LIGHTCURVE ANALYSIS OF HILDA ASTEROIDS AT THE CENTER FOR SOLAR SYSTEM STUDIES: 2016 SEPTMEBER-DECEMBER

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Lightcurves for 19 Hilda asteroids were obtained at the Center for Solar System Studies (CS3) from 2016 August through December.

CCD photometric observations of 19 Hilda asteroids were made at the Center for Solar System Studies (CS3) from 2016 September through December. This is another in a planned series of papers on this group of asteroids, which is located between the outer main-belt and Jupiter Trojans in a 3:2 orbital resonance with Jupiter. The goal is to determine the spin rate statistics of the group and find pole and shape models when possible. We also look to examine the degree of influence that the YORP effect (Rubincam, 2000) has on distant objects and to compare the spin rate distribution against the Jupiter Trojans, which can provide evidence that the Hildas are more "comet-like" than main-belt asteroids.

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.

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.

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. Catalog magnitudes were usually taken from the CMC-15 (*http://svo2.cab.inta-csic.es/vocats/cmc15/)* or APASS (Henden *et al.*, 2009) catalogs. The MPOSC3 catalog was used as a last resort. The last catalog is based on the 2MASS catalog (*http://www.ipac.caltech.edu/2mass*) with magnitudes converted from J-K to BVRI (Warner, 2007). The nightly zero points for the catalogs are generally consistent to about ±0.05 mag or better, but on occasion reach 0.1 mag and more. There is a systematic offset among the catalogs so, whenever possible, the same catalog is used throughout the observations for a given asteroid. Period analysis is also done with *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 (rΔ) 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.

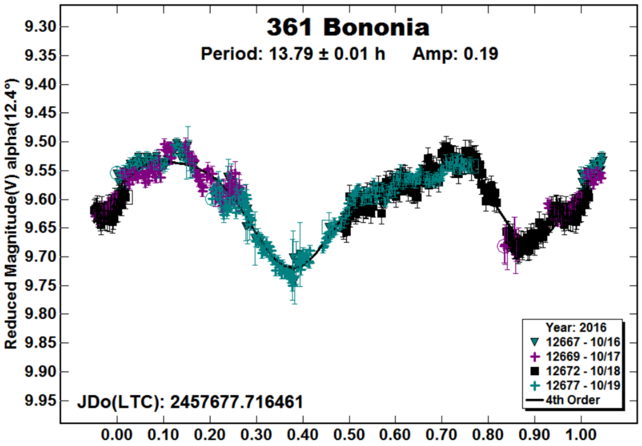
If the plot includes an amplitude, *e.g.*, "Amp: 0.65", this is the amplitude of the Fourier model curve and *not necessarily the adopted amplitude for the lightcurve*.

Number	Name	2016 mm/dd	Pts	Phase	L_{PAB}	B_{PAB}	Period	P.E.	Amp	A.E.	Obs
361	Bononia	10/16-10/19	677	12.5,11.8	60	9	13.79	0.01	0.19	0.01	BDW
958	Asplinda	12/17-12/20	216	6.6,7.5	68	7	17.55	0.03	0.18	0.01	BDW
1439	Vogtia	10/07-10/12	287	3.7,4.9	0	-3	12.898	0.006	0.33	0.02	BDW
1529	Oterma	08/31-09/11	271	18.3,17.7	53	-8	8.956	0.002	0.12	0.01	DRC
2246	Bowell	10/20-10/22	227	3.2,3.6	16	-5	4.993	0.003	0.20	0.02	BDW
2483	Guinevere	10/07-10/11	356	1.7,2.4	14	5	14.730	0.002	0.89	0.02	BDW
3415	Danby	12/03-12/10	245	12.3,10.7	115	-1	2.837	0.001	0.11	0.01	BDW
3923	Radzievskij	09/02-09/24	304	18.4,16.7	56	-4	39.93	0.02	0.95	0.03	DRC
5368	Vitagliano	09/29-10/09	551	3.7,1.5	19	-4	59.36	0.05	0.29	0.03	RDS
5653	Camarillo	12/08-12/10	229	15.6,16.8	69	13	4.835	0.001	0.43	0.02	BDW
15505	1999 RF56	10/20-11/02	481	1.2,4.1	24	4	15.11	0.02	0.10	0.02	RDS
16927	1998 FX68	07/05-07/30	781	15.5,11.6	33	+11	33.856	0.003	0.73	0.04	DRC
19034	Santorini	12/02-12/25	576	1.1,9.3	68	1	247	2	0.43	0.05	BDW
26761	Stromboli	10/04-10/11	364	0.9,0.6,1.6	13	2	15.96	0.03	0.12	0.02	RDS
31817	1999 RK134	10/14-10/20	285	4.8,3.2	36	6	9.856	0.005	0.21	0.02	BDW
56982	2000 SE189	11/06-11/11	286	4.1,3.7	49	10	43.2	0.1	0.47	0.03	BDW
62408	2000 SU176	11/23-11/25	174	3.6,4.0	57	9	3.197	0.002	0.17	0.02	BDW
87811	2000 SO145	11/04-11/11	327	2.7,5.0	36	-4	55.2	0.2	0.45	0.05	BDW
193449	2000 WW146	11/03-11/10	478	8.2,6.4	54	-13	38.44	0.06	0.20	0.03	RDS

Table II. Observing circumstances. 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 (see Harris *et al.*, 1984), unless two values are given (first/last date in range). The Obs column gives the observer.

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.

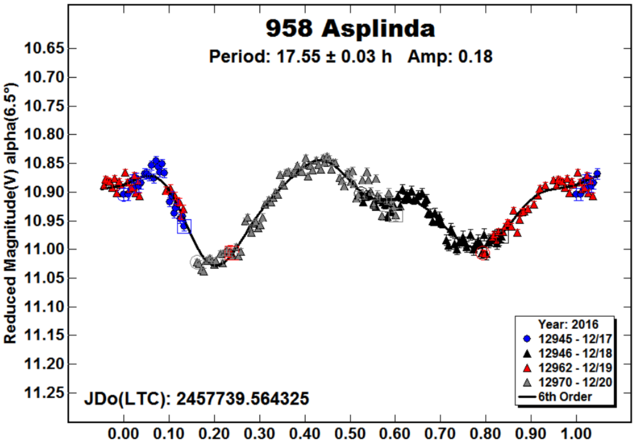
361 Bononia. The first reported period for the 140 km Bononia came from Binzel and Sauter (1992), who found 13.83 h. Hanus *et al.* (2015), using a combination of dense-in-time and sparse-in-time data, found a sidereal period of 13.80634 h and two possible pole positions with ecliptic longitude-latitudes of (294°, +13°) and (115°, +45°). Our period of 13.79 h is in good agreement with the earlier results.



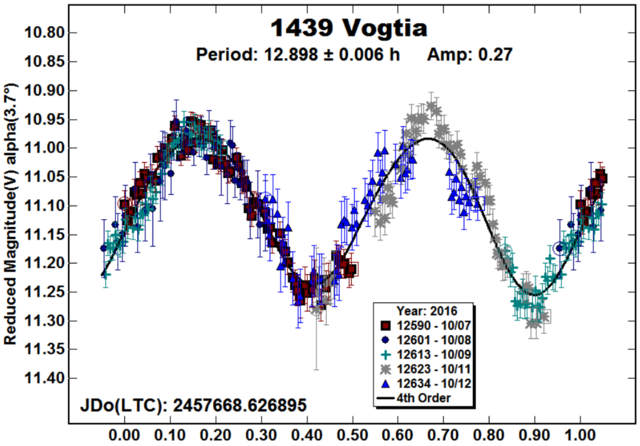
958 Asplinda. Dahlgren *et al.* (1998) found a period of 25.3 h based on two consecutive nights in 1994 February. However, their phased lightcurve, which was based on an assumed bimodal shape that covered about 0.6 rotation phase, went from a minimum to a maximum in only 0.15 rotation phase.

Given the amplitude of about 0.6 mag, it is a reasonable assumption that the lightcurve would be fairly symmetrical and so not have significantly different halves and, therefore, the time from one extreme to the next would be about 0.25x the period. A shorter period would come closer to meeting the requirement.

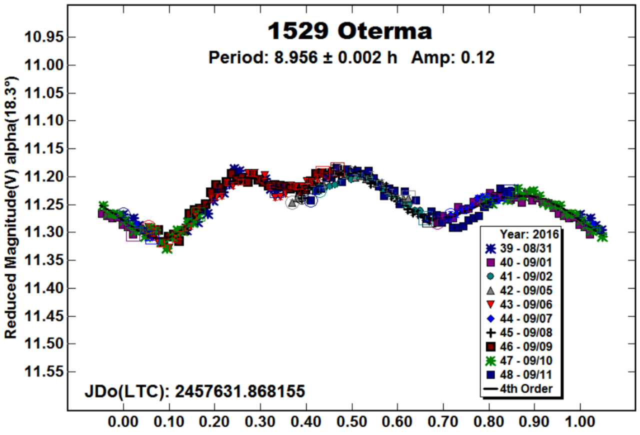
The CS3 data obtained in 2016 led to a period of 17.55 h, which we consider secure. From this, we surmise that Dahlgren *et al.* may have presumed that the two nights represented the same half of the bimodal lightcurve instead of each night being part of an opposing half.



1439 Vogtia. Dahlgren *et al.* (1998) found a period of 12.95 h using two data sets, one from 1993 December and the other from 1994 December. The latter provided coverage of most of the presumed period and so their result seems reasonably secure. The analysis of our 2016 observations supports the 12.9 h period.



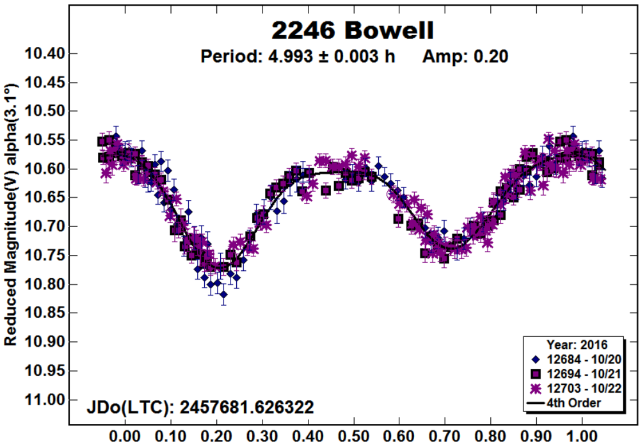
1529 Oterma.



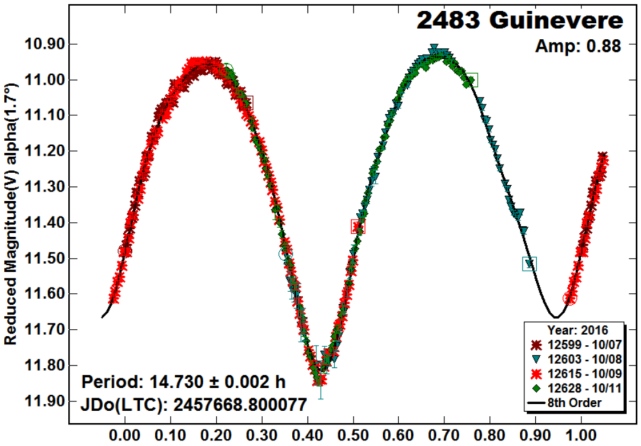
Dahlgren *et al.* (1998) found a period of 15.75 h based on four nights in 1994 January-February. If the session from Jan 24.9 is removed, the resulting lightcurve is nearly symmetrical, raising the possibility that their period is the result of a *rotational alias*, *i.e.*, where the actual number of rotations over the span of the observations is not certain.

The 2016 CS3 data led to a lightcurve that was not symmetrical, which helped avoid finding a period based on an inaccurate count of rotations. Our data set was also much more extensive, covering 10 days with 7 of those being consecutive. We consider the resulting period of 8.956 h to be secure and adopt it as the more likely rotation period for the 54 km asteroid.

2246 Bowell. Our result of 4.993 h is in good agreement with the period of 4.992 h found by Dahlgren *et al.* (1998). The asteroid was not only discovered by but is named for Edward ("Ted") Bowell, who was on the staff at Lowell Observatory for many years. He is an expert in several areas of asteroid research, celestial mechanics and astrometry being among them. He is a strong supporter of amateur astronomers wanting to do high-level research. We take this opportunity to say "Thanks, Ted" for all your support and contributions.

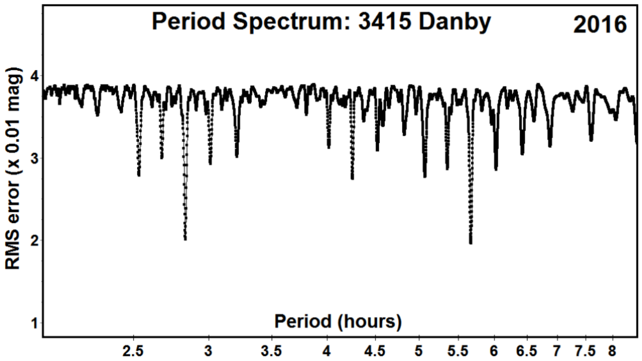


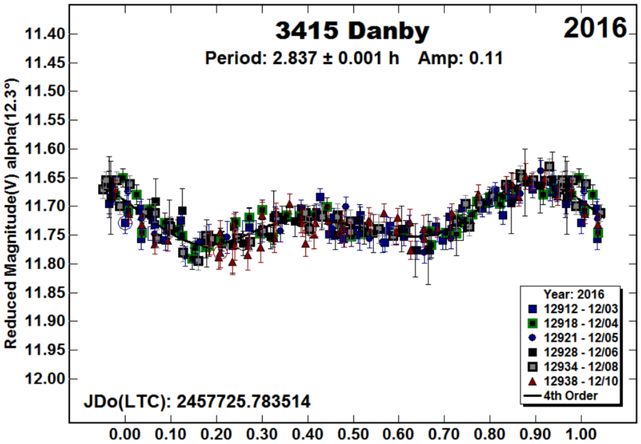
2483 Guinevere. Dahlgren *et al.* (1998) found a period of 14.733 h for Guinevere. Durech *et al.* (2016) reported a similar sidereal period along with a pole with ecliptic longitude-latitude coordinates of either (19°, +70°) or (194°, +59°). Our period of 14.730 h is in good agreement with the earlier results.

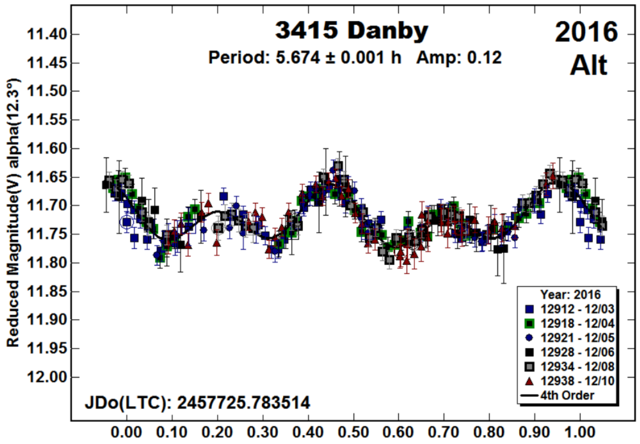


3415 Danby. The namesake for asteroid 3415 is John Michael Anthony Danby (1929-2009) who published a classic textbook on Celestial Mechanics (Danby 1962) that is still in print. Danby also helped found the journal *Celestial Mechanics* and the Division for Dynamical Astronomy of the American Astronomical Society. For the estimated 32 km asteroid 3415 Danby, Dahlgren *et al.* (1998) found a period of 2.851 h. However, subsequent results were all near the double period (5.6 h) and were quadramodal (four minimum-maximum pairs per rotation), *e.g.*, Warner and Higgins (2008; 5.666 h) and Behrend (2007web, 2015web; 5.6706 h). In all cases, the amplitude of the lightcurve was < 0.20 mag. This is about the upper limit of where harmonics from higher orders can have nearly the same amplitude as the usually dominant second order (Harris *et al.* 2014) and so calls into question whether or not the true solution is a bimodal or quadramodal lightcurve.

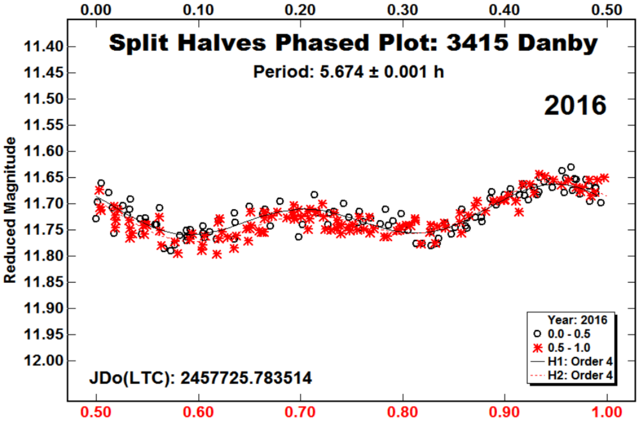
The period spectrum based on the 2016 CS3 shows two dominant solutions of nearly equal strength. The one with the shorter period is represented by a bimodal lightcurve while the other requires a quadramodal lightcurve. Both lightcurves are shown below.



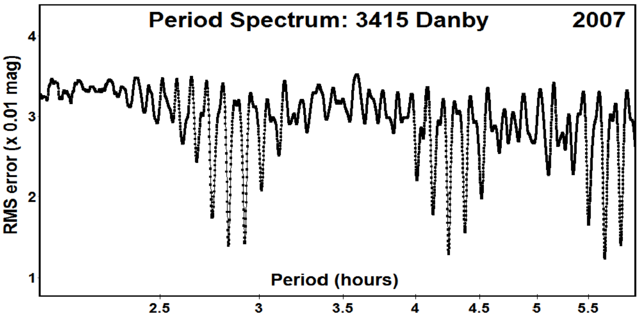


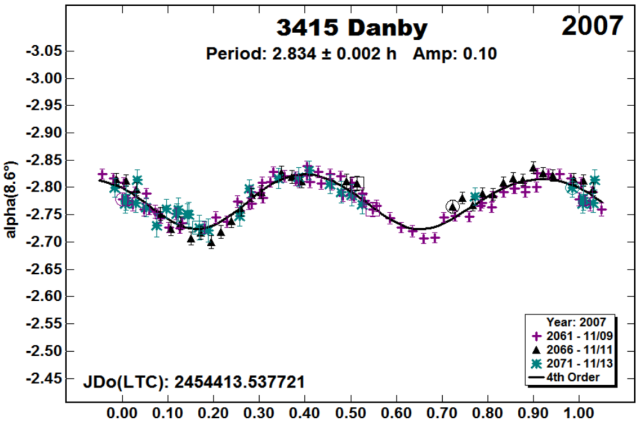


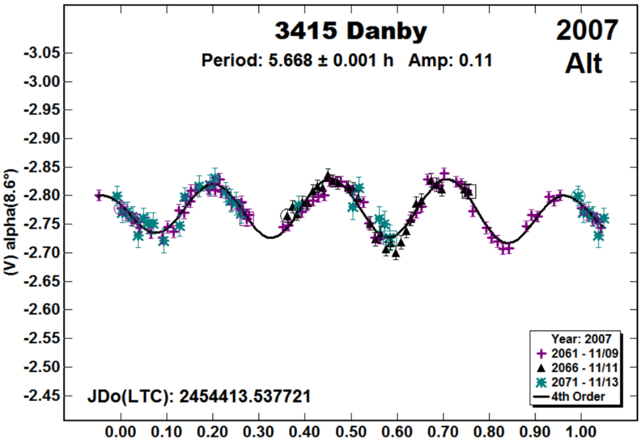
Since either solution fits the data equally well, the assumption of a bimodal lightcurve is not unequivocal. So, it would seem difficult, if not impossible, to adopt one period over the other. However, there is a technique that can be used to help resolve the ambiguity. The process is to produce a so-called *split-halves* plot where the longer period is assumed but the two halves are superimposed over one another to judge the degree of symmetry in the lightcurve. Harris *et al.* (2014) used this technique with success to determine that an extraordinary asteroid with an unusually fast period was just an ordinary one once it was shown that the double-period was the correct solution. We used this technique on the 2016 data and found that the two halves were too symmetrical and so adopted the shorter period of 2.837 h, similar to what Dahlgren *et al.* found.



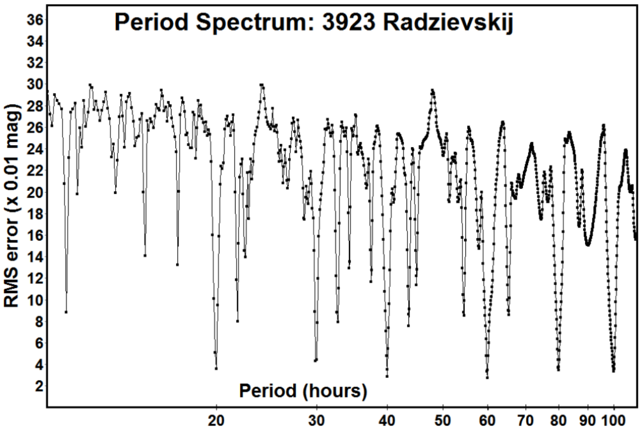
These results prompted another look at the data obtained by Warner and Higgins (2008). The period spectrum again showed a number of nearly equal solutions, each being about double the previous one. We forced the 2007 data to find periods of about 2.8 and 5.6 hours. It seems clear to us that the shorter period is the better choice since the quadramodal lightcurve appears to be a *fit by exclusion*, which is where the Fourier analysis finds the lowest RMS by minimizing the number of overlapping data points.

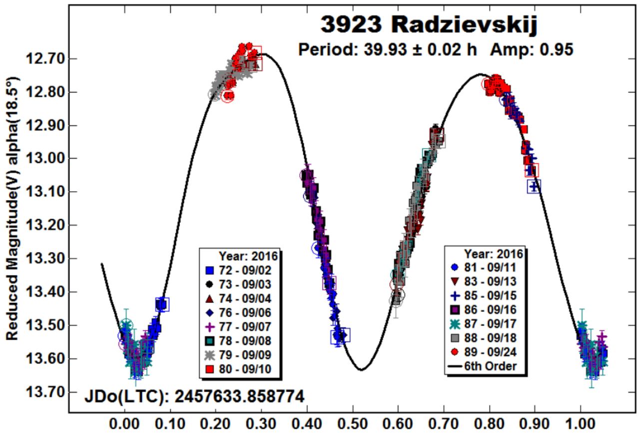






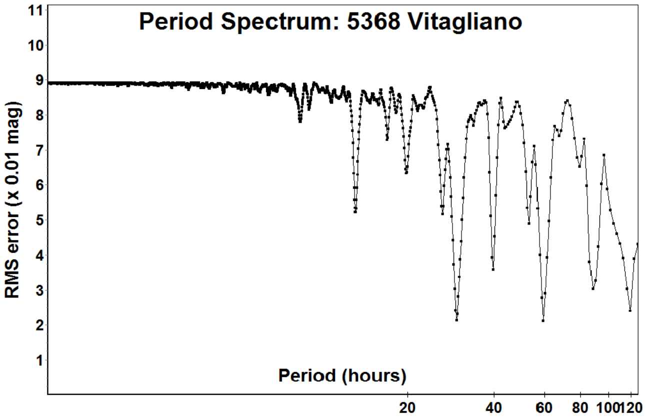
3923 Radzievskij. Dahlgren *et al.* (1998) found a period of 39 h based on two consecutive nights in 1994 February. They based their "probable" solution assuming the two nights were opposing halves for a bimodal lightcurve. Our data set leads to the same result using the same presumption of a bimodal lightcurve, though we consider it more secure given the several overlapping sessions.

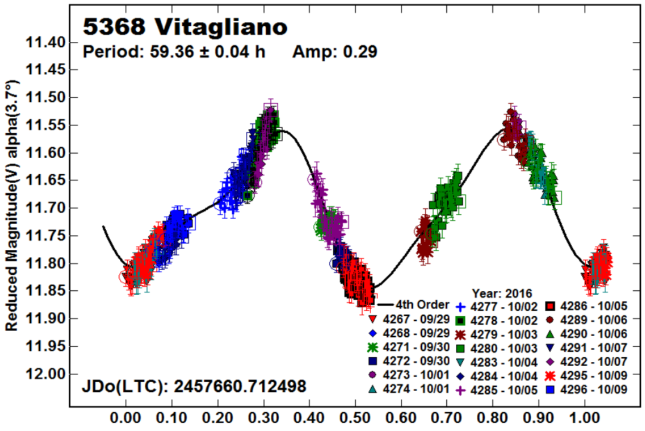




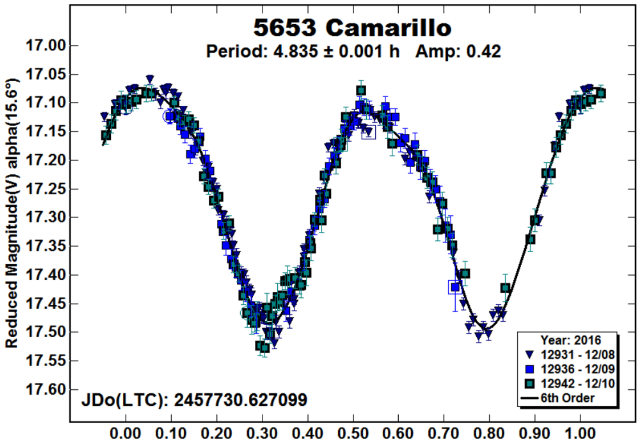
5368 Vitagliano. Dahlgren *et al.* (1998) found a bimodal lightcurve with period of 31 h based on four consecutive nights in 1995 February. That lightcurve seems sufficiently asymmetrical to accept the result. However, there is almost no overlap of data, which leads to the speculation that the result might be another case of a *fit by exclusion* or a *rotational alias*.

The period spectrum based on the 2016 CS3 data shows valid solutions for 30 and 60 h. We have chosen the latter because the much more extensive data set results in a bimodal lightcurve and there are a number of overlapping sessions that remove most of the *rotational alias* concerns.

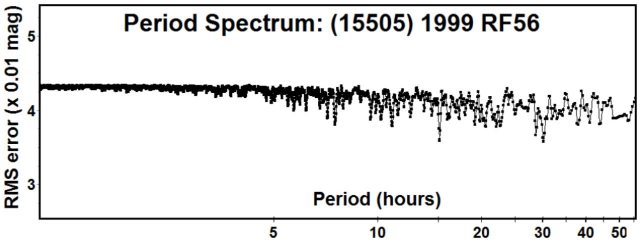


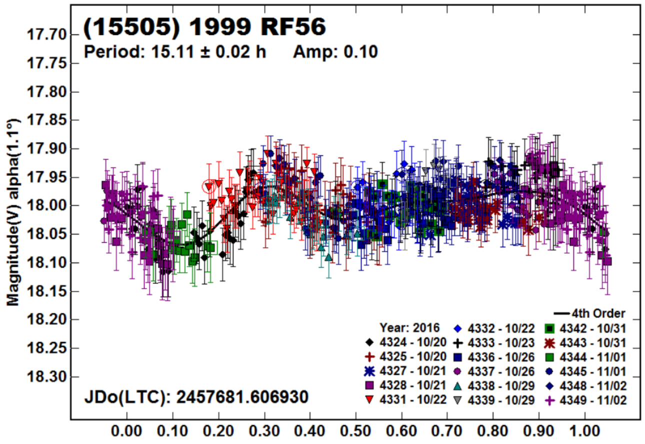


5653 Camarillo. Previously reported periods were all near 4.83 h, *e.g.*, Mottola *et al*. 1995, Pravec *et al.* (1999 web), and Wazczak *et al*. (2015). Our period of 4.835 h concurs with those earlier results.



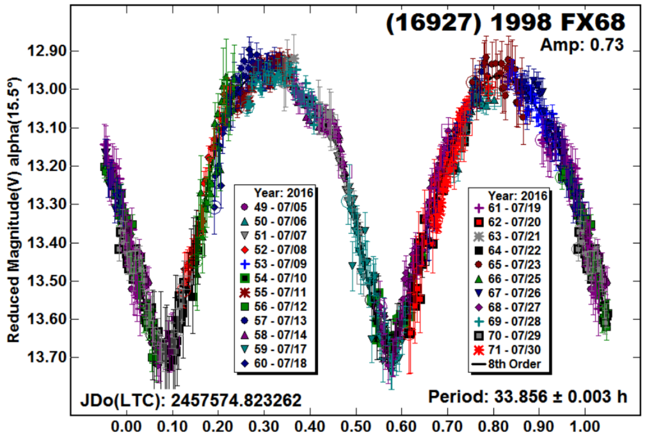
(15505) 1999 RF56. We found no entry in the asteroid lightcurve database (LCDB; Warner *et al.* 2009) for this 28 km Hilda. Analysis of observations on 9 nights spanning about 14 days resulted in an asymmetric, low-amplitude lightcurve with a period of 15.11 h. The fits to periods half and double our adopted result were not convincing.





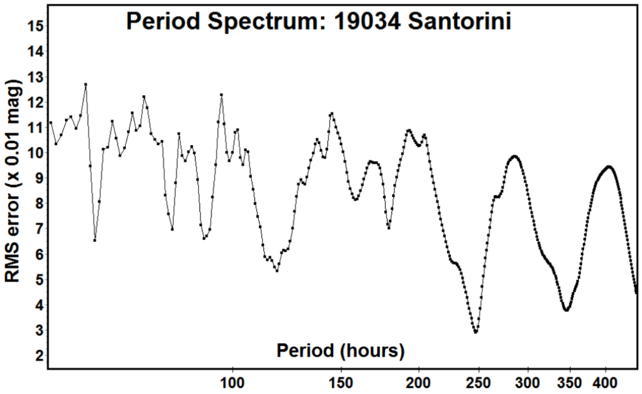
(16927) 1998 FX68. The LCDB (Warner *et al.* 2009) did not have any reported periods, though it does include an entry from Sonnett *et al*. (2015), who reported a lightcurve amplitude of 0.92 mag based on infrared observations.

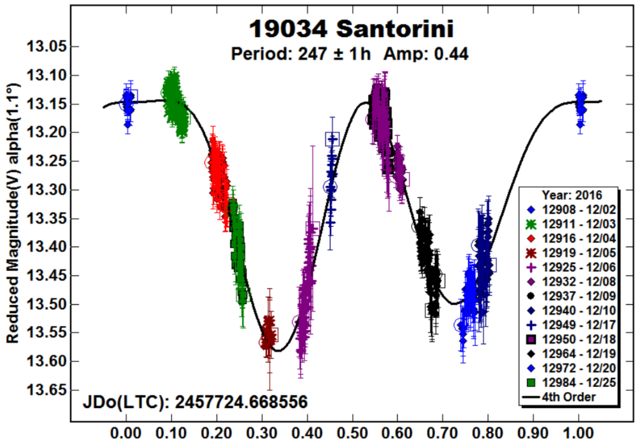
The large amplitude and relatively low phase angle at which our observations were made virtually assure a bimodal lightcurve (Harris *et al*., 2014). This leads to what we consider a secure period of 33.856 h.



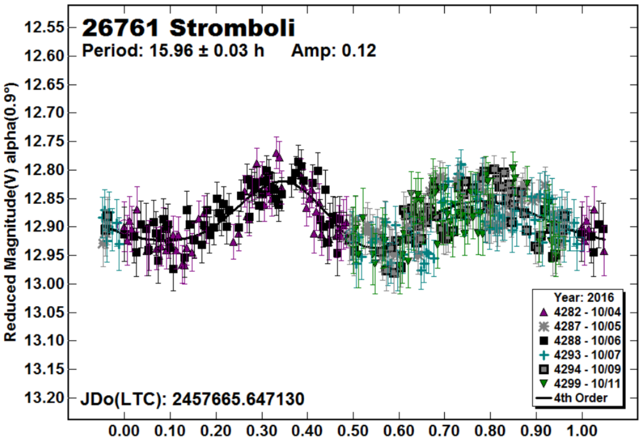
19034 Santorini. These appear to be the first reported results for Santorini, which has an estimated diameter of 15 km. Assuming the period of 247 h is correct, the asteroid is a good candidate for *tumbling* (non-principal axis rotation: NPAR; see Pravec *et al.* 2014 and references therein).

There are no outward signs of tumbling, such as the slope of the data from a given session not matching the slope of the model lightcurve. However, the data set is somewhat limited and there is almost no coverage of a second cycle to confirm if the lightcurve repeats itself. Any tumbling is probably at a low-level and so hidden within the noise and uncertainties of the night-to-night zero point calibrations.

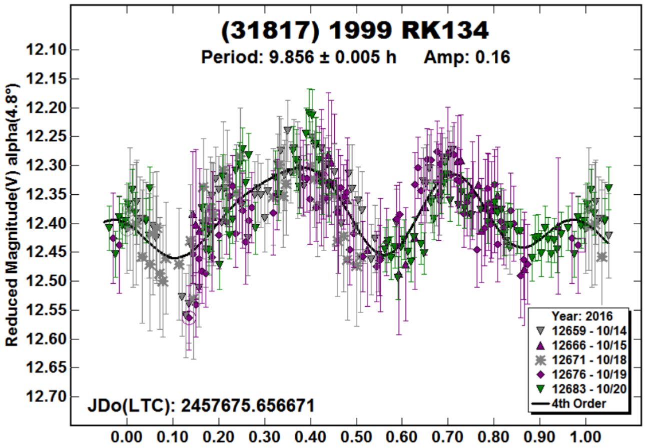




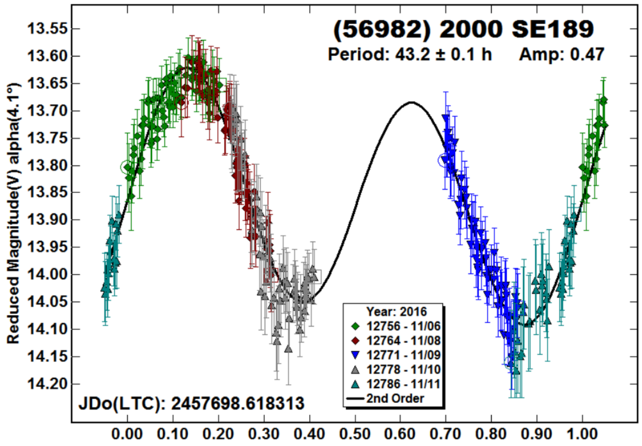
26761 Stromboli. There is no previously reported rotational period for this Hilda in the asteroid lightcurve database (LCDB; Warner *et al.*, 2009). Observations on five nights spanning a week show a classic bimodal lightcurve with at 15.96 h rotational period.



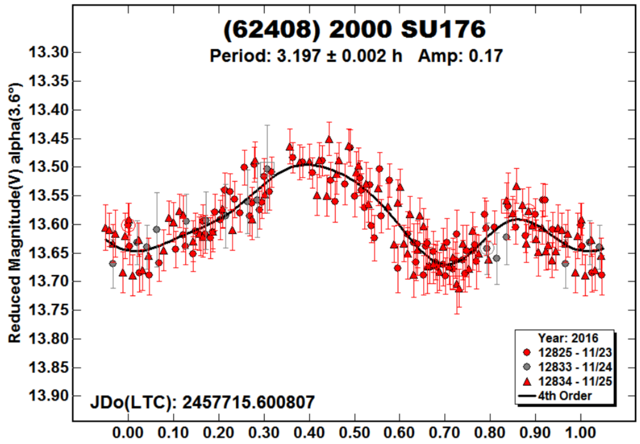
(31817) 1999 RK134. Waszczak *et al.* (2015) used limited dense-in-time data from the Palomar Transient Factory to find a period of 9.429 h for this 23 km Hilda. Our data were somewhat noisy, but they still led to a reasonably secure result of 9.856 h. Given our denser data set, we have adopted our period as being the more likely solution.



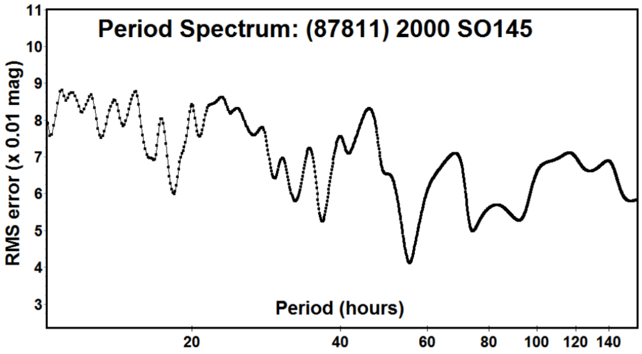
(56982) 2000 SE189. Despite the lack of complete coverage of the bimodal lightcurve at 43.2 h, we believe this to be a fairly secure result since both minimums and one maximum were covered and there is duplicate coverage for rotation phases 0.0-0.3. This is another case where a bimodal solution is virtually assured due the amplitude and phase angle (Harris *et al.*, 2014). There were no previous entries in the LCDB (Warner *et al.*, 2009).

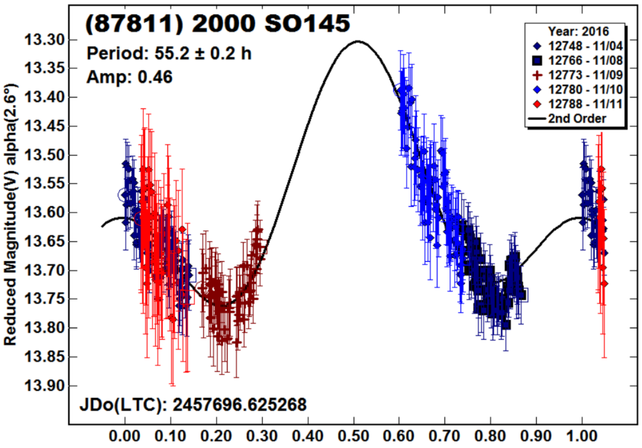


(62408) 2000 SU176. The apparently first-time result of 3.197 h is considered secure due to data from each of three consecutive nights covering more than one cycle of the adopted period.

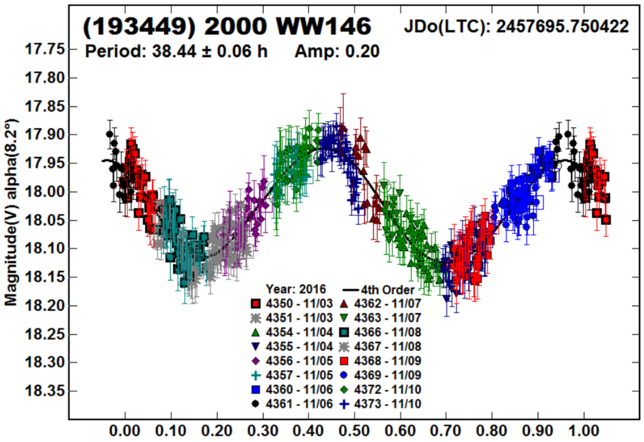


(87811) 2000 SO145. Despite the strong preference in the period spectrum for a period near 55 h, the large gaps in the lightcurve and uncertainty about the maximums do not lead to a secure solution. However, it is sufficiently likely to be used in rotation rate studies.





(193449) 2000 WW146. This Hilda was not in the asteroid lightcurve database (LCDB; Warner *et al.*, 2009) and no results could be found in a search of the literature or web sites. We consider the period of 38.44 h to be secure.



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ROTATION PERIOD DETERMINATION FOR 3077 HENDERSON AND 12044 FABBRI

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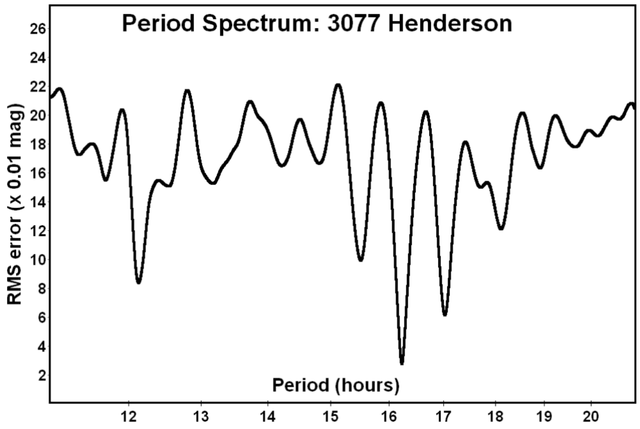
Photometric observations of two main-belt asteroids were made from the Astronomical Observatory of the University of Siena (Italy) in order to determine their rotation periods. For 3077 Henderson, the synodic rotation period was found to be 16.235 ± 0.003 h with a lightcurve amplitude of 0.67 mag. For 12044 Fabbri, the synodic rotation is 4.422 ± 0.001 h with a lightcurve amplitude of 0.14 mag.

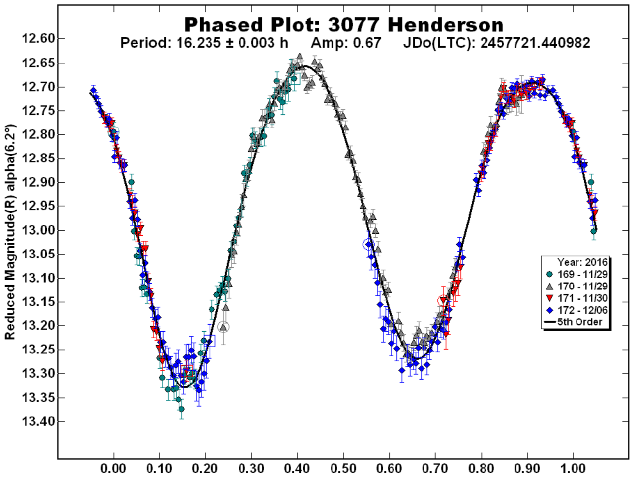
CCD photometric observations of two main-belt asteroids were carried out in 2016 November-December at the Astronomical Observatory of the University of Siena (K54) using a 0.30-m *f*/5.6 Maksutov-Cassegrain telescope, SBIG STL-6303E CCD camera, and clear filter; the pixel scale was 2.30 arcsec with 2x2 binning. All exposures were 300 seconds. Data processing and analysis were done with *MPO Canopus* (Warner, 2016). All images were calibrated with dark and flat-field frames and converted to R magnitudes using solar-colored field stars from the CMC15 catalogue distributed with *MPO Canopus*. Table I shows the observing circumstances and results.

A search of the asteroid lightcurve database (LCDB; Warner *et al.*, 2009) indicates that our results appear to be the first reported lightcurve results for these objects.

3077 Henderson (1982 SK) was discovered on 1982 September 22 by E. Bowell at the Anderson Mesa station, Lowell Observatory, at Flagstaff, AZ. The asteroid orbits with a semi-major axis of about 2.241 AU, eccentricity 0.055, inclination 1.47 degrees, and an orbital period of 3.35 years. Its absolute magnitude is H = 12.7 (JPL, 2016; MPC, 2016). The same value was used by the WISE infrared survey to find a diameter of 5.175 ± 0.080 km and albedo of 0.549 ± 0.071 (Masiero *et al.*, 2011).

Our observations of this asteroid were conducted on four nights from 2016 Nov 29 through Dec 7. A total of 308 data points were used in the subsequent analysis. As shown in the period spectrum, the analysis shows a clear solution with a bimodal lightcurve with a period P = 16.235 ± 0.003 h and amplitude A = 0.67 ± 0.03 mag.





12044 Fabbri (1997 FU) was discovered on 1997 March 29 by M. Tombelli and G. Forti at Montelupo. The asteroid orbits with a semi-major axis of about 2.592 AU, eccentricity 0.139, inclination 13.99 degrees, and period of 4.17 years. The absolute magnitude is H = 12.7 (JPL, 2016; MPC, 2016). The WISE infrared survey used H = 12.5 to find a diameter of 7.344 ± 0.160 km and optical albedo of 0.327 ± 0.032 (Masiero *et al.*, 2011).

Our observations of this asteroid were conducted on three nights from 2016 Nov 1-9, collecting a total of 159 data points. The