

Society (2007), which was used to purchase of one the telescopes used in this research. This research was made possible through the use of the AAVSO Photometric All-Sky Survey (APASS), funded by the Robert Martin Ayers Sciences Fund and in was based in on data from CMC15 Data Access Service at CAB (INTA-CSIC) (<http://svo2.cab.inta-csic.es/vocats/cmc15/>). This publication makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation. (<http://www.ipac.caltech.edu/2mass/>)

References

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

Harris, A.W., Young, J.W., Bowell, E., Martin, L.J., Millis, R.L., Poutanen, M., Scaltriti, F., Zappala, V., Schober, H.J., Debehogne, H., Zeigler, K.W. (1989). "Photoelectric Observations of Asteroids 3, 24, 60, 261, and 863." *Icarus* **77**, 171-186.

Harris, A.W., Pravec, P., Galad, A., Skiff, B.A., Warner, B.D., Vilagi, J., Gajdos, S., Carbognani, A., Hornoch, K., Kusnirak, P., Cooney, W.R., Gross, J., Terrell, D., Higgins, D., Bowell, E., Koehn, B.W. (2014). "On the maximum amplitude of harmonics on an asteroid lightcurve." *Icarus* **235**, 55-59.

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

JPL (2018). Small Bodies Database Browser. <https://ssd.jpl.nasa.gov/sbdb.cgi>

Pravec, P., Harris, A.W., Scheirich, P., Kušnirák, P., Šarounová, L., Hergenrother, C.W., Mottola, S., Hicks, M.D., Masi, G., Krugly, Yu.N., Shevchenko, V.G., Nolan, M.C., Howell, E.S., Kaasalainen, M., Galád, A., Brown, P., Degraff, D.R., Lambert, J. V., Cooney, W.R., Foglia, S. (2005). "Tumbling asteroids." *Icarus* **173**, 108-131.

Pravec, P., Scheirich, P., Durech, J., Pollock, J., Kusnirak, P., Hornoch, K., Galad, A., Vokrouhlicky, D., Harris, A.W., Jehin, E., Manfroid, J., Opitom, C., Gillon, M., Colas, F., Oey, J., Vrástil, J., Reichart, D., Ivarsen, K., Haislip, J., LaCluyze, A. (2014). "The tumbling state of (99942) Apophis." *Icarus* **233**, 48-60.

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

Warner, B.D., Harris, A.W., Pravec, P. (2009). "The Asteroid Lightcurve Database." *Icarus* **202**, 134-146. Updated 2018 March. <http://www.minorplanet.info/lightcurvedatabase.html>

Zappala, V., Cellini, A., Barucci, A.M., Fulchignoni, M., Lupishko, D.E. (1990). "An analysis of the amplitude-phase relationship among asteroids." *Astron. Astrophys.* **231**, 548-560.

LIGHTCURVE ANALYSIS OF HILDA ASTEROIDS AT THE CENTER FOR SOLAR SYSTEM STUDIES: 2018 JANUARY-FEBRUARY

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Lightcurves for five Hilda asteroids were obtained at the Center for Solar System Studies (CS3) from 2018 January-February: 361 Bononia, 1902 Shaposhnikov, 3415 Danby, (20038) 1992 UN5, and (20628) 1999 TS40.

CCD photometric observations of five Hilda asteroids were made at the Center for Solar System Studies (CS3) from 2018 January-February. This is another installment of an on-going 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 we look to examine the degree of influence that the YORP (Yarkovsky–O'Keefe–Radzievskii–Paddack) 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 APASS (Henden et al., 2009) or CMC-15 (<http://svo2.cab.inta-csic.es/vocats/cmc15/>) catalogs. The MPOSC3 catalog was used as a last resort. This catalog is based on the 2MASS catalog (<http://www.ipac.caltech.edu/2mass>) with magnitudes converted from J-K to BVRI (Warner, 2007).

Number	Name	2018 mm/dd	Pts	Phase	L _{PAB}	B _{PAB}	Period(h)	P.E.	Amp	A.E.
361	Bononia	01/26-01/28	606	8.0, 7.4	147	12	13.835	0.007	0.17	0.01
1902	Shaposhnikov	01/28-02/09	379	8.5, 6.6	168	13	20.988	0.006	0.31	0.02
3415	Danby	01/28-02/06	219	8.2, 6.3	164	-2	5.675	0.001	0.35	0.03
20038	1992 UN5	01/28-02/07	258	7.6, 7.2	136	23	6.941	0.002	0.28	0.02
20628	1999 TS40	02/10-03/24	340	4.6, 4.1, 4.9	229	3	68.1	0.1	1.04	0.10

Table III. Observing circumstances. The phase angle (α) is given at the start and end of each date range. L_{PAB} and B_{PAB} are each the average phase angle bisector longitude and latitude (see Harris *et al.*, 1984).

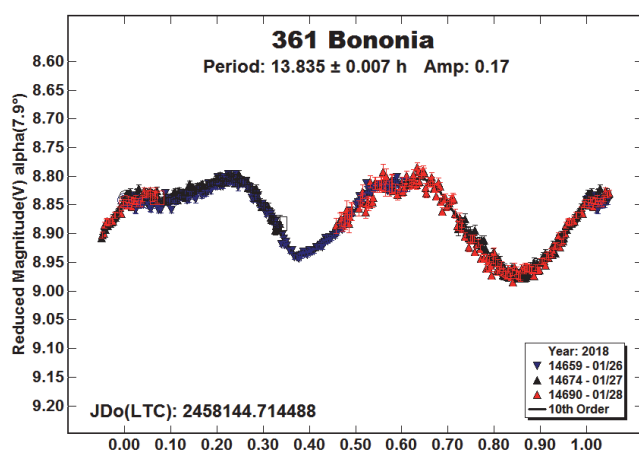
The nightly zero points for the APASS and CMC-15 catalogs are generally consistent to about ± 0.05 mag or better, but occasionally reach >0.1 mag. There is a systematic offset among all the catalogs so, whenever possible, the same catalog is used for all observations of a given asteroid. Period analysis is done with *MPO Canopus*, which implements the FALC algorithm 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 phase angle in the parentheses using $G = 0.15$, unless otherwise stated. The X-axis is the rotational phase ranging from -0.05 to 1.05 .

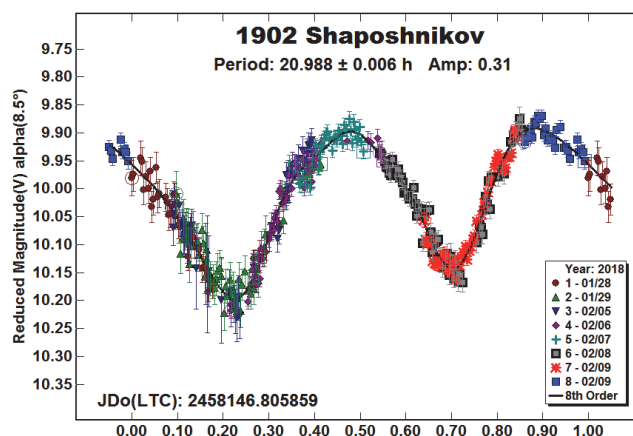
If the plot includes an amplitude, *e.g.*, “Amp: 0.65”, this is the amplitude of the Fourier model curve and *not necessarily the adopted amplitude for the lightcurve*.

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 Bibcode, 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. Binzel and Sauter (1992) reported a period of 13.83 ± 0.02 h for this 140 km Hilda. The only other publically available results are from Hanus *et al.* (2016) who presented a shape and spin axis model with a sidereal period of 13.80634 h, and Warner *et al.* (2017a) who found 13.79 h. The result of 13.835 h is the longest of these all but still in good agreement.

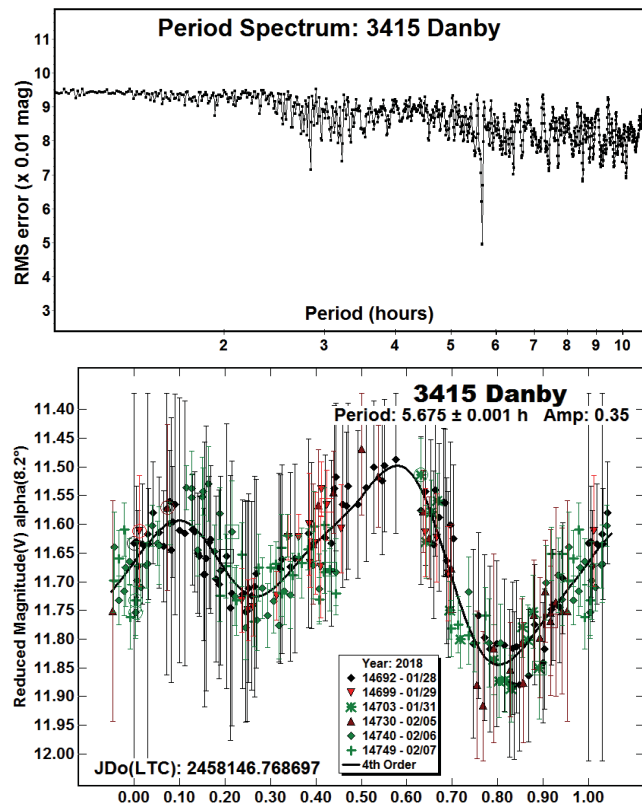


1902 Shaposhnikov has an estimated diameter of about 97 km. The average reported albedo is $p_V \sim 0.035$ (*e.g.*, AKARI, Usui *et al.*, 2011). This is a little lower than the average albedo for Hildas in the LCDB ($p_V = 0.046$) when considering only those that were determined and not assumed values. Hanus *et al.* (2016) found a sidereal rotation period of 20.9959 h. Warner *et al.* (2017b) found a synodic period of 20.987 h. Our latest result is almost exactly the same.

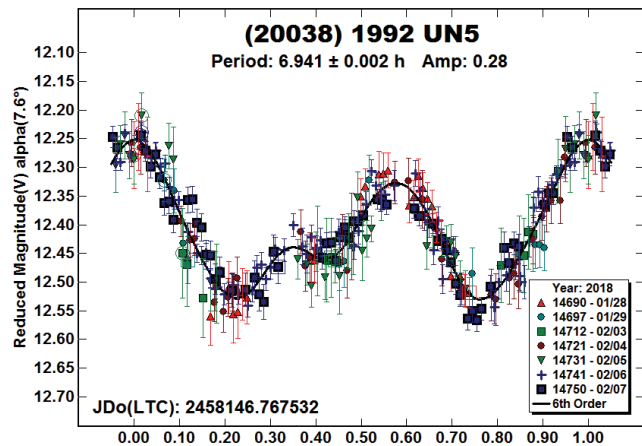


3415 Danby. There are numerous previous results for Danby, which has an estimated diameter of 32 km. Dahlgren *et al.* (1998) found a period of 2.851 h. Warner (2008) found a doubled period of 5.666 h, as did Behrend (2007, 2015; 5.6706 h). When Warner *et al.* (2017a) observed Danby in 2016, they found the shorter period: 2.837 h. On re-examining Warner’s 2007 data, the original result was changed to 2.834 h. However, both of these were stated to be ambiguous solutions, with the double period of about 5.6 h being almost as likely.

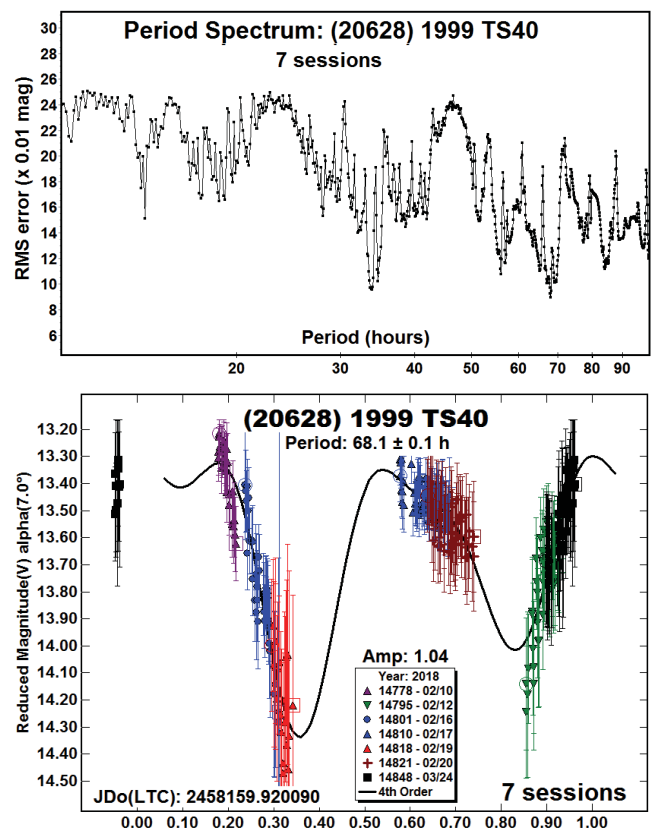
The 2018 observations were hampered by low SNR data (large error bars). Were it not for the large amplitude, by far the largest reported to-date, we would not have been able to give a reliable solution. At this point, we believe a period of 5.675 h is the most likely since the amplitude almost demands a bimodal lightcurve (Harris *et al.*, 2014) and not the quadramodal lightcurves often associated with the 2.8 h solutions. Still, the period cannot be said to be definitively solved and future observations are planned.



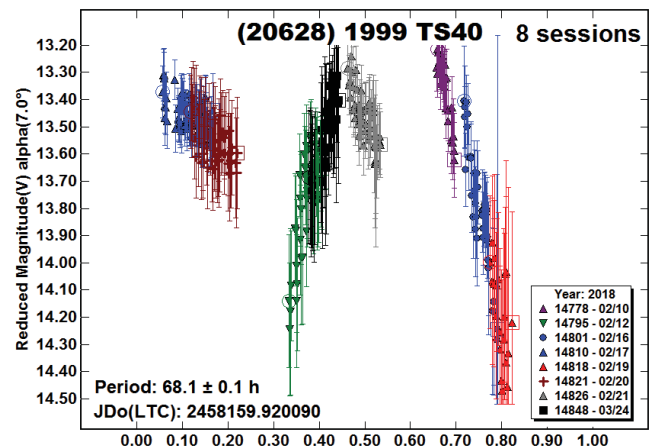
(20038) 1992 UN5. Previous results include Polishook (2011, 6.9 h) and Warner et al. (2017a, 6.944 h). Our period of 6.941 h is in close agreement with our earlier result.



(20628) 1999 TS40. A limited data set of poor quality was all that could be managed for this 18 km Hilda. Using seven of eight sessions (Feb 21 was excluded), the period spectrum showed a very indecisive result, with two possible solutions near 35 hours and 70 hours. Given the apparent large amplitude (see Harris et al., 2014), a bimodal solution was found with a period of 68.1 h, but this can hardly be considered reliable.



When the eighth session (Feb 21) was added to the analysis and the period forced to 68.1 h, it's clear that the Feb 21 session does not fit well with the rest of the data. A period search using all eight sessions covering the same range as in the period spectrum given here was essentially identical.



The ill-fitting lightcurve lends itself to the possibility that the asteroid is tumbling (see Pravec et al., 2005). However, based on even a set of shorter times to go from tumbling to normal rotation (see Pravec et al., 2014), 1999 TS40 is not a likely candidate for tumbling. However, rules of thumb are not rigorous and there are examples in the LCDB where an asteroid should be tumbling but is not and when it should not be tumbling but it is.

MPO Canopus cannot properly analyze tumbling asteroids. However, even if it could, the data set is far too sparse to make even an initial attempt at analysis using software with the needed capabilities. One possibility is that *MPO Canopus* is locking onto

a dominant period in the data set that maybe one of the periods of non-principal rotation (NPAR, “tumbling”) or that it is finding a “beat frequency”, i.e., a period that is nearly an integral ratio of the actual tumbling periods.

The best step towards resolving the mystery is to observe the asteroid under more favorable conditions and involve observers at well-separated longitudes. Looking ahead, the 2023 and 2025 apparitions will be the next ones with $V < 18.0$.

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References

- Behrend, R. (2007, 2015). Observatoire de Geneve web site. http://obswww.unige.ch/~behrend/page_cou.html
- Binzel, R.P., Sauter, L.M. (1992). “Trojan, Hilda, and Cybele asteroids - New lightcurve observations and analysis.” *Icarus* **95**, 222-238.
- Dahlgren, M., Lahulla, J.F., Lagerkvist, C.-I., Lagerros, J., Mottola, S., Erikson, A., Gonano-Beurer, M., Di Martino, M. (1998). “A Study of Hilda Asteroids. V. Lightcurves of 47 Hilda Asteroids.” *Icarus* **133**, 247-285.
- Hanus, J., Durech, J., Oszkiewicz, D.A., Behrend, R., Carry, B., Delbo, M., Adam, O., Afonina, V., Anquetin, R., Antonini, P., and 159 coauthors (2016). “New and updated convex shape models of asteroids based on optical data from a large collaboration network.” *Astron. Astrophys.* **586**, A108.
- 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.
- Harris, A.W., Young, J.W., Bowell, E., Martin, L.J., Millis, R.L., Poutanen, M., Scaltriti, F., Zappala, V., Schober, H.J., Debehogne, H., Zeigler, K.W. (1989). “Photoelectric Observations of Asteroids 3, 24, 60, 261, and 863.” *Icarus* **77**, 171-186.
- Harris, A.W., Pravec, P., Galad, A., Skiff, B.A., Warner, B.D., Vilagi, J., Gajdos, S., Carbognani, A., Hornoch, K., Kusnirak, P., Cooney, W.R., Gross, J., Terrell, D., Higgins, D., Bowell, E., Koehn, B.W. (2014). “On the maximum amplitude of harmonics on an asteroid lightcurve.” *Icarus* **235**, 55-59.
- Henden, A.A., Terrell, D., Levine, S.E., Templeton, M., Smith, T.C., Welch, D.L. (2009). <http://www.aavso.org/apass>
- Usui, F., Kuroda, D., Müller, T.G., Hasegawa, S., Ishiguro, M., Ootsubo, T., Ishihara, D., Kataza, H., Takita, S., Oyabu, S., Ueno, M., Matsuhara, H., Onaka, T. (2011). “Asteroid Catalog Using Akari: AKARI/IRC Mid-Infrared Asteroid Survey.” *Pub. Ast. Soc. of Japan* **63**, 1117-1138.
- Warner, B.D. (2007). “Initial Results of a Dedicated H-G Program.” *Minor Planet Bull.* **34**, 113-119.
- Warner, B.D., Higgins, D. (2008). “Lightcurve Analysis of 3415 Danby.” *Minor Planet Bull.* **35**, 103.
- Warner, B.D., Harris, A.W., Pravec, P. (2009). “The Asteroid Lightcurve Database.” *Icarus* **202**, 134-146. Updated 2018 April. <http://www.minorplanet.info/lightcurvedatabase.html>
- Warner, B.D., Stephens, R.D., Coley, D.R. (2017a). “Lightcurve Analysis of Hilda Asteroids at the Center for Solar System Studies: 2016 September-December.” *Minor Planet Bull.* **44**, 130-137.
- Warner, B.D., Stephens, R.D. (2017b). “Lightcurve Analysis of Hilda Asteroids at the Center for Solar System Studies: 2016 December thru 2017 April.” *Minor Planet Bull.* **44**, 220-222.