

LIGHTCURVE ANALYSIS OF HILDA ASTEROIDS AT THE CENTER FOR SOLAR SYSTEM STUDIES: 2017 JULY THROUGH SEPTEMBER

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Lightcurves for ten Hilda asteroids were obtained at the Center for Solar System Studies (CS3) from 2017 July through September. One, (457175) 2008 GO98, was found to be a comet by Leonard (2017). Numerous confirmation reports were made (Green, 2017) but our rotation period of 10.74 hours appears to be the only one reported.

CCD photometric observations of ten Hilda asteroids were made at the Center for Solar System Studies (CS3) from 2017 July through September. 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 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

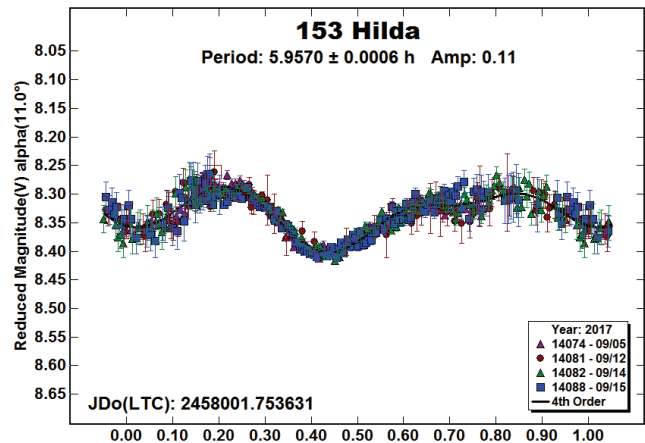
among the catalogs so, whenever possible, the same catalog is used throughout the observations for a given asteroid. Period analysis is also done with *MPO Canopus*, which implements the FALC algorithm developed by Harris (Harris *et al.*, 1989).

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 $-5 \cdot \log(r\Delta)$ 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*.

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.

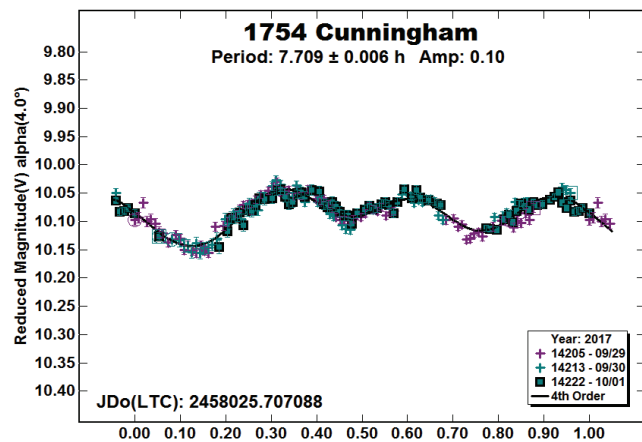
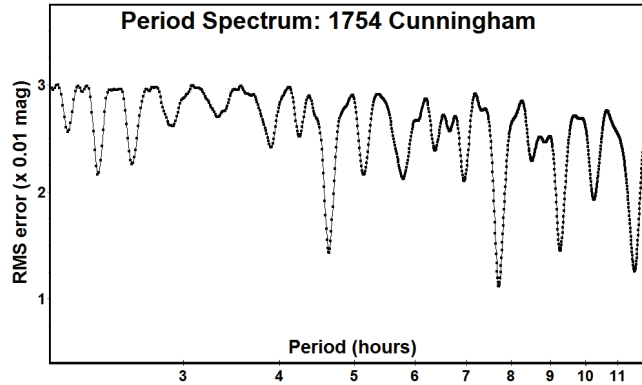
153 Hilda. The first “reliable” (LCDB U ≥ 2) period for the namesake of the Hilda group was found by Lagerkvist *et al.* (1995), who reported a period of 5.11 h. Shevchenko *et al.* (2009) reported a period of 5.9587 h based on an extensive data set that covered apparitions from 1992 through 2006. Warner *et al.* (2017a) found a synodic period of 5.954 h. The period from the 2017 data is in good agreement with previous results.



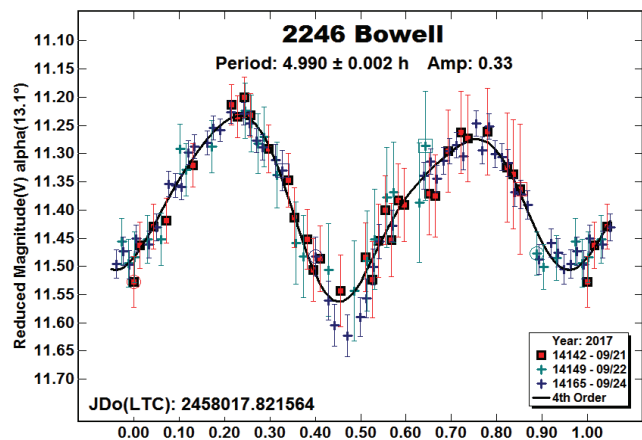
1754 Cunningham. Most previously reported periods for Cunningham were close to 7.7 h, e.g., Stephens (2015h). However, Slyusarev *et al.* (2012) determined a period of 5.16 h. The amplitude for Hilda has always been $A < 0.20$ mag, which makes it possible that a period based on bimodal lightcurve is not necessarily correct (Harris *et al.*, 2014). The period spectrum derived from the 2017 data favors an expected period of 7.709 h, but this requires a trimodal lightcurve. Given the asymmetry of the curve, i.e., it does not appear to be three equally shaped cycles, we’re confident that our solution is correct.

Number	Name	2017 mm/dd	Pts	Phase	L _{PAB}	B _{PAB}	Period(h)	P.E.	Amp	A.E.
153	Hilda	09/05-09/15	484	11.0, 9.2	29	4	5.957	0.0006	0.11	0.01
1754	Cunningham	09/29-10/01	208	4.0, 3.5	18	-8	7.709	0.006	0.1	0.01
2246	Bowell	09/21-09/24	108	13.1, 12.9	61	-7	4.99	0.002	0.33	0.02
5711	Eneev	09/24-10/02	459	3.2, 0.7	11	-1	107.1	0.4	0.15	0.01
6237	Chikushi	09/22-09/24	198	4.6, 4.0	16	-1	7.787	0.005	0.38	0.03
8376	1992 OZ9	09/05-09/18	329	13.1, 10.6	32	-2	16.763	0.005	0.39	0.03
15783	Briancox	09/21-10/02	581	4.8, 1.3	10	3	56.56	0.04	0.32	0.02
17305	Caniff	09/29-10/05	251	12.2, 11.1	51	6	16.85	0.02	0.28	0.03
23186	2000 PO8	09/25-09/28	121	8.7, 8.2	39	-13	5.003	0.003	0.31	0.03
457175	2008 GO98	07/28-08/13	261	7.4, 5.3	320	15	10.74	0.01	0.12	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 each the average phase angle bisector longitude and latitude (see Harris *et al.*, 1984).

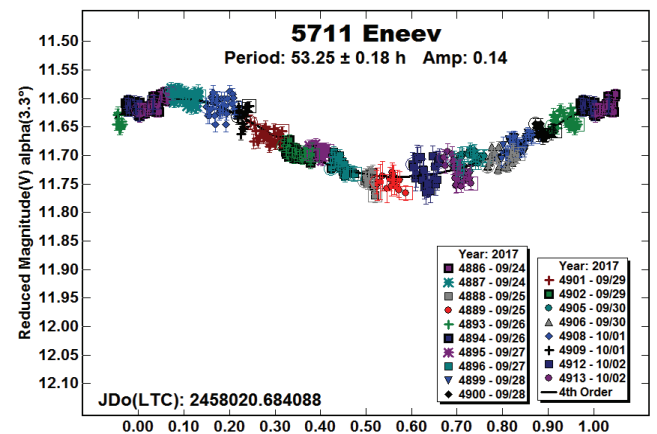
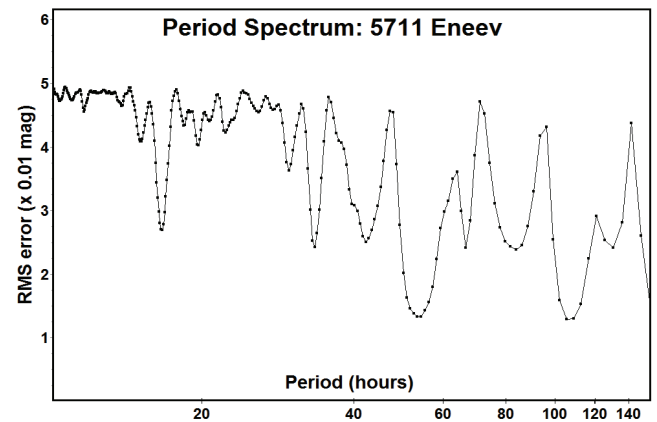


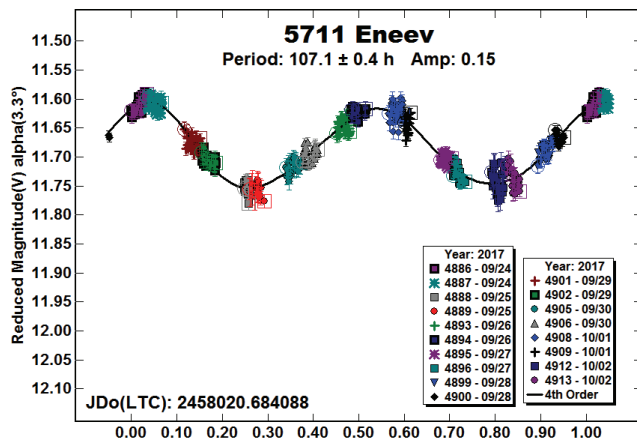
2246 Bowell. Warner *et al.* (2017b) found a period of 4.993 h based on data from 2016. The 2017 data give almost an identical result.



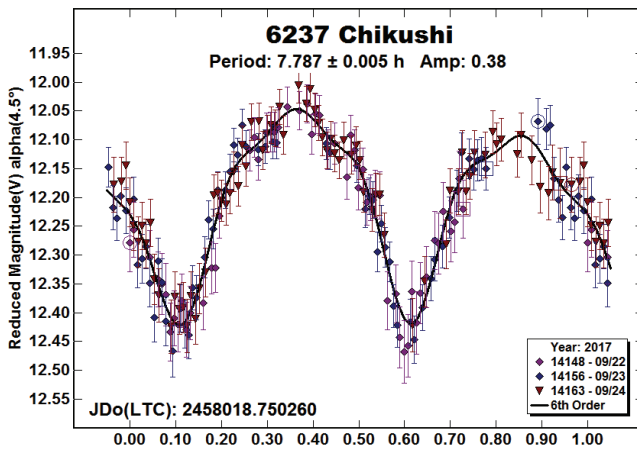
5711 Eneev. Dahlgren *et al.* (1998) could report only $P > 30$ h and $A > 0.1$ mag for this 40-km Hilda. After obtaining data for nine consecutive days in 2017, period analysis found that the period is indeed long, either 107.1 h when assuming a bimodal lightcurve or 53.25 h if assuming a monomodal lightcurve. Since the amplitude is only 0.15 mag, either solution is possible (Harris *et al.*, 2014).

In fact, solutions with three or more extrema cannot be formally excluded. However, those solutions with higher degrees of modality showed too great of symmetry, requiring the asteroid to have a similarly symmetrical shape. This is highly unlikely and so we believe that the period is either 107.1 or 53.25 h. Deciding on the correct solution is difficult. The longer period is slightly favored in the period spectrum, but this could be due to the Fourier analysis minimizing the number of overlapping data points which, in turn, can produce an artificially low RMS fit. For now, we have adopted $P = 107.1$ h, but that could change with additional data in the future.





6237 Chikushi. Waszczak et al. (2015) found a period of 7.812 h using semi-dense data from the Palomar Transient Factory. Our dense lightcurve leads to nearly the same result.



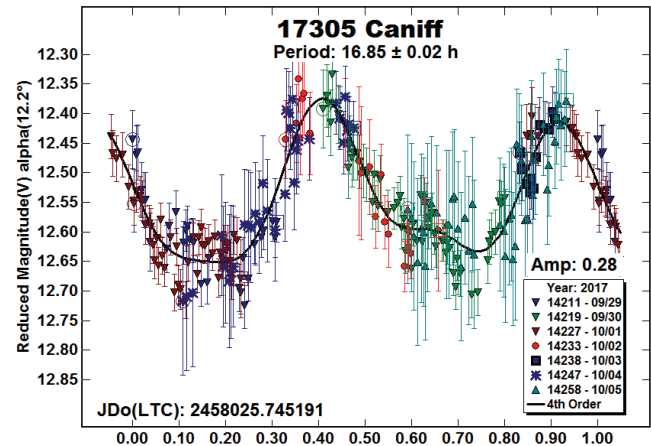
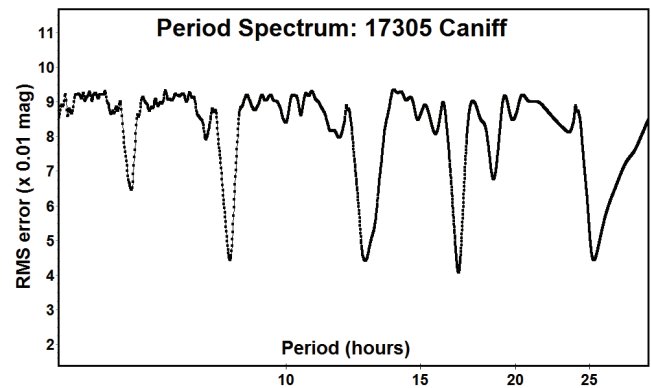
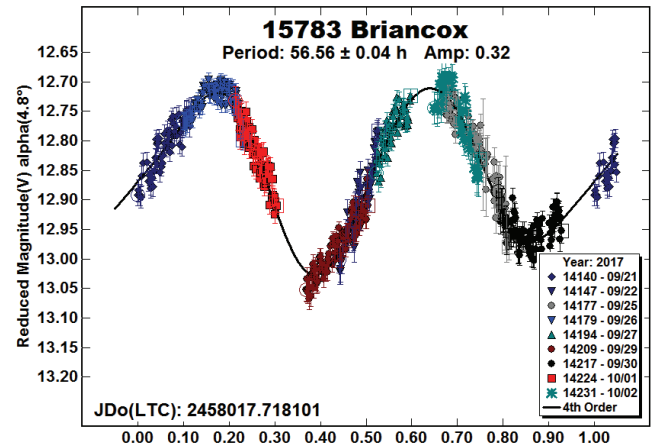
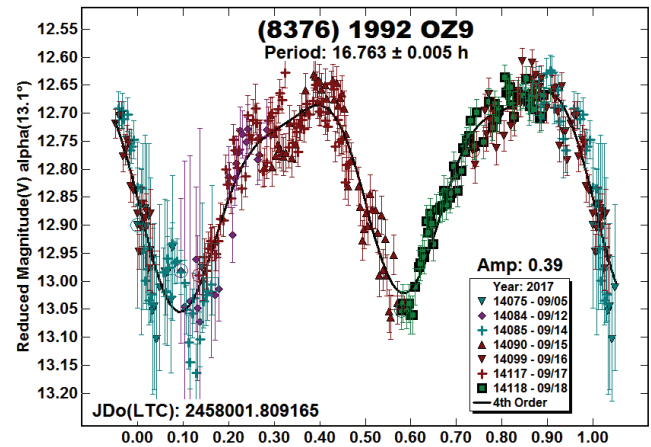
(8376) 1992 OZ9, 15783 Briancox, 17305 Caniff, and (23186) 2000 PO8. These appear to be the first reported periods for these four Hildas. This is deliberate since our program tries to favor “first-timers”, those with no previous period, whenever possible.

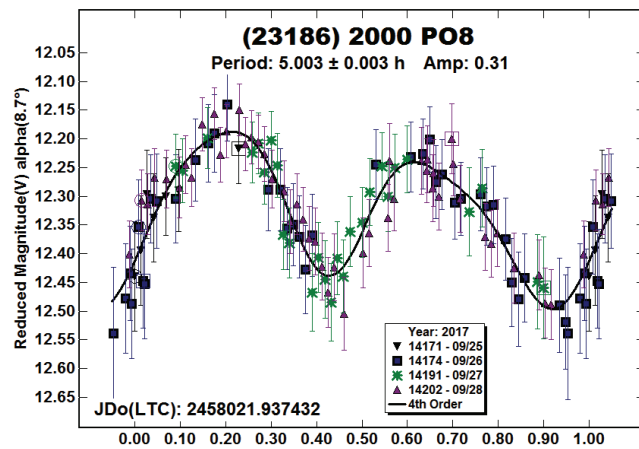
For 1992 OZ9, Usui et al. (2011) in the AKARI mission, using $H = 11.50$, found a diameter of 30.83 km and albedo of $p_V = 0.047$, which is compatible with the average albedo for Hilda members (Warner et al., 2009). The MPCORB gives $H = 11.7$. Using that value would reduce the diameter by only 0.05 km (Harris and Harris, 1997).

The diameter for Briancox can be derived only by using an assumed albedo of $p_V = 0.057$ (Warner et al., 2009) and $H = 12.1$ (MPCORB). These give $D = 21.2$ km.

The period spectrum for Caniff shows several nearly equal minimums. Given the amplitude of 0.28 mag, the solution is very likely tied to a bimodal lightcurve (Harris et al., 2014), which leads to a period of 16.85 h. Its estimated diameter using $p_V = 0.057$ (Warner et al., 2009) and $H = 12.0$ (MPCORB).

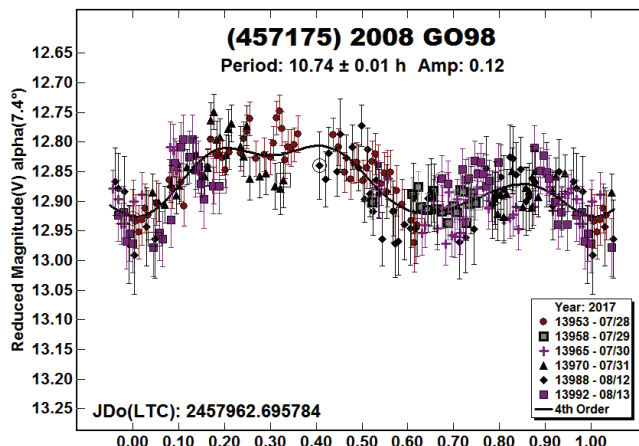
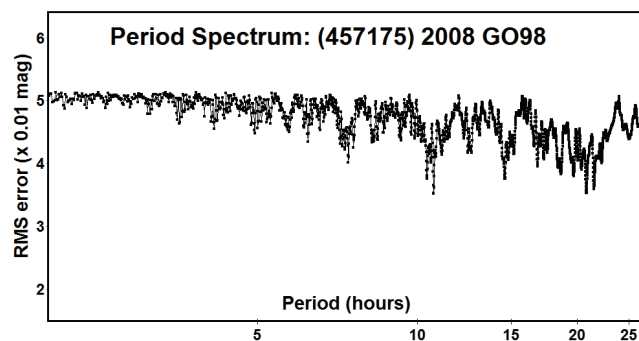
The estimated diameter for 2000 PO8 is $D = 27.9$ km if using $p_V = 0.057$ (Warner et al., 2009) and $H = 11.5$ (MPCORB) give 27.9 km.





(457175) 2008 GO98. Leonard (2017) first reported the cometary nature of this Hilda based on observations on 2017 July 3. He found a coma of 7"-10" with a tail about 15" long. Follow-up reports in the same CBET and a follow-up CBET (Green et al., 2017) confirmed the cometary nature of the asteroid. This was an opportunity missed at CS3. The object had a "fuzzy" appearance on images but this was dismissed to be due to poor seeing because the CBET announcements had not yet been seen.

Getting a lightcurve for a comet can be difficult since outgassing from the nucleus and changes in the coma can lead to lightcurve changes that are not due to the rotation of the nucleus alone. Even so, we were able to obtain a reasonably good lightcurve with a period of 10.74 h. We did not find other reports of a period in our literature search. However, and unfortunately, it's not uncommon for results to be posted on web sites that are known to a limited number of people.



Acknowledgements

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ASTEROID LIGHTCURVE ANALYSIS AT CS3-PALMER DIVIDE STATION: 2017 JULY THROUGH OCTOBER

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Lightcurves for 17 main-belt asteroids were obtained at the Center for Solar System Studies-Palmer Divide Station (CS3-PDS) from 2017 July through October. All but two of the asteroids were *targets of opportunity*, i.e., in the field of planned targets, demonstrating a good reason for data mining images.

CCD photometric observations of 17 main-belt asteroids were made at the Center for Solar System Studies-Palmer Divide Station (CS3-PDS) from 2017 July through October. Table I lists the telescope/CCD camera combinations that were used. All the cameras use the KAF-1001E blue-enhanced CCD chip 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 cause a 0.1-0.3 mag 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 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 (Munos, 2017) 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).

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 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 lightcurves 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*.

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., 2009a). 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, when possible, to cross-check with the original references listed in the LCDB.

89 Julia. This 150 km inner main-belt asteroid was observed at the request of Josef Hanus as part of an effort to update a previous shape and spin axis model (Hanus et al., 2017b). The period of 11.3831 h closely matches previous results found in the LCDB.