. However, the dataset was too sparse to make a useful search.

There are two plausible solutions for *PORB*. One, P_{ORB17} = 17.41 h, is somewhat near that reported by Pravec et al. (2015web). The alternate solution was forced to near the Oey et al. (2018) result, giving P_{ORB33} = 33.4 h.

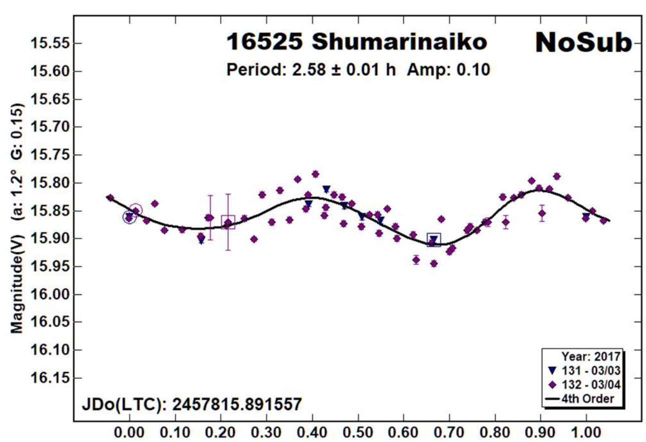


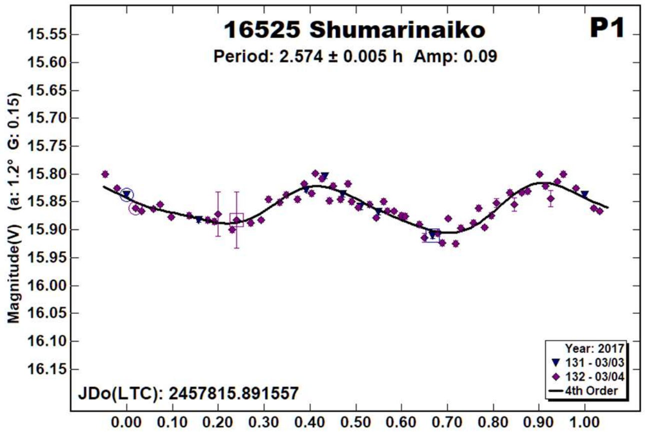


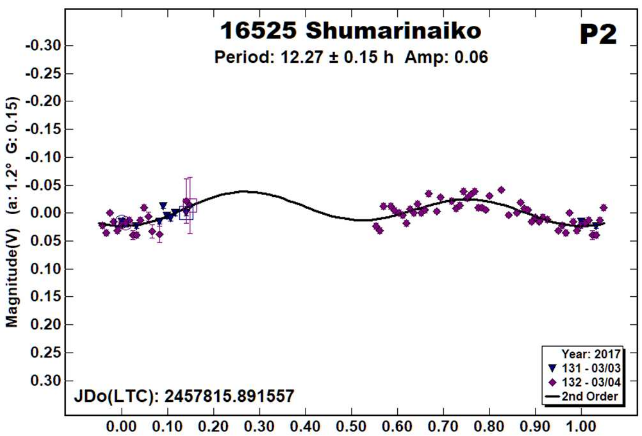


The shorter 17-h lightcurve could have easily been interpreted as showing mutual events, leading to $Ds/Dp \geq 0.31$. Given the near commensurability of both potential orbital solutions with an Earth day, a more extended dataset might have been able to confirm the binarity and remove the ambiguity for P_{ORB}, especially with help from an observer at a different longitude.

16525 Shumarinaiko. Warner and Coley (2013) reported this inner main-belt asteroid to be binary, finding P_1 = 2.5932 h and P_{ORB} = 14.409 h. There were signs of mutual events, but mainly the P_{ORB} lightcurve showed the typical "bowed" shape of a tidally-locked and elongated satellite.

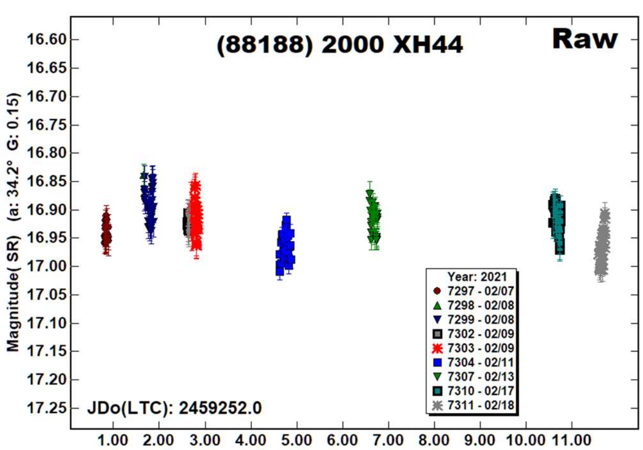




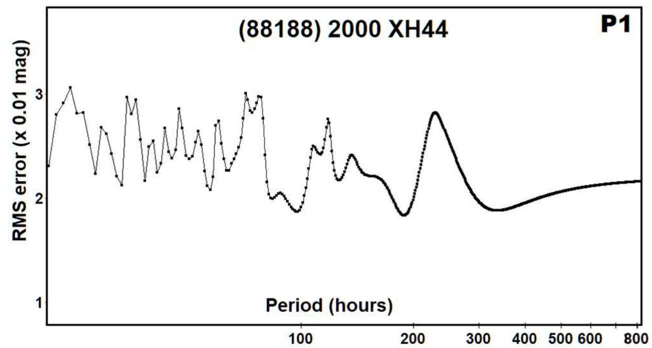


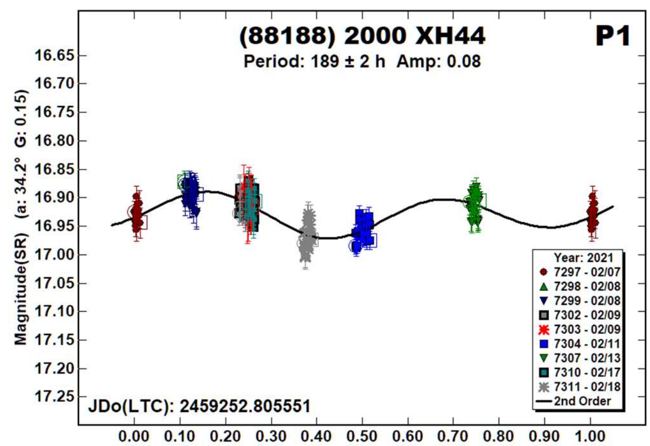
We were able to extract a very limited dataset from 2017 with fewer than 100 data points obtained over two nights. Even so, we attempted to duplicate the results from the 2013 observations. While the "NoSub" plot seemed to show an attenuation and we did eventually extract a similar primary period of P_1 = 2.58 h, the dataset was too sparse to find an accurate solution for the orbital period. The P_2 plot shows the best fit that we could find using a second-order Fourier fit.

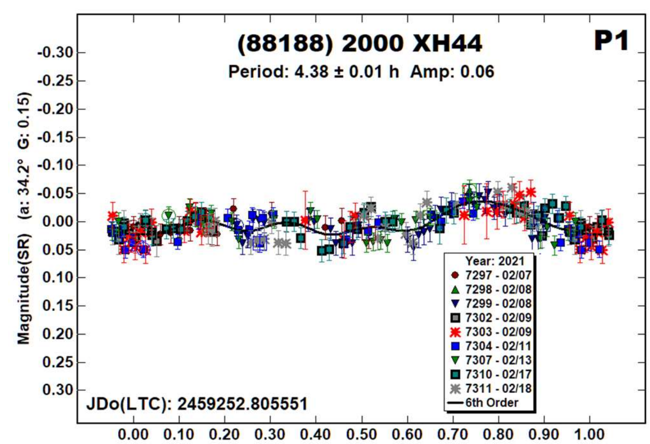
<u>(88188) 2000 XH44</u>. Behrend (2004web) reported a period of 5.16 h, but it is rated as unreliable in the LCDB. Galad et al. (2005) reported a reliable period of 2.6906 h.



The raw plot of our 2021 data seemed to show a long-period component after resetting the zero-point adjustments that were made to get a single period solution back to 0. The dual-period search found a few long-period solutions; we adopted the one that fit to a bimodal lightcurve, i.e., P_1 = 189 h. This seems to fit with the raw data plot but there are caveats to that comparison that depend on the true period and the sampling rate of the sessions.





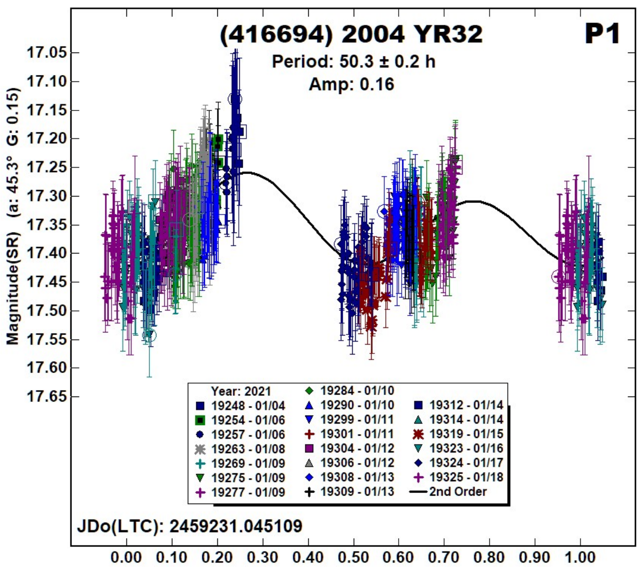


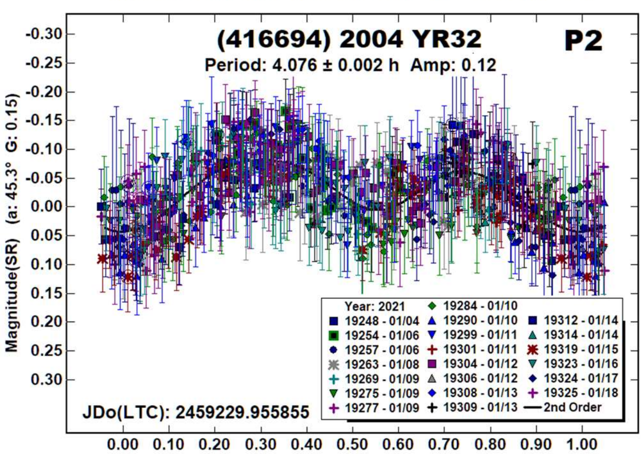
The dual-period search also found a weak P_2 = 4.38 h, but it could just as well be the result of the Fourier analysis locking onto noise in the dataset. If the period actually has a physical cause, i.e., a small satellite at a significant distance from the primary, then the asteroid would be a candidate for a *very wide binary* (see, e.g., Warner, 2016).

(416694) 2004 YR32. There were no previously reported periods in the LCDB for the near-Earth asteroid. Mainzer et al. (2019) found a diameter of 2.3 km using $H = 17.6$. This leads to a derived albedo of 0.03, which is atypically low for NEAs, which presumes that they are type S and have an albedo of 0.20 ± 0.11 (Warner et al., 2009). The higher albedo value would lead to a diameter of 900 m.

A plot of the raw data from our 2021 observations, not shown here, indicated that a period of about 48 h (or 24 h) was probable. Since this is in the realm for *very wide binary* asteroids (Warner, 2016), we used the dual-period search in *MPO Canopus* to see if a short period component was hiding in the data.

Despite the very noisy dataset, the effort was successful, finding a well-defined second period of $P_2 = 4.076$ h based on $P_1 = 50.3$ h. While $P_1 \sim 25$ h cannot be formally excluded, the resulting lightcurve would have a significantly larger amplitude, enough so that we are comfortable with adopting $P_1 = 50.3$ h. as the correct solution.

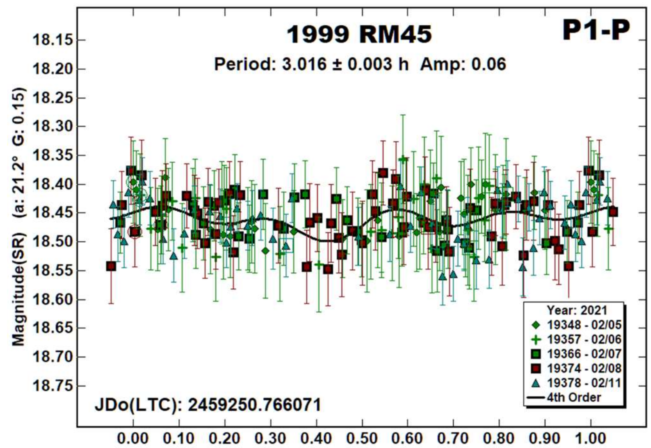


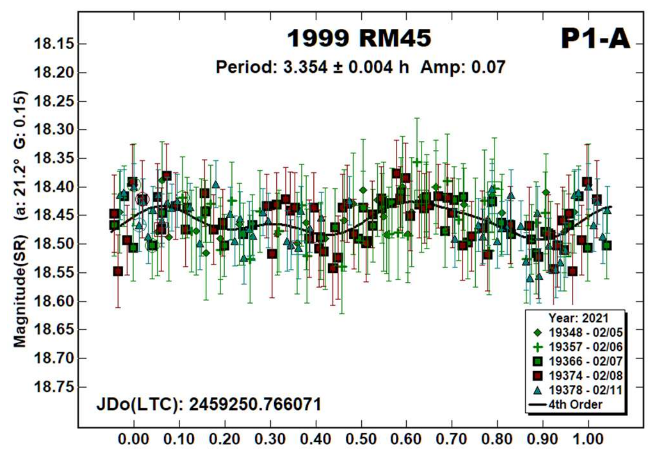


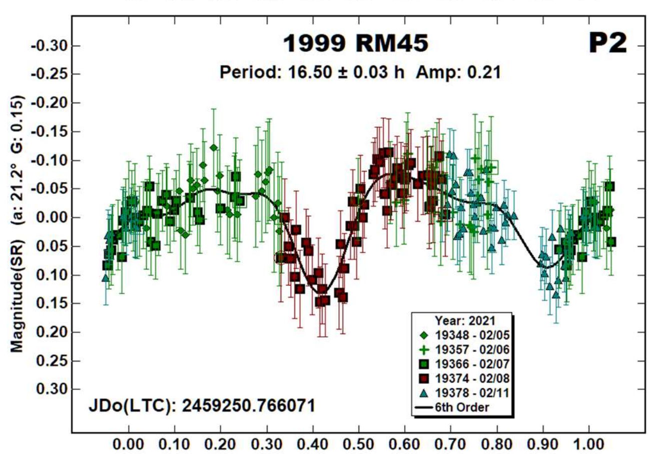
1999 RM45. Pravec et al. (2021) were first to report that this NEA is a binary asteroid. They found $P1 = 3.0697$ h, $P_{ORB} = 16.445$ h, and $Ds/Dp \geq 0.45$.

Our independent observations were made about the same time. The data clearly showed a period of about 16.5 h and what could be interpreted as mutual events caused by an elongated satellite. However, the dataset was insufficient to find a more refined and certain period beyond $P_2 = 16.50$ h.

The dataset was not only too sparse but too noisy to extract the period found by Pravec et al. (2021). A repeated iteration using our P_2 and forcing a solution near 3.07 h found two, unconvincing solutions of $P_1 = 3.016$ h or 3.354 h, which have a close to 10:9 ratio. The shorter $P_1 = 3.016$ h is close to Pravec et al. (2021) and so is labeled “P1-P” (preferred) even though the fit of our data to $P_1 = 3.354$ h was better.







Number	Name	20yy mm/dd	Phase	L_{PAB}	B_{PAB}	Period(h)	P.E.	Amp	A.E.	Grp/Dr
2419	Moldavia	20/12/16-01/09	19.0,12.7	131	-6	2.4117	0.0001	0.13	0.01	FLOR
						10.154	0.003	0.10	0.01	<0.3
2873	Binzel	13/08/24-09/21	5.5,18.0	326	-7	[F]2.7037	0.0001	0.06	0.01	FLOR
						[F]42.90	0.01	0.02	0.01	
3561	Devine	21/02/20-03/23	2.3,8.9	144	5	4.7985	0.0006	0.05	0.01	HIL
						39.20	0.02	0.18	0.03	
4383	Suruga	15/10/07-10/14	5.6,7.8	10	-10	3.4073	0.0003	0.11	0.01	MB-I
						16.329	0.005	0.12	0.01	≥0.22
4666	Dietz	18/05/29-06/18	21.2,28.6	217	0	2.9525	0.0001	0.30	0.02	MB-I
						33.08	0.02			≥0.38
		11/05/27-05/29	10.2,10.4	250	13	2.9514	0.0005	0.29	0.03	MB-I
						[PO]17.41	0.06	0.14	0.02	≥0.31
						[F]33.4	0.6	>0.1		
16525	Shumarinaiko	17/03/03-03/04	1.3,0.9	164	1	2.574	0.005	0.09	0.01	MB-I
						12.27	0.15	0.06	0.01	
88188	2000 XH44	21/02/07-02/18	34.2,40.2	108	12	189	2	0.08	0.01	NEA
						4.38	0.01	0.06	0.01	
416694	2004 YR32	21/01/04-01/18	45.3,64.9	143	31	50.3	0.2	0.16	0.02	NEA
						4.076	0.002	0.12	0.03	
	1999 RM45	21/02/05-02/11	21.2,18.9	151	-10	[F]3.354	0.004	0.07	0.03	NEA
						[A]3.354	0.004	0.07	0.03	
						16.50	0.03	0.21	0.03	

Table II. Observing circumstances. [A]Alternate primary period. [F]Period is forced to another result. [P]Preferred primary period. [PO]Preferred orbital 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; 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).

Acknowledgements

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References

References from web sites should be considered transitory, unless from an agency with a long lifetime expectancy. Sites run by private individuals, even if on an institutional web site, do not necessarily fall into this category.

Behrend, R. (2004web; 2011web) Observatoire de Geneve web site. *http://obswww.unige.ch/~behrend/page_cou.html*

Binzel, R.P.; Xu, S.; Bus, S.J.; Bowell, E. (1992). "Small main-belt asteroid lightcurve survey." *Icarus* **99**, 225-237.

Birlan, M.; Barucci, M.A.; Angeli, C.A.; Doressoundiram, A.; De Sanctis, M.C. (1996). "Rotational properties of asteroids: CCD observations of nine small asteroids." *Planet. Space Sci*. **44**, 555-558.

Galad, A.; Pravec, P.; Kusnirak, P.; Gajdos, S.; Kornos, L.; Vilagi, J. (2005). "Joint Lightcurve Observations of 10 Near-Earth asteroids from Modra and ONDREJOV." *Earth, Moon, and Planets* **97**, 147-163.

Harris, A.W.; Young, J.W.; Scaltriti, F.; Zappala, V. (1984). "Lightcurves and phase relations of the asteroids 82 Alkmene and 444 Gyptis." *Icarus* **57**, 251-258.

Henden, A.A.; Terrell, D.; Levine, S.E.; Templeton, M.; Smith, T.C.; Welch, D.L. (2009). *http://www.aavso.org/apass*

Mainzer, A.; Bauer, J.; Cutri, R.; Grav, T.; Kramer, E.; Masiero, J.; Sonnett, S.; Wright, E. Eds. (2019). "NEOWISE Diameters and Albedos V2.0." NASA Planetary Data System. urn:nasa:pds:neowise_diameters_albedos::2.0. *https://doi.org/10.26033/18S3-2Z54*

Oey, J.; Kusnirak, P.; Pravec, P.; Hornoch, K.; Pray, D.; Benishek, V.; Montaigut, R.; Leroy, A.; Vilagi, J. (2018). *CBET* **4536**.

Pravec, P.; Wolf, M.; Sarounova, L. (2011web, 2015web). *http://www.asu.cas.cz/~ppravec/neo.htm*

Pravec, P.; Fatka, P.; Vokrouhlicky, D.; Scheeres, D.J.; Kusnirak, P.; Hornoch, K.; Galad, A.; Vrastil, J.; Pray, D.P.; Krugly, Yu.N.; Gaftonyuk, N.M.; Inasaridze, R.Ya.; Ayvazian, V.R.; Kvaratskhelia, O.I.; Zhuzhunadze, V.T.; Husarik, M.; Cooney, W.R.; Gross, J.; Terrell, D.; Világi, J.; Kornos, L.; Gajdos, S.; Burkhonov, O.; Ehgamberdiev, Sh.A.; Donchev, Z.; Borisov, G.; Bonev, T.; Rumyantsev, V.V.; Molotov, I.E. (2018). "Asteroid clusters similar to asteroid pairs." *Icarus* **304**, 110-126.

Pravec, P.; Hornoch, K.; Fatka, P.; Kusnirak, P. (2021). *CBET* **4631**.

Tonry, J.L.; Denneau, L.; Flewelling, H.; Heinze, A.N.; Onken, C.A.; Smartt, S.J.; Stalder, B.; Weiland, H.J.; Wolf, C. (2018). “The ATLAS All-Sky Stellar Reference Catalog.” *Ap. J.* **867**, A105.

Vachier, F.; Pravec, P.; Kucakova, H.; Hornoch, K.; Kusnirak, P.; Pray, D.; Cooney, W.; Gross, J.; Terrell, D.; Flanagan, B.; Pellerin, B.; Durkee, R.; Benishek, V.; Berthier, J.; Klotz, A.; Teng, J.-P.; Peyrot, A.; Thierry, P. (2019). *CBET* **4628**.

Warner, B.D. (2007). “Initial Results of a Dedicated H-G Program.” *Minor Planet Bul.* **34**, 113-119.

Warner, B.D. (2013). “Lightcurve Photometry Opportunities: 2013 April-June.” *Minor Planet Bull*. **40**, 119-121.

Warner, B.D. (2016). “Three Additional Candidates for the Group of Very Wide Binaries.” *Minor Planet Bul.* **43**, 306-309.

Warner, B.D.; Coley, D. (2013). “16525 Shumarinaiko: A New Nysa Binary.” *Minor Planet Bull*. **40**, 124-125.

Warner, B.D.; Harris, A.W.; Pravec, P. (2009). “The Asteroid Lightcurve Database.” Icarus **202**, 134-146. Updated 2020 Aug. *http://www.minorplanet.info/lightcurvedatabase.html*

LIGHTCURVE AND ROTATION PERIOD DETERMINATIONS FOR 25 ASTEROIDS

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Lightcurves and synodic rotation periods for 25 asteroids determined from CCD photometric data acquired at Sopot Astronomical Observatory (SAO) over the time span 2020 July - 2021 April are summarized in this paper.

Photometric observations of 25 asteroids were conducted at Sopot Astronomical Observatory (SAO) from 2020 July through 2021 April in order to determine the asteroids’ synodic rotation periods. For this purpose, two 0.35-m *f*/6.3 Meade LX200GPS Schmidt-Cassegrain telescopes were employed. The telescopes are equipped with a SBIG ST-8 XME and a SBIG ST-10 XME CCD cameras. The exposures were unfiltered and unguided for all targets. Both cameras were operated in 2×2 binning mode, which produces image scales of 1.66 arcsec/pixel and 1.25 arcsec/pixel for ST-8 XME and ST-10 XME cameras, respectively. Prior to measurements, all images were corrected using dark and flat field frames.

Photometric reduction was conducted using *MPO Canopus* (Warner, 2018). Differential photometry with up to five comparison stars of near solar color ($0.5 \leq B\text{-}V \leq 0.9$) was performed using the Comparison Star Selector (CSS) utility. This helped ensure a satisfactory quality level of night-to-night zero-point calibrations and correlation of the measurements within the standard magnitude framework. Field comparison stars were calibrated using standard Cousins R magnitudes derived from the Carlsberg Meridian Catalog 15 (VizieR, 2021) Sloan r' magnitudes using the formula: $R = r' - 0.22$ in all cases presented in this paper. In some instances, small zero-point adjustments were necessary in order to achieve the best match between individual data sets in terms of achieving the most favorable statistical indicators of Fourier fit goodness.

Lightcurve construction and period analysis was performed using *Perfindia* custom-made software developed in the R statistical programming language (R Core Team, 2020) by the author. The essence of its algorithm is reflected in finding the most favorable solution for rotational period by minimizing the *residual standard error* of the lightcurve Fourier fit.

The lightcurve plots presented in this paper show so-called 2% error for rotational periods, i.e., an error that would cause the last data point in a combined data set by date order to be shifted by 2% (Warner, 2012) and represented by $\Delta P = (0.02 \cdot P^2) / T$, where P and T are the rotational period and the total time span of observations, respectively. Both of these quantities must be expressed in the same units.

Some of the targets presented in this paper were observed within the Photometric Survey for Asynchronous Binary Asteroids (*BinAstPhot Survey*) under the leadership of Dr. Petr Pravec from Ondřejov Observatory, Czech Republic.

Table I gives the observing circumstances and results.