ASTEROID LIGHTCURVE ANALYSIS AT CS3-PALMER DIVIDE STATION: 2014 DECEMBER – 2015 MARCH

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Lightcurves for 13 main-belt asteroids were obtained at the Center for Solar System Studies-Palmer Divide Station (CS3-PDS) from 2014 December through 2015 March. All but two were members of the Hungaria orbital group or collisional family and observed as follow-up to previous apparitions to check for undiscovered satellites or to obtain data for spin axis and shape modeling.

CCD photometric observations of 13 main-belt asteroids were made at the Center for Solar System Studies-Palmer Divide Station (CS3-PDS) from 2014 December through 2015 March. Table I lists the telescope/CCD camera combinations used for the observations. All the cameras use CCD chips from the KAF blue-enhanced family and so have essentially the same response. The pixel scales for the combinations range from 1.24-1.60 arcsec/pixel.

Desig	Telescope	Camera
Squirt	0.30-m f/6.3 Schmidt-Cass	ML-1001E
Borealis	0.35-m f/9.1 Schmidt-Cass	FLI-1001E
Eclipticalis	0.35-m f/9.1 Schmidt-Cass	STL-1001E
Australius	0.35-m f/9.1 Schmidt-Cass	STL-1001E
Zephyr	0.50-m f/8.1 R-C	FLI-1001E

Table I. List of CS3-PDS telescope/CCD camera combinations.

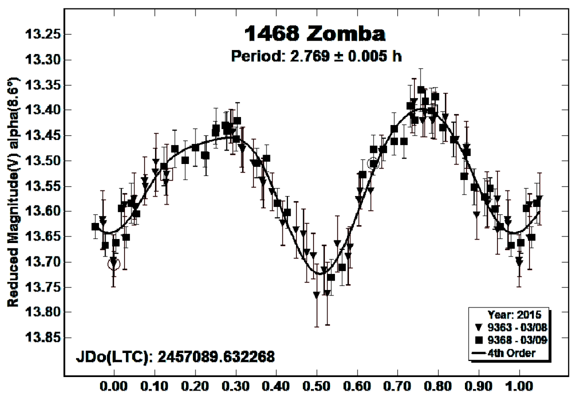
All lightcurve observations were unfiltered since a clear filter can result in a 0.1-0.3 magnitude loss. The exposure duration varied depending on the asteroid's brightness and sky motion. Guiding on a field star sometimes resulted in a trailed image for the asteroid.

Measurements were done using *MPO Canopus*. If necessary, an elliptical aperture with the long axis parallel to the asteroid's path was used. The Comp Star Selector utility in *MPO Canopus* found up to five comparison stars of near solar-color for differential photometry. Catalog magnitudes were usually taken from the MPOSC3 catalog, which is based on the 2MASS catalog (*http://www.ipac.caltech.edu/2mass*) but with magnitudes converted from J-K to BVRI using formulae developed by Warner (2007c). When possible, magnitudes are taken from the APASS catalog (Henden *et al.*, 2009) since these are derived directly from reductions based on Landolt standard fields. Using either catalog, the nightly zero points have been found to be consistent to about ± 0.05 mag or better, but on occasion are as large as 0.1 mag. This consistency is critical to analysis of long period and/or tumbling asteroids. Period analysis is also done using *MPO Canopus*, which implements the FALC algorithm developed by Harris (Harris *et al.*, 1989).

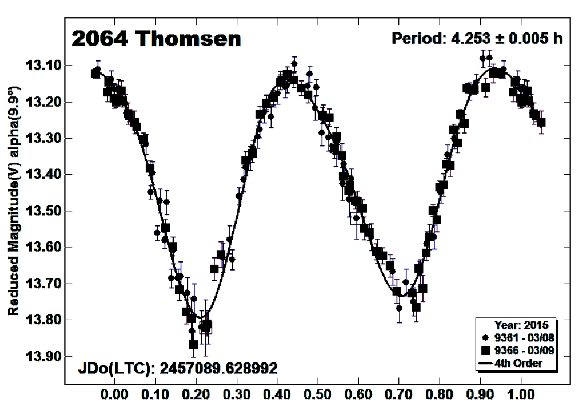
In the plots below, the "Reduced Magnitude" is Johnson V as indicated in the Y-axis title. These are values that have been converted from sky magnitudes to unity distance by applying $-5*\log(r\Delta)$ to the measured sky magnitudes with r and Δ being, respectively, the Sun-asteroid and Earth-asteroid distances in AU. The magnitudes were normalized to the given phase angle, e.g., alpha(6.5°), using $G = 0.15$, unless otherwise stated. The X-axis is the rotational phase ranging from –0.05 to 1.05.

For the sake of brevity, only some of the previously reported results may be referenced in the discussions on specific asteroids. For a more complete listing, the reader is directed to the asteroid lightcurve database (LCDB; Warner *et al.*, 2009). The on-line version at *http://www.minorplanet.info/lightcurvedatabase.html* allows direct queries that can be filtered a number of ways and the results saved to a text file. A set of text files of the main LCDB tables, including the references with bibcodes, is also available for download. Readers are strongly encouraged to obtain, when possible, the original references listed in the LCDB for their work.

1468 Zomba. Wisniewski *et al.* (1987) reported a period of 2.77 h for this Mars-crosser. Later results include Alkema (2014, 2.773 h) and Benishek (2014, 2.772 h). The period found here is within the stated error of those earlier results.

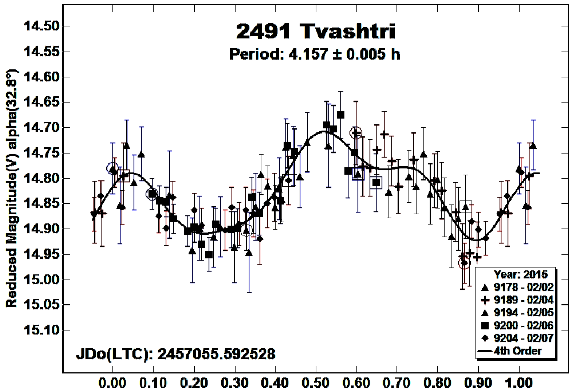


2064 Thomsen. Earlier results for this Mars-crosser include Wisniewski (1991, 4.233 h) and Behrend (2003, 4.2267 h). The amplitude for those lightcurves were also $A > 0.60$ mag, indicating an elongated object with a minimum a/b ratio of ~1.8:1 when assuming a simple triaxial ellipsoid.

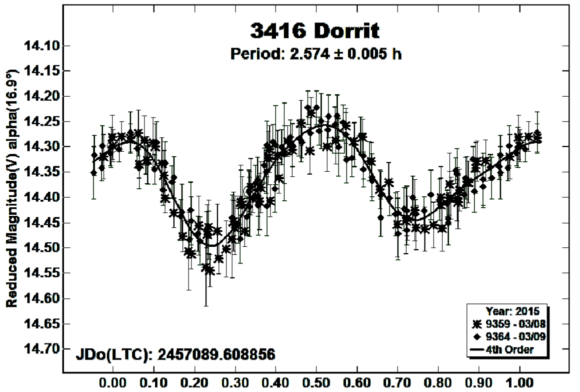


2491 Tvashtri. This Hungaria asteroid has been observed previously by the author: Warner (2008, 4.0839 h; 2013, 4.084 h). Both of those previous results were rated U = 2 in the asteroid lightcurve database (LCDB; Warner *et al*., 2009), meaning that the periods were not certain and could be in error by 30% or the result of a *rotational alias*, i.e., a miscount in the number of rotations over the span of the observations. The uncertainty was made more so by the amplitude at both apparitions being < 0.1 mag.

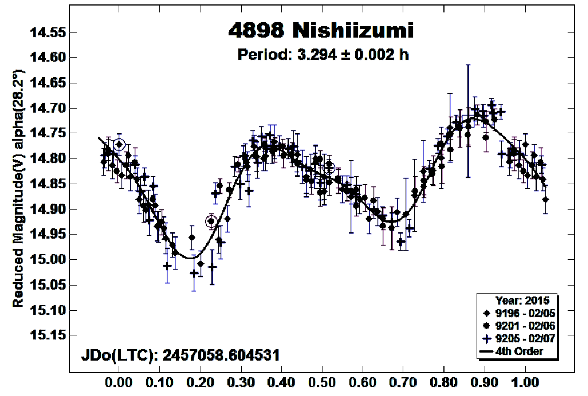
The results from the 2015 observations, even though they covered five nights with four of them consecutive and had an amplitude of 0.24 mag, did not resolve the uncertainty and – in fact – seem to make it worse since the period of 4.157 h is nearly 0.07 h (~2%) longer. Attempts to fit the data from the previous two apparitions to the longer period and those from 2015 to the shorter period were fruitless.



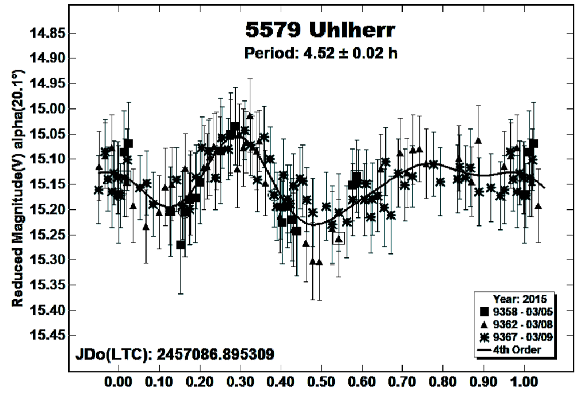
3416 Dorrit. Bennefeld *et al.* (2009) found a period of 2.714 h for this Mars-crosser. Warner (2010) reported 2.574 h, which is the same result found from the data obtained in 2015 March.



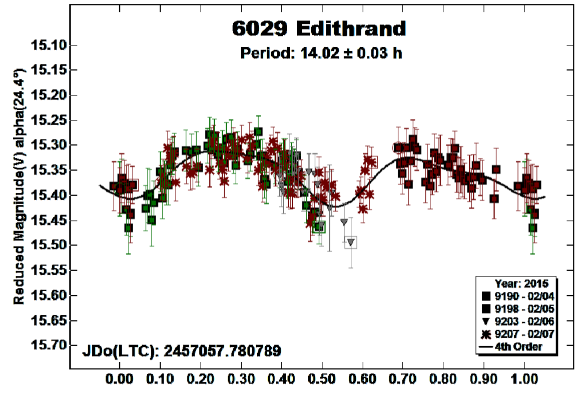
4898 Nishiizumi. The 2015 apparition was the third one at which the author observed this Hungaria asteroid. It appears to be a member of the collisional family based on the high albedo (p_V = 0.9938) reported by the WISE survey (Mainzer *et al.*, 2011; Masiero *et al.*, 2012). As noted in Warner (2012b and references therein), the unexpectedly high albedos reported for the Hungarias initially reported by WISE – far above the average value for type E asteroids of about 0.46 (Warner *et al.*, 2009) – was likely due to poorly-determined values for *H*, the absolute magnitude of the asteroids. Warner (2012b) used his observations to find a revised value of *H* =14.31 (versus *H* = 13.9 used by WISE), which lead to a more likely albedo of p_V = 0.5545. Even with the significant change in the two parameters, the net effect was to reduce the size of the asteroid by only 10%, from about 2.2 km to 2.0 km.



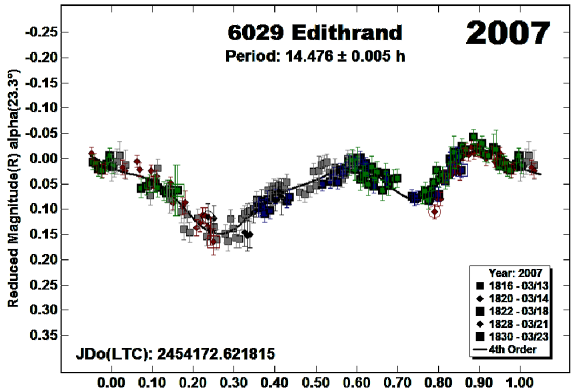
5579 Uhlherr. The previous results by the author (Warner, 2009, 4.754 h, U = 2; 2012, 4.774 h, U = 1) are significantly different from *P* = 4.52 h found from the 2015 observations. At least one more apparition is needed to find a definitive period.



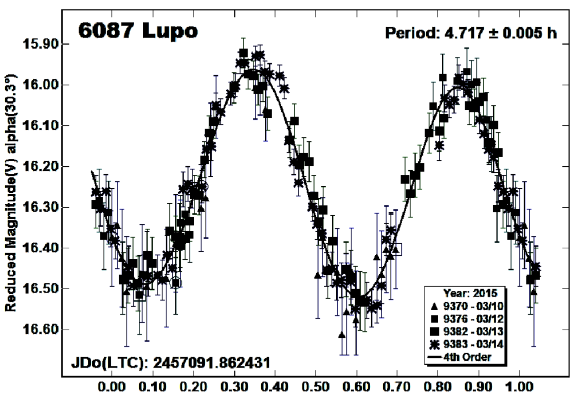
6029 Edithrand. The period of 14.02 h found from the 2015 observations is significantly shorter from earlier results: Warner (2007b, 14.472 h; 2012a, 14.45 h).



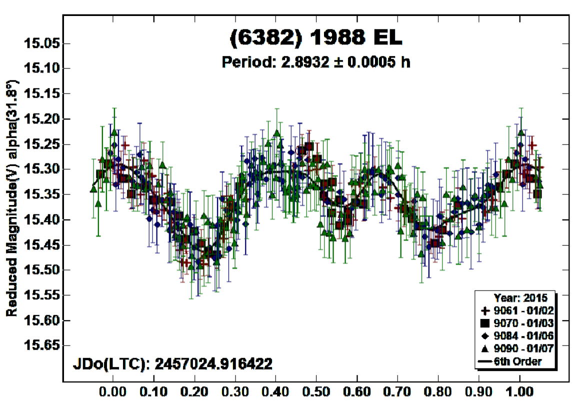
Because of the difference, the data from the earlier apparitions were checked to see if a result closer to the one from 2015 could be found. The data from 2011 were relatively sparse and so were not helpful. The 2007 data set was better and, with some very minor changes to zero points (< 0.02 mag), a slightly different period of 14.476 ± 0.005 h was found with a very strong spike in the period spectrum indicating no possibility of the shorter period fitting the data.



6087 Lupo. The results from the 2015 observations at CS3 for this Hungaria are in good agreement with past results: Warner (2011, 4.712 h; 2012b, 4.717 h).

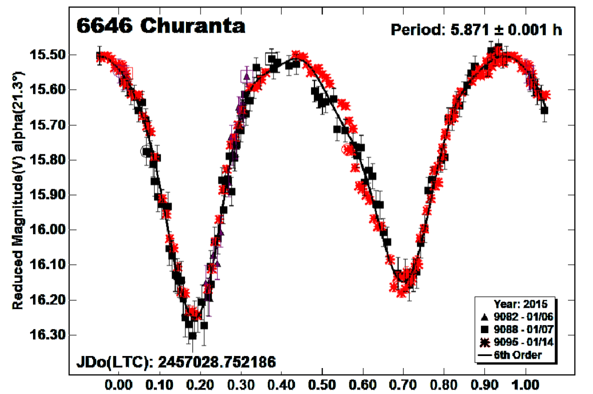


(6382) 1988 EL. The period of 2.8932 h found from 2015 observations matches earlier results from the author, e.g., Warner (2012a, 2.894 h). The amplitude at the four previous apparitions observed by the author was < 0.1 mag.

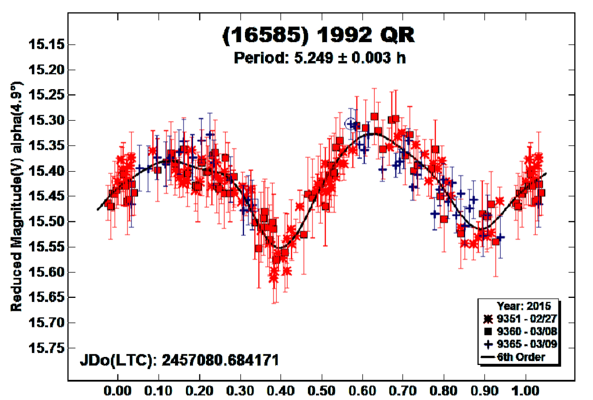


In 2015, the amplitude was 0.15 mag, which was somewhat unexpected because the phase angle bisector longitude and latitude (see Harris *et al.*, 1984) was very similar to two previous apparitions. Observations by Maisero *et al.* (2012) indicate a lower albedo that makes it likely that this asteroid is not a member of the Hungaria collisional family but an interloper in Hungaria orbital space.

6646 Churanta. Previous results include Warner (2007a, 5.8711 h; 2012a, 5.877 h). All three apparitions showed a lightcurve amplitude of $A \sim 0.75$ mag. Masiero *et al.* (2012) found an albedo compatible with a type E object, the same taxonomic type for members of the Hungaria collisional family.



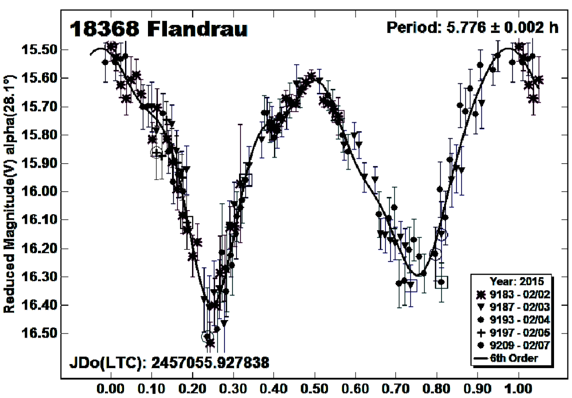
(16585) 1992 QR. The period of 5.249 ± 0.003 h found from 2015 observations is in good agreement with previous results: Warner (2007a, 5.273 h; 2012, 5.255 h). The 2012 observations by the author also found an albedo of $p_V = 0.4970$, which is compatible with a type E asteroid.



Number	Name	2015 mm/dd	Pts	Phase	L_{PAB}	B_{PAB}	Period	P.E.	Amp	A.E.	Group
1468	Zomba	03/08-03/09	98	26.1,26.1	89	5	2.769	0.005	0.33	0.03	MC
2064	Thomsen	03/08-03/09	141	9.9,10.3	144	-3	4.253	0.005	0.69	0.03	MC
2491	Tvashtri	02/02-02/07	97	1.3,2.3	311	-2	4.157	0.005	0.24	0.03	H
3416	Dorrit	03/08-03/09	179	17.0,17.2	142	23	2.574	0.005	0.24	0.02	MC
4898	Nishiizumi	02/05-02/07	152	28.2,28.7	94	24	3.294	0.002	0.28	0.02	H
5579	Uhlherr	03/05-03/09	126	20.1,19.5	184	32	4.52	0.02	0.18	0.03	H
6029	Edithrand	02/02-02/07	302	24.8,23.9	161	26	14.02	0.03	0.11	0.02	H
6087	Lupo	03/10-03/14	162	30.3,29.6	215	24	4.717	0.005	0.56	0.03	H
6382	1988 EL	01/02-01/07	323	31.9,31.0	156	13	2.8932	0.0005	0.15	0.02	H
6646	Churanta	01/06-01/14	234	21.3,17.5	130	17	5.871	0.001	0.75	0.03	H
16585	1992 QR	02/27-03/09	196	4.9,6.6	162	8	5.249	0.003	0.22	0.03	H
18368	Flandrau	02/02-02/07	139	28.1,27.2	170	31	5.776	0.002	0.9	0.03	H
32800	1990 QC19	[11]08/25-09/20	487	21.7,18.6,19.0	356	25	3.709	0.001	0.15	0.02	H
32800	1990 QC19	02/05-02/07	109	19.0,20.0	109	4	3.726[A]	0.006	0.14	0.02	H

Table II. Observing circumstances. [11] Observations in 2011. [A] preferred period of an ambiguous solution. The phase angle (α) is given at the start and end of each date range, unless it reached a minimum, which is then the second of three values. If a single value is given, the phase angle did not change significantly and the average value is given. L_{PAB} and B_{PAB} are each the average phase angle bisector longitude and latitude, unless two values are given (first/last date in range). The Group column gives the orbital group to which the asteroid belongs. The definitions and values are those used in the LCDB (Warner *et al.*, 2009). H = Hungaria; MC = Mars-crosser.

18368 Flandrau. Warner (2012b) found a period of 5.777 h based on observations in 2012 January. The 2015 result is essentially identical in both period and amplitude. Given this and the fact that the phase angle bisector longitudes for the two apparitions differ by 82°, this would indicate a spin axis with a low obliquity, i.e., a pole near one of the ecliptic poles. The albedo from Masiero *et al.* (2012) favors this being a type E object.

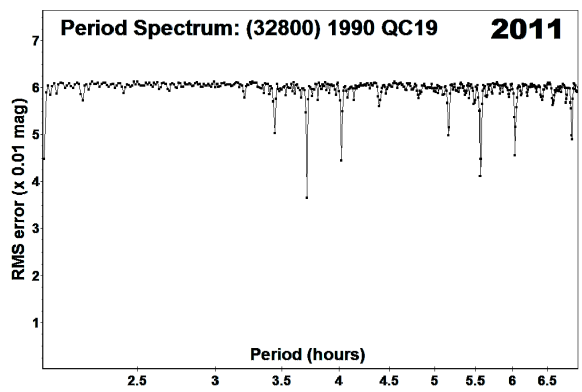


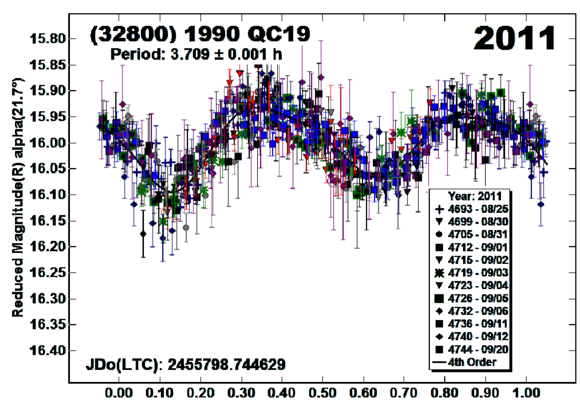
(32800) 1990 QC19. Masiero *et al.* (2012) found an albedo of 0.24 for 1990 QC19. This makes it more likely an interloper in Hungaria orbital space rather than a member of the Hungaria collisional family.

The asteroid was first observed by the author in 2011 (Warner, unpublished). At that time, one session showed what appeared to be an attenuation, possibly due to a satellite. Observations were requested from other locations. Data provided by Adrian Galad (private communications) seemed to show a second attenuation. Analysis by Petr Pravec (private communications) found several possible solutions for an orbital period, one being about 53 h. Follow-up observations in 2011 by Warner did not find any further evidence for the satellite.

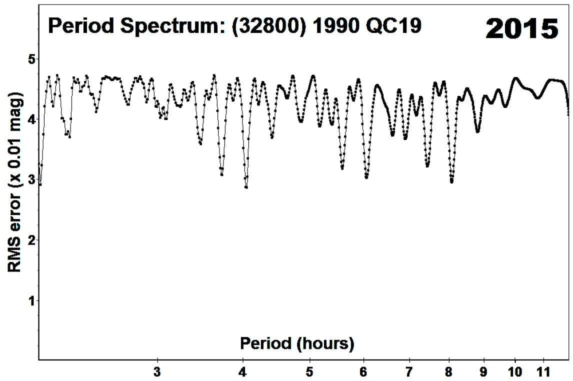
The original 2011 data from Warner alone were re-examined, where it was found that a minor shift of the zero point by 0.02 mag for the one night in question caused the attenuation to disappear into the noise, thus making it highly questionable. At this point, the likelihood of 1990 QC19 being a binary is very small, but enough so to encourage observations at future apparitions.

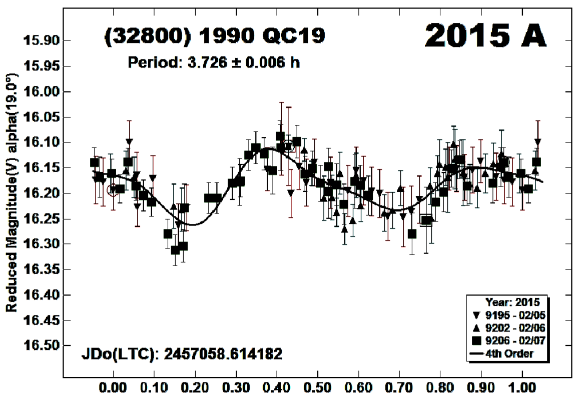
Looking at the 2011 data from the perspective of a single object, the period spectrum shows a very sharp minimum at 3.709 h. There is a "sideband" period at about 4.0 h, which represents a one-half rotation difference over a 24 hour period. The asymmetry of the lightcurve precludes the longer period, i.e., there was no miscount of the number of rotations over the span of the data set, sometimes called a *rotational alias*.

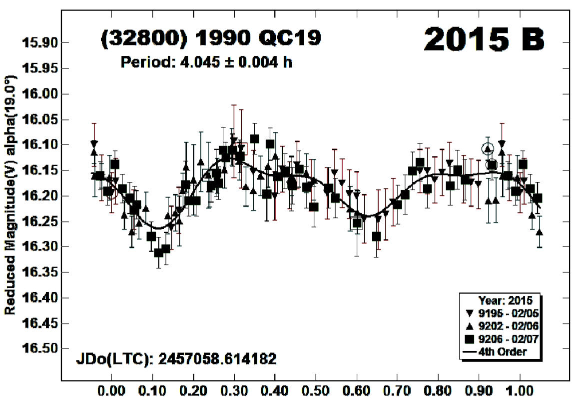




The data set for 2015 was much less extensive than in 2011. As a result, the period spectrum is not as definitive and, in fact, favors the 4-hour period over the shorter one from 2011. The plots show the 2015 data plotted to the two likely periods. All things considered, the period of 3.709 h found from 2011 is adopted for this paper.







Acknowledgements

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LIGHTCURVE ANALYSIS OF NEA (361071) 2006 AO4

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CCD photometric observations of Amor-type asteroid (361071) 2006 AO4 were made on 2013 September 23. From the lightcurve we obtained a synodic period of 4.09 ± 0.17 h with an amplitude of 0.13 mag.

Remote Observatory Theoretical Astrophysics Tübingen (ROTAT) is a 60-cm remotely operated telescope located on the Observatoire de Haute-Provence (OHP) site at Haute-Provence, France, about 100 km north-east of Marseille. ROTAT was formerly located and operated in Tübing by the Dept. for Theoretical Astrophysics, University of Tübingen.

Image acquisition was made with an SBIG STL-1100M CCD camera attached to the *f*/3.2 Newtonian focus of the ROTAT telescope, resulting in a pixel scale of 1.94 arcsec/pixel with 2x2 binning. No filters were used. All images were measured using *Astrometrica*, *i.e.* PSF-based all-sky photometry. Dark and flat images were applied.

Magnitudes were reduced to unity distance and times were corrected for light-time. The observations show a fair amount of scatter. Hence the period search was done with two different methods. First, a period scan using the Phase Dispersion Minimization algorithm (PDM; Stellingwerf, 1978) was done. Second, the period was determined by performing fourth-order Fourier fits to a range of possible periods. Both approaches showed a most likely period around 4 h.

The final period P = 4.09 ± 0.17 h with an amplitude A = 0.13 mag was obtained from a fourth-order Fourier fit, similar to the FALC method developed by Harris (Harris *et al.*, 1989). The computations were done with a Python/SciPy script developed by the authors. The PDM algorithm is provided by the Python PyAstronomy package (*https://github.com/sczesla/ PyAstronomy*). Our results are consistent with those of Warner (2014) who reported another lightcurve, observed in 2013 August, from which he obtained a period P = 4.093 ± 0.001 h.

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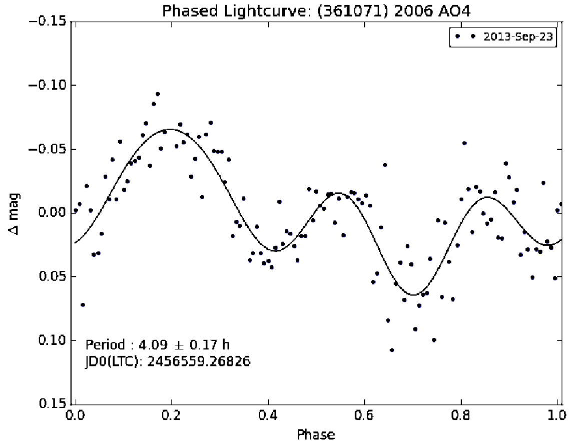

NEAR-EARTH ASTEROID LIGHTCURVE ANALYSIS AT CS3-PALMER DIVIDE STATION: 2015 JANUARY – MARCH

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Lightcurves for 35 near-Earth asteroids (NEAs) were obtained at the Center for Solar System Studies-Palmer Divide Station (CS3-PDS) from 2014 December through 2015 March. One object, (159454) 2000 DJ8, may be a highly bifurcated body, or a close binary.

CCD photometric observations of 35 near-Earth asteroids (NEAs) were made at the Center for Solar System Studies-Palmer Divide