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POTENTIAL BINARY AND TUMBLING ASTEROIDS FROM THE CENTER FOR SOLAR SYSTEM STUDIES

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CCD photometric observations of four main-belt and one near-Earth asteroid were made in 2019. Of these, the Vestoid 2602 Moore and Hungaria (27568) 2000 PT6 were confirmed to be binary asteroids. The Hungaria 3880 Kaiserman is a suspected binary. Near-Earth asteroid (142040) 2002 QE15 was found to have a long period (46.4 h). Re-evaluation of data for the asteroid from two previous apparitions found a secondary period that is consistent with the system being a candidate for the rare class of very wide binary asteroids. New analysis of the data from 2016 for Phocaea member 2937 Gibbs found two periods (the second being ambiguous). It could not be determined if the asteroid is binary or in a tumbling state.

CCD photometric observations of five asteroids were conducted in 2019 April-July as part of ongoing work at the Center for Solar System Studies (CS3) to find the rotation periods of asteroids. The primary targets are near-Earth asteroids but, when there are no such objects within reach of our instruments or they are poorly placed, we observe main-belts objects, concentrating on Jupiter Trojans, Hildas, and Hungarias.

Telescopes	Cameras
0.30-m *f*/6.3 Schmidt-Cass	FLI Microline 1001E
0.35-m *f*/9.1 Schmidt-Cass	FLI Proline 1001E
0.35-m *f*/11 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.

Table I lists the telescopes and CCD cameras that are combined to make observations. Up to nine telescopes can be used for the campaign, although 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. All lightcurve observations were unfiltered since a clear filter can result in a 0.1-0.3 magnitude loss. The exposures varied depending on the asteroid's brightness and sky motion.

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. Comp star magnitudes were taken from ATLAS catalog (Tonry et al., 2018), which has Sloan *griz* magnitudes that were derived from the GAIA and Pan-STARR catalogs, among others. The authors state that systematic errors are generally no larger than 0.005 mag, although they can reach 0.02 mag in small areas near the Galactic plane. BVRI magnitudes were derived by Warner using formulae

Number	Name	20xx/mm/dd	Phase	L_{PAB}	B_{PAB}	Period(h)	P.E.	Amp	A.E.	Grp
2602	Moore	19/04/17-05/15	22.1,27.1	164	2	3.46723	0.00003	0.43	0.01	V
	Satellite					27.455	0.003	0.15	0.01	
2937	Gibbs	16/12/17-12/19	8.8,7.9	103	-7	2.984	0.001	0.25	0.02	MC
	P2 Alt1					5.62	0.01	0.14	0.02	
	P2 Alt2					7.49	0.01	0.14	0.02	
3880	Kaiserman	19/07/01-07/07	11.9,23.4	280	10	5.2694	0.0007	0.14	0.01	H
	Satellite?					16.09	0.02	0.05	0.01	
27568	2000 PT6	19/06/26-07/07	21.9,43.4	268	31	3.5006	0.0003	0.25	0.02	H
	Satellite					16.099	0.008	0.18	0.02	
142040	2002 QE15	19/05/24-06/02	9.6,11.7	245	15	46.4	0.2	0.19	0.03	NEA
142040	2002 QE15	15/07/14-07/21	51.7,53.4	349	43	47.1	0.1	0.11	0.01	
	Satellite?					3.891	0.001	0.15	0.02	
142040	2002 QE15	17/08/21-08/29	46.6,48.7	288	44	48.1	0.2	0.20	0.03	
	Satellite?					3.856	0.003	0.11	0.02	

Table II. Observing circumstances. 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). The additional lines after the first, complete line give the periods associated with a satellite or alternate solutions for a second period. The Grp column gives the family/group (Warner et al., 2009). H: Hungaria; MC: Mars-crosser; NEA: Near-Earth asteroid; V: Vestoid.

from Kostov and Bonev (2017). The overall errors for the BVRI magnitudes, when combining those in the ATLAS catalog and the conversion formulae, are on the order of 0.04-0.05.

Even so, we found in most cases that nightly zero point adjustments on the order of only 0.02-0.03 mag were required during period analysis. There were occasional exceptions that required up to 0.10 mag. These may have been related in part to using unfiltered observations, poor centroiding of the reference stars, and not correcting for second-order extinction terms. Regardless, the systematic errors seem to be considerably less than other catalogs, which reduces the uncertainty in the results when analysis involves data from extended periods or the asteroid is tumbling.

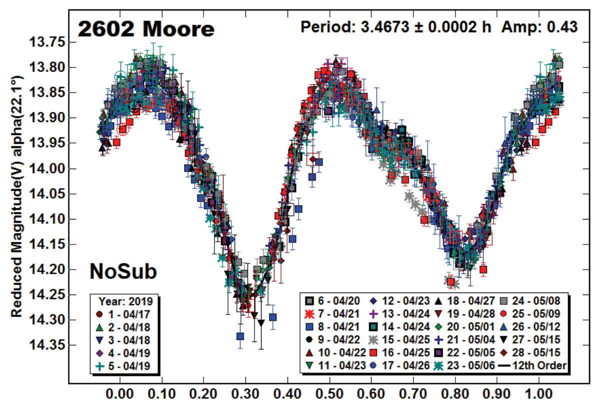
Period analysis was done with *MPO Canopus*, which implements the FALC algorithm by Harris (Harris *et al.,* 1989). The same algorithm is used in an iterative fashion when it appears there is more than one period. This works well for binary but not for tumbling asteroids.

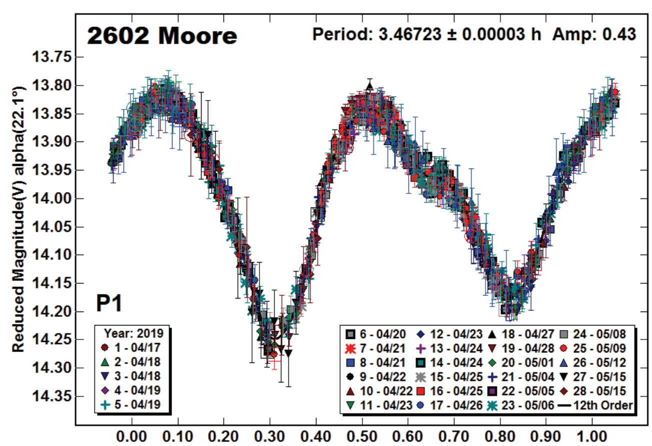
In the plots below, the "Reduced Magnitude" is Johnson V. These have been converted from sky magnitudes to unity distance by applying –5*log (rΔ) with r and Δ being, respectively, the Sun-asteroid and Earth-asteroid distances in AU. The magnitudes were normalized to the phase angle in parentheses using *G* = 0.15. The X-axis is the rotational phase ranging from –0.05 to 1.05. If the plot includes an amplitude, it is for the Fourier model curve and *not necessarily the adopted amplitude for the lightcurve*.

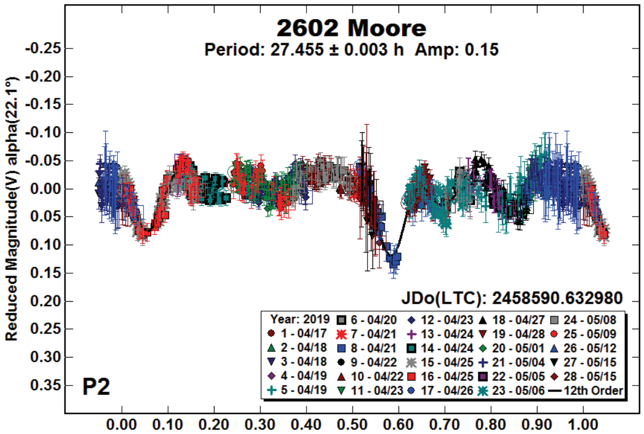
Our initial search for previous results started with the asteroid lightcurve database (LCDB; Warner *et al.,* 2009) found on-line at *http://www.minorplanet.info/lightcurvedatabase.html*. Readers are strongly encouraged to obtain, when possible, the original references listed in the LCDB.

2602 Moore. Stephens observed this asteroid in 2019 April and May. Soon after the observations began, there were indications of attenuations that might be attributed to a satellite. An extensive campaign covered almost a month and confirmed the attenuations as being occultation and/or eclipses (*mutual events*) due to a satellite.

The three plots show the data without subtracting a second period followed by the results of the dual-period search. The depth of the attenuations ranged from 0.08-0.14 mag. Using the smaller value, we estimate an effective diameter ratio of satellite-to-primary *Ds/Dp* ≥ 0.28 ± 0.02. There were no previous lightcurve results posted in the LCDB.

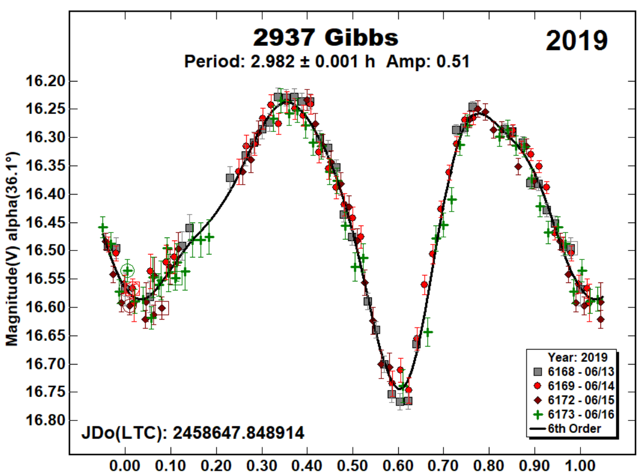




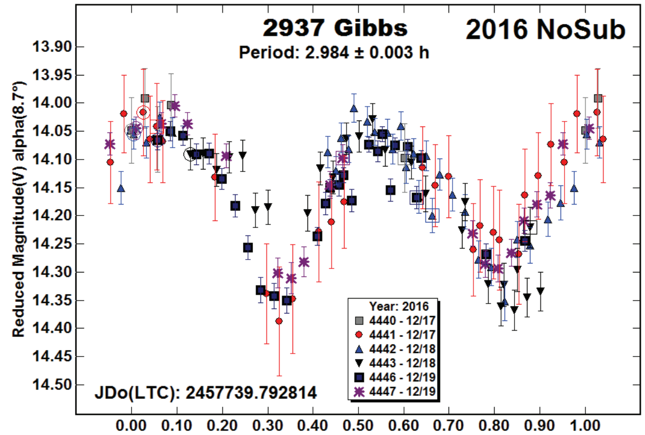


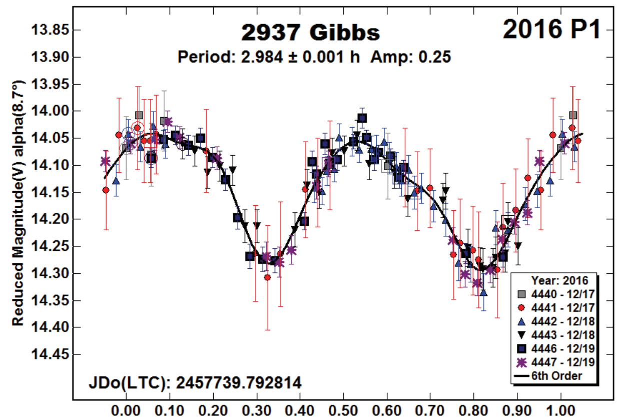
2937 Gibbs. There were several results posted in the LCDB for this 6-km Phocaea asteroid. Behrend (2005) reported 3.06153 h based on observations in 2005 August. His group observed again four months later and found a similar but less precise P = 3.06 h. Co-author Stephens (2017) found P = 3.189 h using data from 2016 December. This is similar to the Behrend results but differs by several sigma.

New observations made in 2019 June led to a significantly shorter period of 2.982 h. The new data could not be fit to the previous results. Given the large amplitude and relatively low solar phase angle, we adopted 2.982 h to be the true period and took another look at the data from 2016, forcing it to be near 2.98 h.

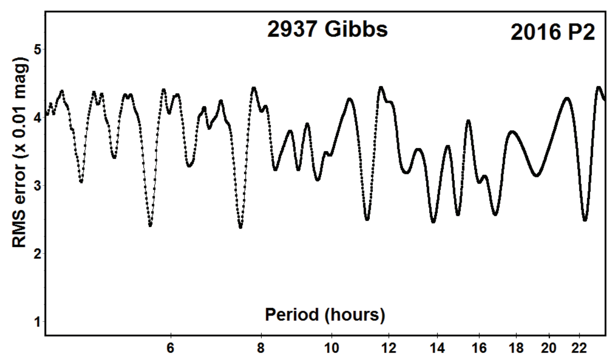


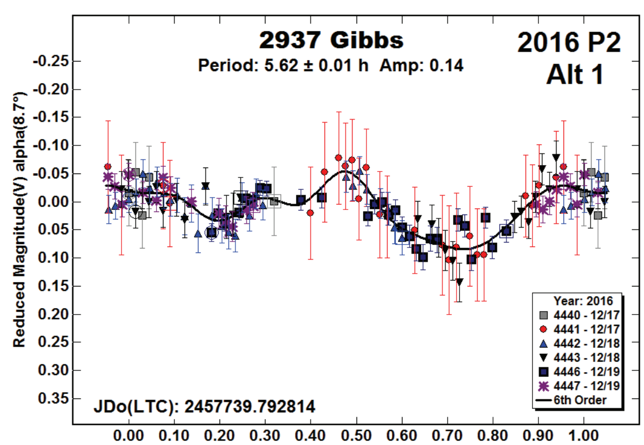
The "NoSub" plot shows what appear to be deviations in the lightcurve but the nosier data and smaller amplitude made those uncertain, at least to start. Our dual-period search found a very good fit to P_1 = 2.984 h after subtracting each of several possible secondary periods, P_2. Regardless of which secondary period was used, the result for P_1 remained the same.

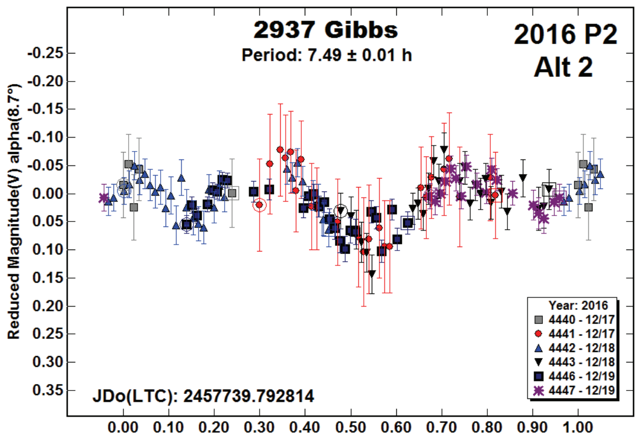


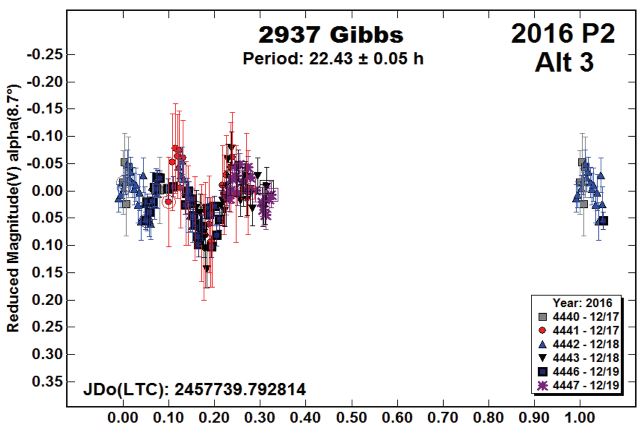


The period spectrum for the secondary period ("2016 P2") showed four possibilities with the one near 11 hours being the half-period of the longest solution of about 22 hours.









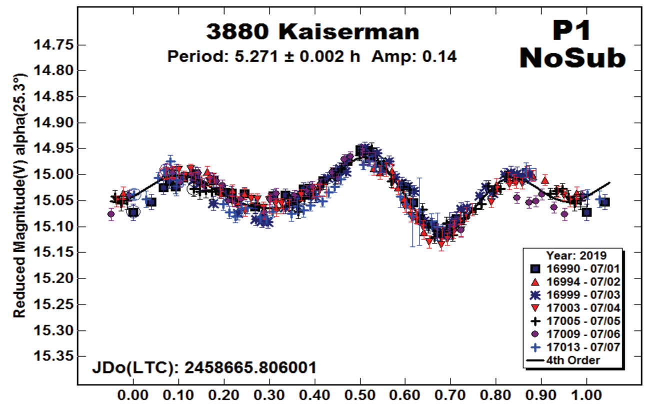
We examined the solutions at 5.6 h, 7.49 h, and 22.43 h to see which would produce the most plausible result. At P_2 = 5.62 h, the fit is acceptable given the scatter in the data set. It's important to note that this P_2 is not harmonically related to P_1, i.e., they do not have an integer ratio.

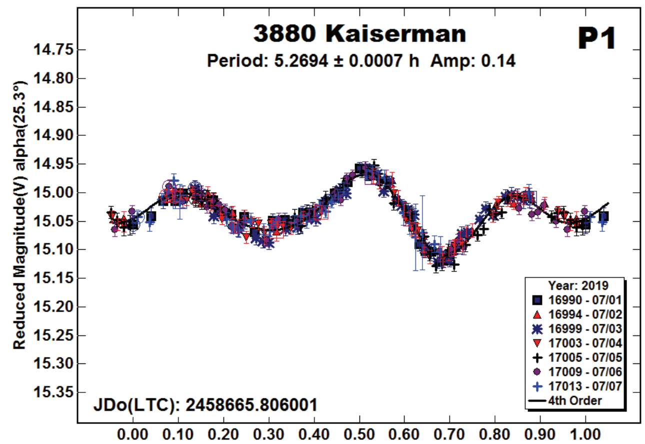
On the other hand, the remaining two solutions have *nearly* integral ratios with P_1. The lightcurve at P_2 = 7.49 h is almost trimodal, which is possible because of the low amplitude (Harris et al., 2014). The lightcurve at P_2 = 22.43 h is clearly wrong and simply a *fit by exclusion*, which is where the Fourier algorithm finds a local RMS minimum by minimizing the number of overlapping data points.

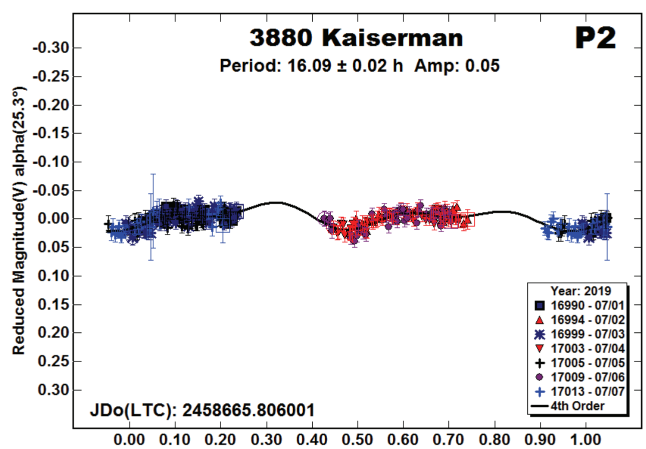
The harmonic relation between P_1 and P_2 = 7.49 h raises the possibility that the asteroid is in a low-level tumbling state where P_1 = 2.984 h dominates the solution and a linear combination of rotation and precession frequencies produces a "beat frequency" that is *n*/7.49, with *n* being an integer value. This is not uncommon (see Harris et al., 2014; Pravec et al., 2014; 2005).

3880 Kaiserman. We observed this Hungaria member twice before the latest observations. Warner (2012b) found a period of 5.270 h. In 2014 Warner (2015b) found a period of 5.227 h as well as indications of a secondary period of 22.16 h that was attributed to a possible satellite.

Our 2019 data also gave indications of a secondary period. The dual-period analysis found P_1 = 5.271 h, in agreement with Warner (2012b), and P_2 = 16.09 h. The lightcurve for P_2 is low amplitude (0.05 mag) but appears to be bimodal and has a shape typically seen for elongated satellites that are tidally-locked to the orbital period.

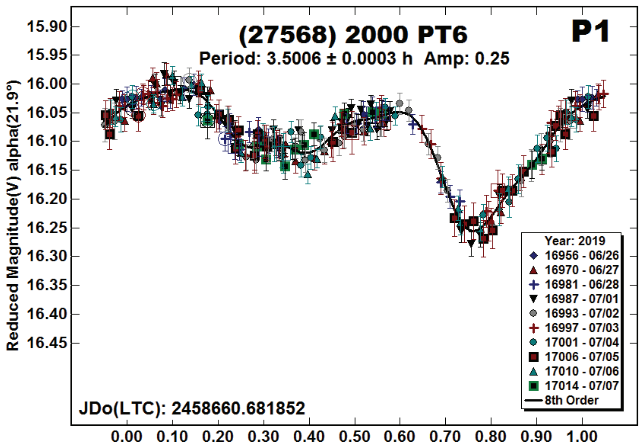


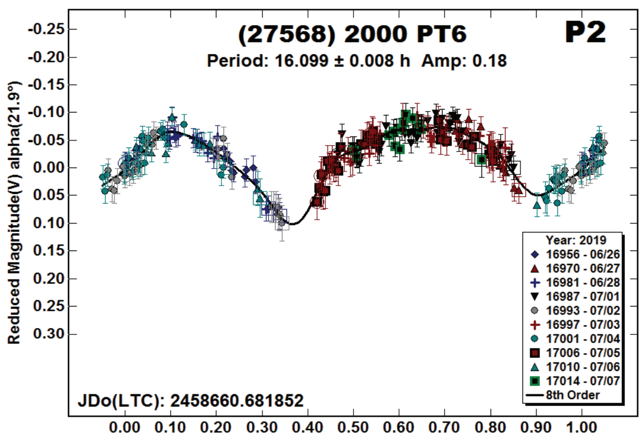




(27568) 2000 PT6. This was the fourth time we observed this Hungaria. Warner (2012a) reported a period of 3.624 h, but this was revised to 3.493 h after the data from observations in 2013 (Warner and Stephens, 2013) led to a period of 3.4885 h. They also reported the possibility of the asteroid being binary, with an orbital period of 16.353 h and estimated *Ds/Dp* of 0.22. Follow-up observations in 2014 (Warner, 2015a) found indications of a satellite but the orbital period was 11.73 h and there was no estimate of the effective diameters ratio.

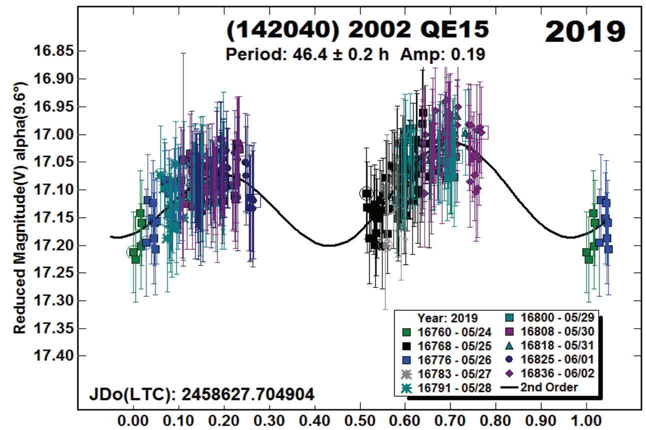
The 2019 data leave little doubt that the asteroid is binary with an the satellite tidally-locked to an orbital period of 16.099 h. The satellite's lightcurve shape indicates an elongated body. We estimate *Ds/Dp* ≥ 0.23 ± 0.04





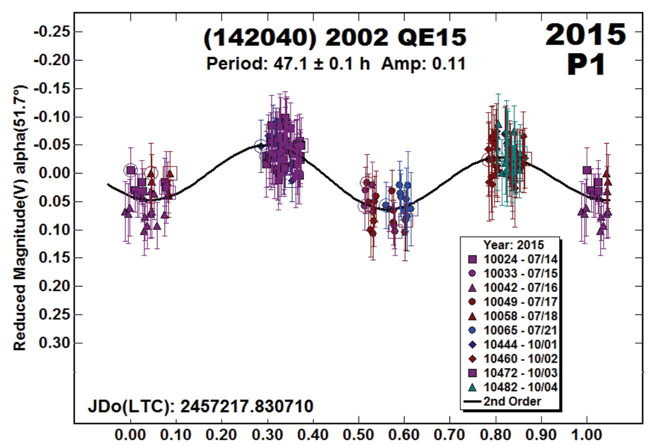
(142040) 2002 QE15. Pravec et al. (2002) observed this NEA in 2002 September-October and reported a period of 2.5811 h. When we observed it in 2015 (Warner, 2016) and 2017 (Warner, 2018), we did not think that our 3.88 h lightcurves were superimposed on a long period lightcurve. Then again, as we found we did in the past, the adjustments of the nightly zero points maybe have removed the traces of a long period.

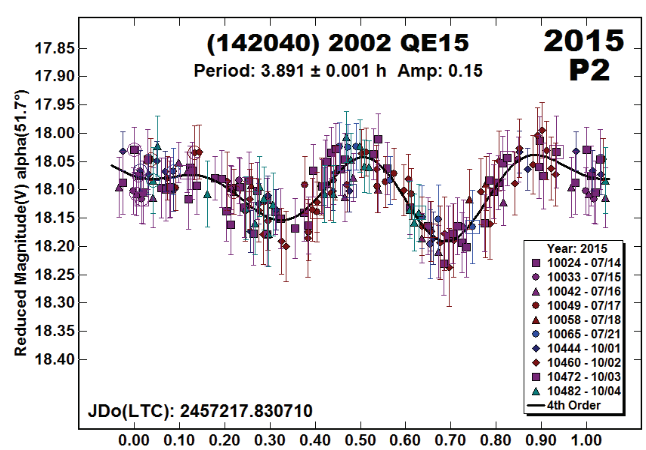
We observed the asteroid again in 2019 May and June. With the ATLAS catalog (Tonry et al., 2018) and the higher confidence in nightly zero points, we found a $P = 46.4$ h. This made it a possible *very wide binary asteroid* (see, e.g., Warner and Stephens, 2019; and references therein). This rare class has about 30 candidates, some with very convincing evidence, that features a primary long primary period (> 24 h to 500+ h) with an underlying short period (usually 2-5 h) with a lightcurve that looks like a typical primary of an "ordinary" binary asteroid.

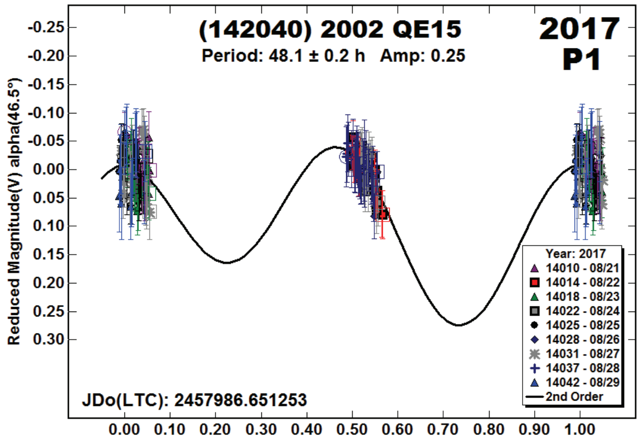


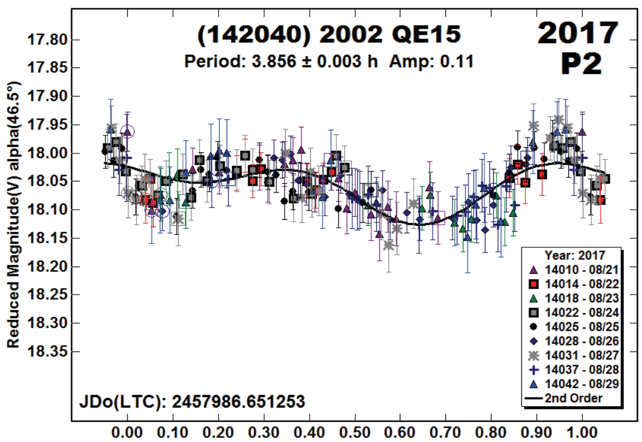
The data set in 2019 was too sparse and noisy to find a secondary period, especially if it had a particularly low amplitude. However, we returned to our previous data sets to see if we might have overlooked something. Part of this was to reset zero points and not change them significantly.

The new analysis of the 2015 data set found a low-amplitude (0.11 mag) lightcurve with a period of 47.1 h, which was in reasonable agreement with the 2019 result. Once that long period was subtracted in a dual-period search, we found a convincing solution of 3.891 h, which is close to what we found in the previous single period result. The 2017 data set provided a convincing case as well with the long-period lightcurve period of 48.1 h and a short period of 3.856 h, in reasonable agreement with the short period from the 2015 reanalysis and single period results.









Acknowledgements

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PHOTOMETRIC OBSERVATIONS FOR 7 MAIN-BELT ASTEROIDS: 2019 FEBRUARY – MAY

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Photometric observations of seven main-belt asteroids were obtained on four nights between 2019 February 13 and May 26. The following rotational periods were determined: 1551 Argelander, 4.066 ± 064 h; 1677 Tycho Brahe, 3.86 ± 0.01 h; 1774 Kulikov, 3.823 ± 0.001 h; 2564 Kayala, 3.01 ± 0.01 h; 26355 Grueber, 4.495 ± 0.028 h; and (47369) 1999 XA88, 2.56 ± 0.09 h. No well-defined period could be derived for 11155 Kinpu.

Photometric observations of asteroids obtained with two of the Southeastern Association for Research in Astronomy (SARA) consortium telescopes are reported. For the nights of 2019 February 13 and March 10, the 1-m Jacobus Kapteyn Telescope at the Observatorio del Roque de los Muchachos on the Spanish island of La Palma was used. The telescope is coupled with an Andor iKon-L series CCD. For the nights of 2019 March 24 and May 26, we used the 0.9-m telescope at Kitt Peak National Observatory. The telescope is coupled with an ARC CCD. A detailed description of the instrumentation and setup can be found in the paper by Keel et al. (2017). The data were calibrated using *MaximDL* and photometric analysis was performed using *MPO Canopus* (Warner, 2017).

1551 Argelander. Our group observed this asteroid previously in 2017 (Fauerbach and Brown, 2018). It was observed again in order to confirm the earlier result and lay the basis for shape modeling of it. Observations were made on a single night for approximately 5 hours.

A rotational period of 4.066 ± 064 h with lightcurve amplitude of 0.50 mag was derived. This is in excellent agreement with two previous measurements based on sparse data (Waszczak et al., 2015; Ďurech at al., 2016), as well as the data from our group from 2017. Baxter et al. (2019) reported a period of 2.313 ± 0.011 h based on data obtained in 2016. Neither our data from 2017 nor the current data can reproduce the result by Baxter et al. (2019).

Number	Name	yyyy mm/dd	Phase	L_{PAB}	B_{PAB}	Period(h)	P.E.	Amp	A.E.	Grp
1551	Argelander	2019 02/13-02/13	16.3	106	1	4.066	0.064	0.50	0.04	MB-I
1677	Tycho Brahe	2019 03/10-03/10	11.7	141	4	3.86	0.01	0.42	0.03	EUN
1774	Kulikov	2019 02/14-03/25	11.5,3.4	176	0	3.823	0.001	0.40	0.02	KOR
2564	Kayala	2019 03/10-03/25	6.4,14.0	158	0	3.01	0.01	0.39	0.02	FLOR
11155	Kinpu	2019 02/14-03/25	12.4,12.1	155	-8			0.16	0.02	EUN
26355	Grueber	2019 02/13-02/13	15.4	109	6	4.495	0.028	0.74	0.06	MB-I
47369	1999 XA88	2019 05/26-05/26	26.2	184.4	8	2.56	0.09	0.28	0.06	V

Table I. Observing circumstances and results. The phase angle is given for the first and last date. If preceded by an asterisk, the phase angle reached an extrema during the period. L_{PAB} and B_{PAB} are the approximate phase angle bisector longitude/latitude at mid-date range (see Harris et al., 1984). Grp is the asteroid family/group (Warner et al., 2009).