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LIGHTCURVE ANALYSIS OF HILDA ASTEROIDS AT THE CENTER FOR SOLAR SYSTEM STUDIES: 2016 JUNE-SEPTEMBER

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Lightcurves for 16 Hilda asteroids were obtained at the Center for Solar System Studies (CS3) from 2016 June to September.

CCD photometric observations of 16 Hilda asteroids were made at the Center for Solar System Studies (CS3) from 2016 June to September. This is the first of a planned series on this group of asteroids located between the outer main-belt and Jupiter Trojans. The overall goal is to determine the spin rate statistics of this group that has a 3:2 orbital resonance with Jupiter. More specifically we look to examine the degree of influence that the YORP effect (Rubincam, 2000) has on more distant objects and to compare the spin rate distribution to 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).

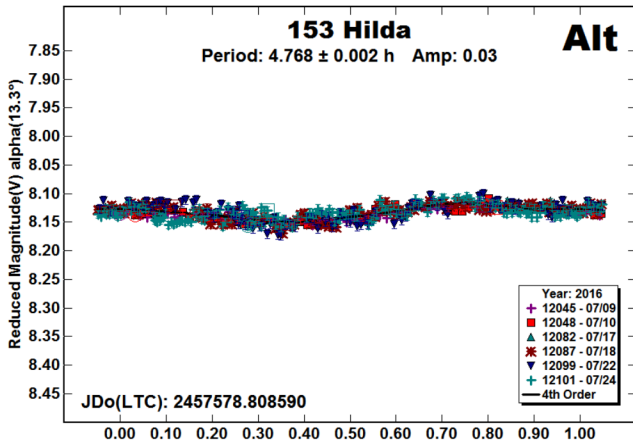
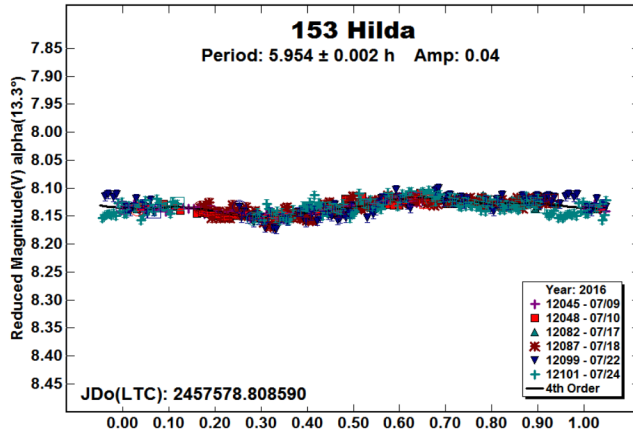
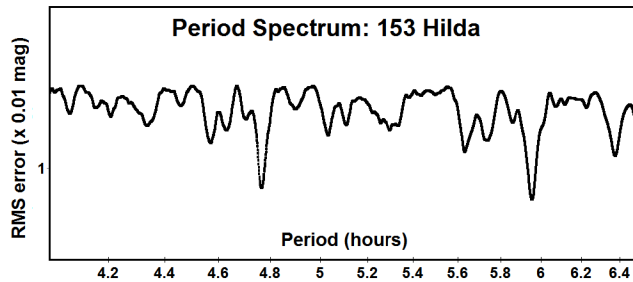
In the plots below, the “Reduced Magnitude” is Johnson V as indicated in the Y-axis title. These are values that have been converted from sky magnitudes to unity distance by applying $-5 \cdot \log(r\Delta)$ to the measured sky magnitudes with r and Δ being, respectively, the Sun-asteroid and Earth-asteroid distances in AU. The magnitudes were normalized to the given phase angle, e.g., $\alpha(6.5^\circ)$, 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*. The value is meant only to be a quick guide.

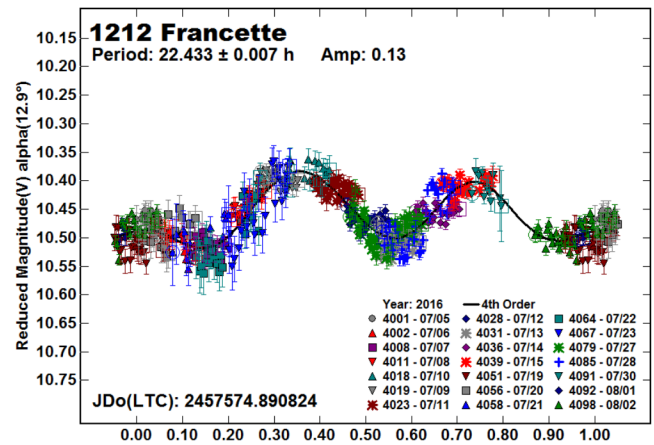
For the sake of brevity, only some of the previously reported results may be referenced in the discussions on specific asteroids. For a more complete listing, the reader is directed to the asteroid lightcurve database (LCDB; Warner *et al.*, 2009). The on-line version at <http://www.minorplanet.info/lightcurvedatabase.html> 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.

153 Hilda. This 170 km asteroid is the namesake for the Hildas. Shevchenko *et al.* (2008) found a period of 5.9587 h based on data from several apparitions. Our period spectrum shows a strong solution at 5.954 h, but one at 4.768 h cannot be formally excluded. The two periods differ by almost exactly one rotation over 24 hours. Solutions that differ by integral or half-rotations over the span of the observations are sometimes called *rotational aliases* because the true number of rotations is not certain.

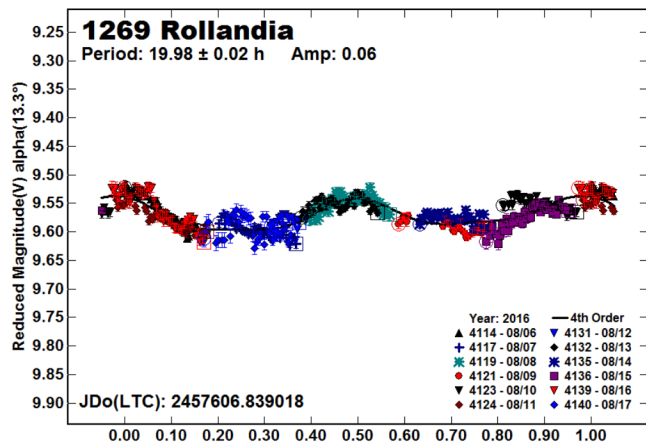
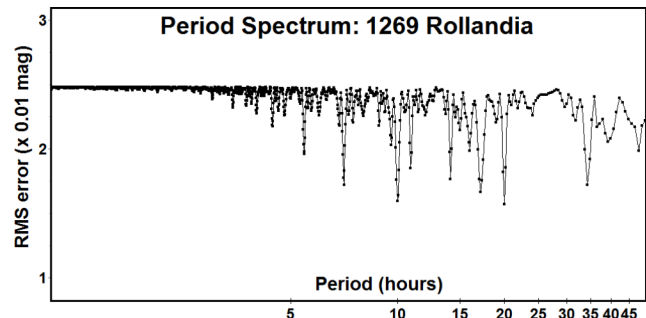


1212 Francette. Taylor *et al.* (1976) reported only that the period seemed to be longer than 16 h. The CS3 period of 22.433 h is nearly commensurate with an Earth day, which made it difficult to get full coverage of the lightcurve from our single location.



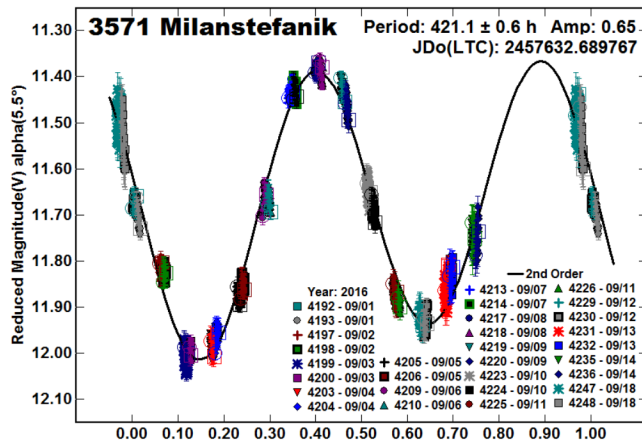
1269 Rollandia. Franco *et al.* (2012w) found a period of 15.4 hours with an amplitude of only 0.08 mag. That solution was refined by Fauvaud and Fauvaud (2013), who found 15.32 h based on observations only a few days after the Franco *et al.* data were obtained in 2012 March.

The CS3 data set was denser than those earlier efforts and did not support the 15.4 h period. Instead the most favored solution in the period spectrum was 19.98 hours, which produced a bimodal lightcurve with an amplitude of 0.06 mag. Since a bimodal solution is not guaranteed with so low an amplitude (Harris *et al.*, 2014), an alternate, monomodal solution at 9.99 hours is also a possibility, especially if the asteroid is nearly spheroidal.

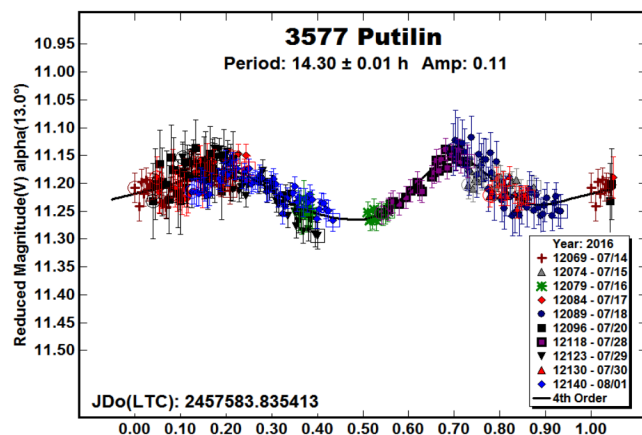
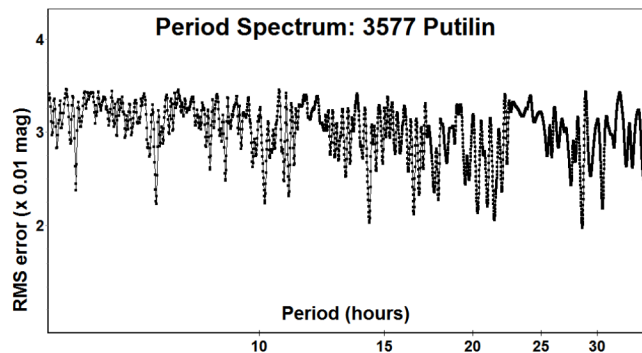


3571 Milanstefanik. There were no previously reported rotation periods in the asteroid lightcurve database (LCDB; Warner *et al.*, 2009). Due to interference from the full Moon, we could not obtain data covering the second maxima. However, the data covered more than one cycle of the adopted period. The estimated damping time from tumbling to single axis rotation for this

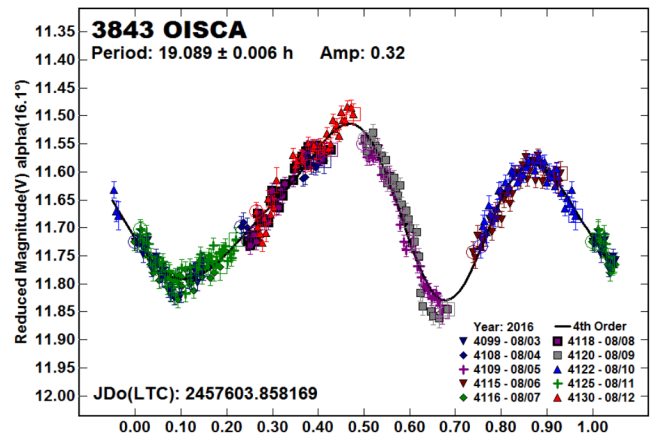
asteroid exceeds the age of the Solar System (Pravec *et al.*, 2014, and references therein). There were no *obvious* signs of tumbling, such as the slope of the data for a given night not agreeing with the slope of the Fourier curve. More extensive coverage of the asteroid would be required to determine its true rotational state.



3577 Putilin. The period spectrum shows several nearly likely solutions, including the 29 hours found by Dahlgren *et al.* (1998) and the 18.270 hours found by Brinsfield (2011). Those solutions require unlikely multimodal lightcurves when using the CS3 data, so we adopted a period of 14.30 h for this paper.

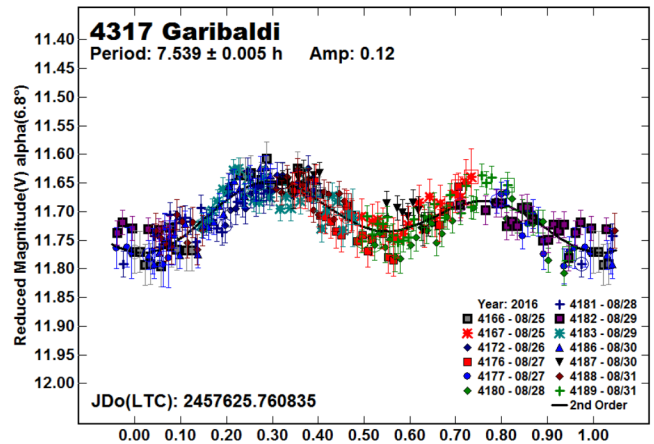
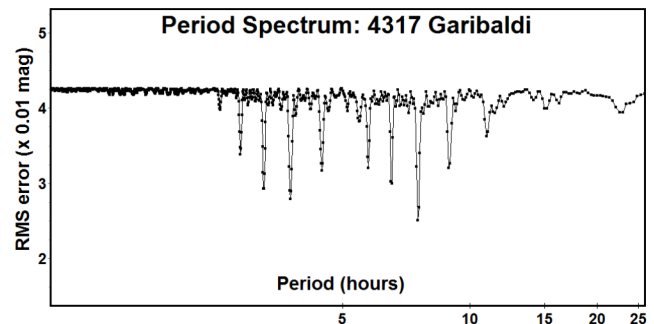


3843 OISCA. De Sanctis *et al.* (1994) reported finding a period exceeding 16 h. Dahlgren *et al.* (1998) found a period of 19.078 h based on sparse data that still produced convincing bimodal lightcurves. Our observations over ten nights are in good agreement with the Dahlgren results.



4317 Garibaldi. Dahlgren *et al.* (1998) observed this Hilda on three nights in 1994. Their phased lightcurve covers only about half their period of 28.5 hours. Our much denser data set spans seven nights. The period spectrum shows the primary and half-period solutions.

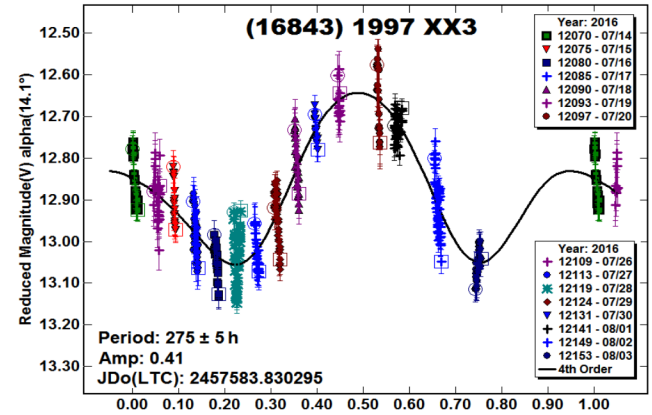
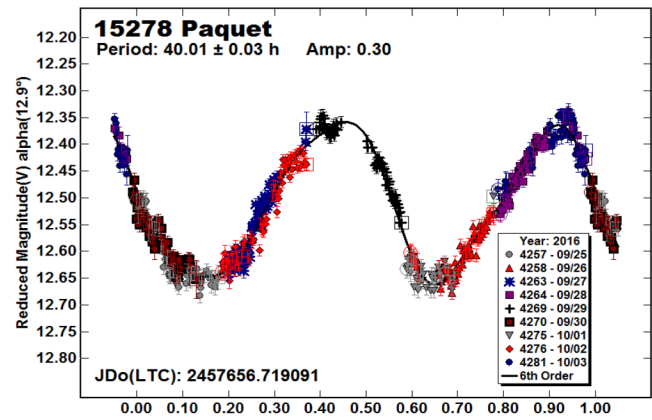
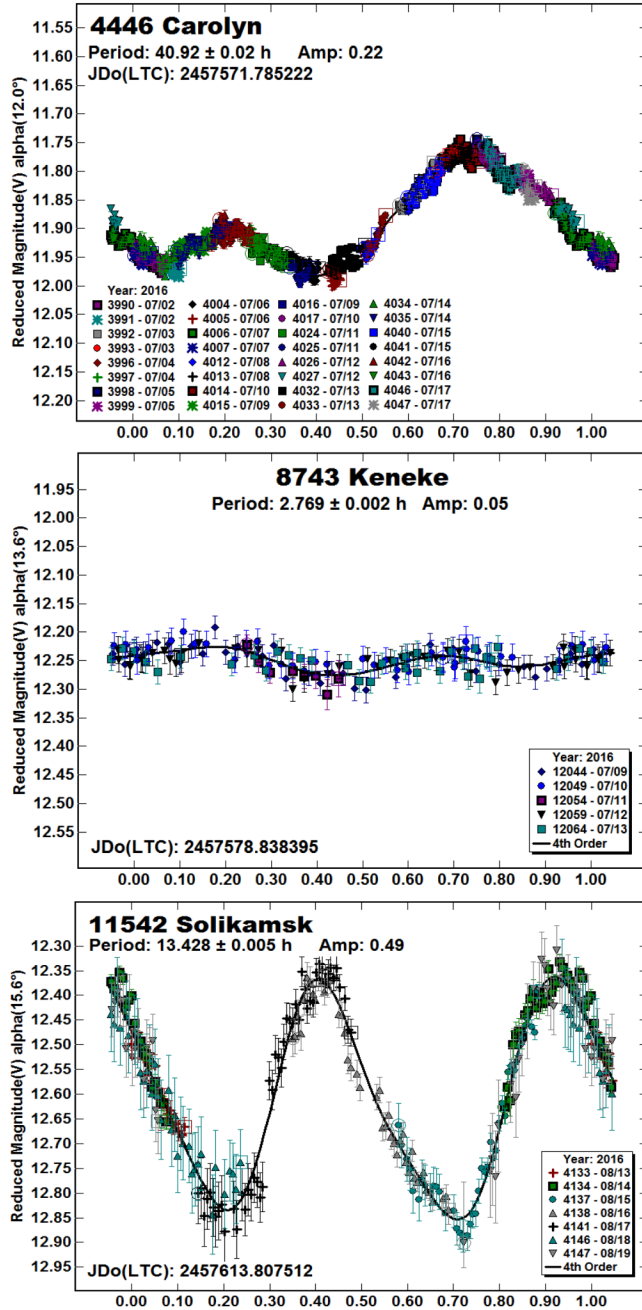
While our data set leads to a strong solution at 7.539 h, this is based on the assumption of a typical bimodal lightcurve. Given the low amplitude, there is the possibility of a monomodal solution at about 3.77 hours. However, the RMS value for the half-period solution in the period spectrum is significantly larger and we're confident that the adopted period of 7.539 h is the correct one.



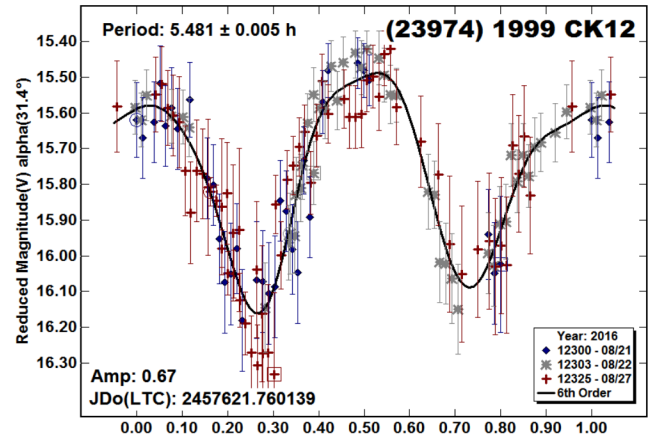
4446 Carolyn, 8743 Keneke, 11542 Solikamsk, 15278 Paquet, (16843) 1997 XX3. There were no previously reported periods in the LCDB for these five Hildas.

Given the lightcurve amplitudes, the periods for 4446 Carolyn, 11542 Solikamsk, and 15278 Paquet are considered secure. The low amplitude for 8743 Keneke again raises the possibility of a

solution that has one or three or more maximum/minimum pairs (Harris *et al.*, 2014). A monomodal solution would require a period of only 1.38 hours. Given the diameter of about 28 km, this can be safely ruled out. For (16843) 1997 XX3, the period of 275 h makes it a tumbling candidate and, in fact, there are some sessions where the slope of the data on some nights does not quite correspond with the Fourier curve.



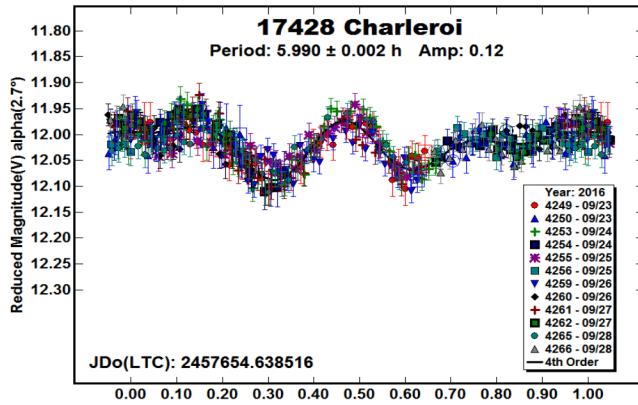
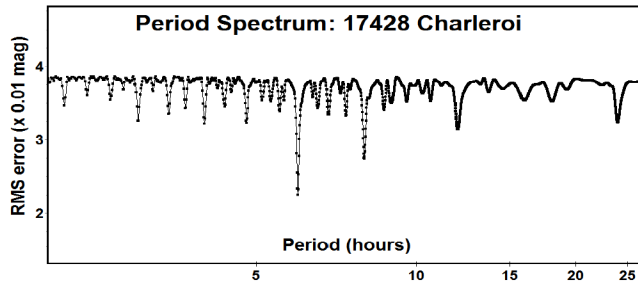
(23974) 1999 CK12. Warner (2012) reported a period of 5.485 h. The latest result of 5.481 h is in good agreement.



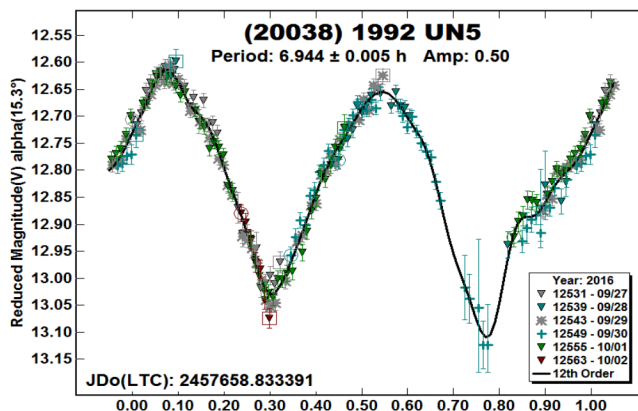
17428 Charleroi. There were no previous entries in the LCDB for Charleroi. Here is another example of a low amplitude lightcurve having an unusual, but not necessarily unexpected, shape (see Harris *et al.*, 2014). The unusual features in the lightcurve repeated several times, which gives us full confidence in the derived period of 5.990 h.

Number	Name	2016 mm/dd	Pts	Phase	L_{PAB}	B_{PAB}	Period	P.E.	Amp	A.E.	Group
153	Hilda	07/09–07/24	480	13.3, 10.5	336	9	5.954	0.002	0.04	0.01	HIL
1212	Francette	07/05–08/02	464	12.9, 10.8	165	–3	22.433	0.007	0.13	0.02	HIL
1269	Rollandia	08/08–08/17	432	13.1, 12.3	20	–3	19.98	0.02	0.06	0.02	HIL
3571	Milanstefanik	09/01–09/18	1039	5.5, 2.6	356	9	421.1	0.6	0.65	0.05	HIL
3577	Putilin	07/14–08/01	319	13.0, 10.7	352	4	14.30	0.01	0.11	0.01	HIL
3843	OISCA	08/03–08/12	349	16.1, 15.4	19	–1	19.089	0.006	0.32	0.02	HIL
4317	Garibaldi	08/25–08/31	284	6.8, 5.5	359	–8	7.539	0.005	0.12	0.02	HIL
4446	Carolyn	07/02–07/17	770	12.0, 7.4	310	8	40.92	0.01	0.22	0.02	HIL
8743	Keneke	07/09–07/13	147	13.6, 12.9	334	0	2.769	0.002	0.05	0.01	HIL
11542	Solikamsk	08/13–08/19	270	15.6, 14.7	15	–1	13.428	0.005	0.49	0.02	HIL
15278	Paquet	09/25–10/02	487	12.9, 11.2	40	8	40.01	0.03	0.30	0.02	HIL
16843	1997 XX3	07/14–08/03	444	14.1, 9.4	339	1	275	5	0.41	0.04	HIL
17428	Charleroi	09/23–09/28	400	2.7, 2.4, 2.5	4	9	5.990	0.002	0.12	0.02	HIL
20038	1992 UN5	09/27–10/02	214	15.3, 14.2	51	–5	6.944	0.005	0.50	0.02	HIL
32460	2000 SY92	08/25–09/16	1397	10.3, 8.4	26	12	49.67	0.03	0.22	0.02	HIL
51874	2001 PZ28	07/06–07/13	206	10.5, 12.2	257	13	3.685	0.002	0.19	0.03	HIL

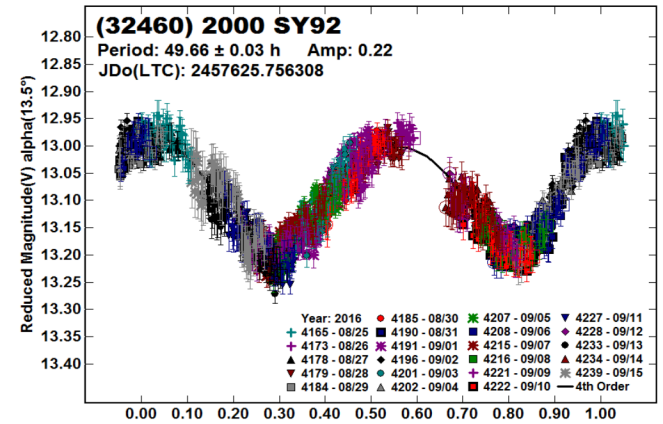
Table II. Observing circumstances. The phase angle (α) is given at the start and end of each date range, unless it reached a minimum, which is then the second of three values. If a single value is given, the phase angle did not change significantly and the average value is given. L_{PAB} and B_{PAB} 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 Group column gives the orbital group to which the asteroid belongs (all Hildas in this case). The definitions and values are those used in the LCDB (Warner *et al.*, 2009).



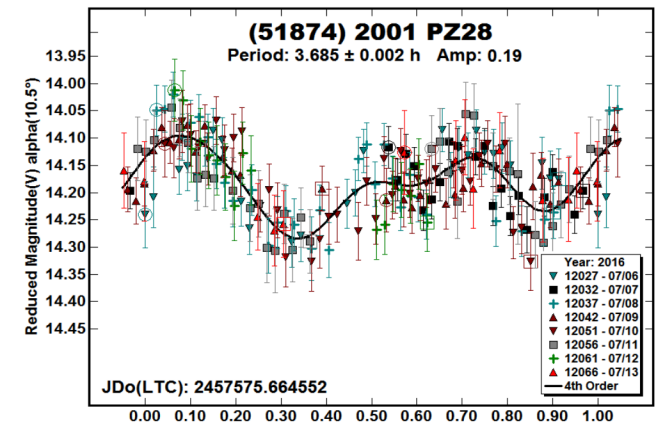
(20038) 1992 UN5. Polishook (2011) found a period of 6.9 h for this 27 km Hilda. Our result is consistent with that result.



(32460) 2000 SY92. This appears to be the first reported period for 2000 SY92. Due to the period being almost commensurate with an Earth day and a full Moon (the bane of asteroid photometry), we were not able to get a complete lightcurve. However, the gap in coverage is relatively small and can be extrapolated without ambiguity and so we consider the period of 49.66 hours to be secure. The period is far short of that required to make the asteroid a candidate for tumbling (Pravec *et al.*, 2014).

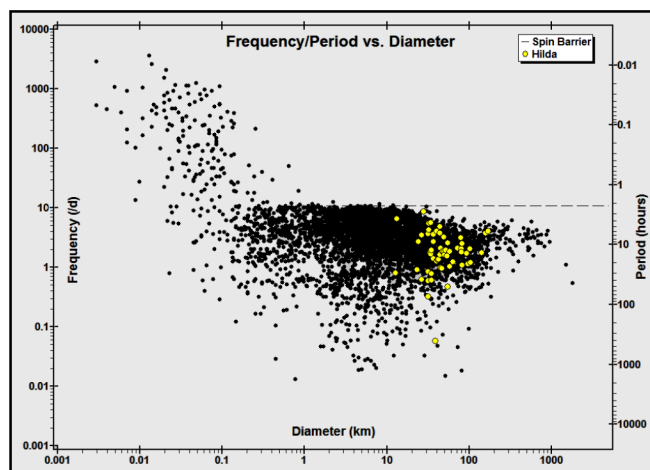


(51874) 2001 PZ28. There were no previous entries in the LCDB for 2001 PZ28, which has an estimated diameter of 13 km.



Closing Remarks

The additional results from this paper bring to 106 the number of Hilda asteroids with statistically useful periods (see Warner *et al.*, 2009). These are shown as yellow (light) circles in the frequency-diameter plot from the LCDB as of 2016 October 4.



Of particular note is the number Hildas with $D < 15$ km, which account for about 27% of the total of 106. These will be more likely subject to thermal forces such as YORP. Since the Hildas tend to be lower albedo ($p_V \sim 0.05$), it will be a challenge to extend the rotation statistics to smaller members of the orbital group. With a 0.75-meter telescope to come on-line in the near future at CS3, we believe we'll be able to add a significant number of rotation periods for the smaller Hildas.

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