

LIGHTCURVE ANALYSIS OF HILDA ASTEROIDS AT THE CENTER FOR SOLAR SYSTEM STUDIES: 2019 DECEMBER - 2020 APRIL

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Telescopes	Cameras
0.30-m f/6.3 Schmidt-Cass	FLI Microline 1001E
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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.

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.

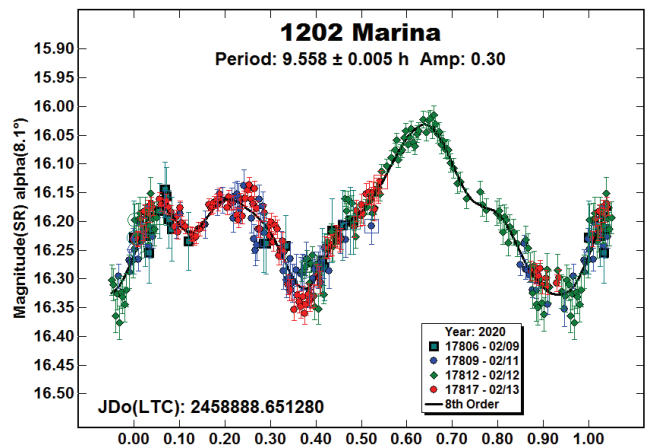
To reduce the number of times and amounts of adjusting nightly zero points, we use the ATLAS catalog r' (SR) magnitudes (Tonry et al., 2018). Those adjustments are usually ≤ 0.03 mag. The few corrections that were greater may have been related in part to using unfiltered observations, poor centroiding of the reference stars, and not correcting for second-order extinction.

The Y-axis values are ATLAS SR “sky” (catalog) magnitudes. During period analysis, the magnitudes were normalized to the comparison stars used in the earliest session and to the phase angle given in parentheses using $G = 0.15$. If “Reduced” is seen, the magnitudes were converted to unity distances by using $-5\log_{10}(r\Delta)$ where $r\Delta$ is the product of the Sun-asteroid and Earth-asteroid

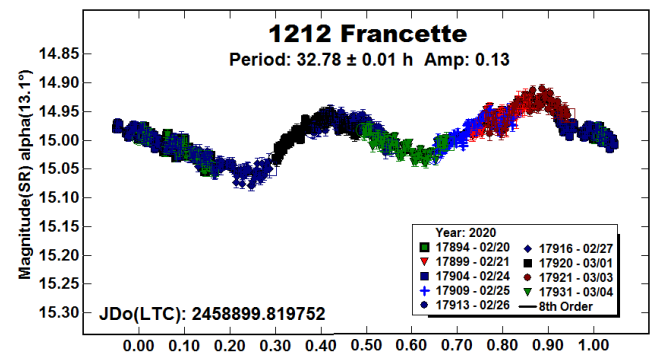
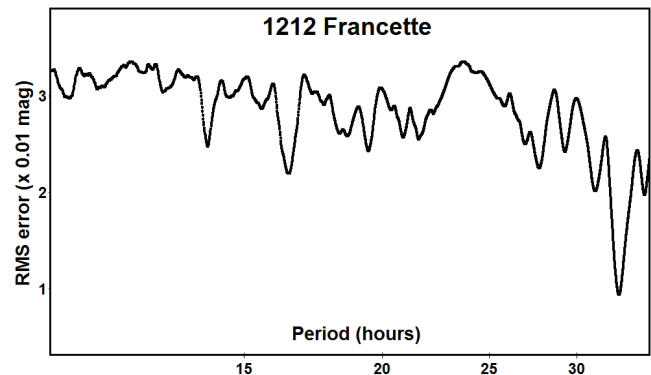
distances in au. The X-axis shows rotational phase from -0.05 to 1.05 . If the plot includes the amplitude, e.g., “Amp: 0.65”, this is the amplitude of the Fourier model curve and *not necessarily the adopted amplitude for the lightcurve*.

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1202 Marina. Dahlgren et al. (1998) reported a period of 9.45 h based on data from 1993. Our period is similar to theirs but is based on a denser data set.



1212 Francette. Previous results for the 82-km Francette are 22.433 h (Warner and Stephens, 2017) and 16.2879 h (Pál et al., 2020) using data from TESS. Our data show a strong preference for a period near 32 h, or double that from Pál et al. (2020).



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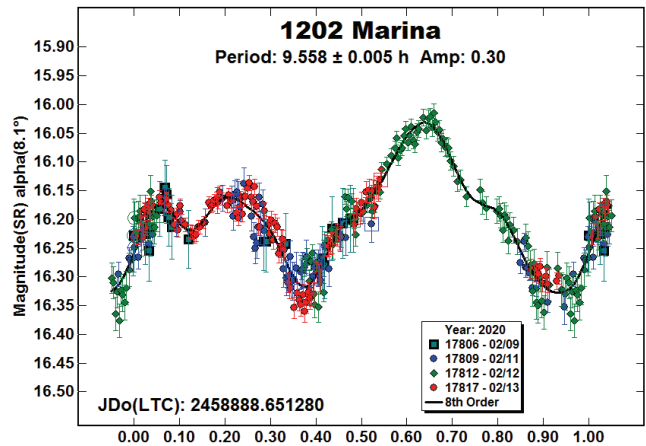
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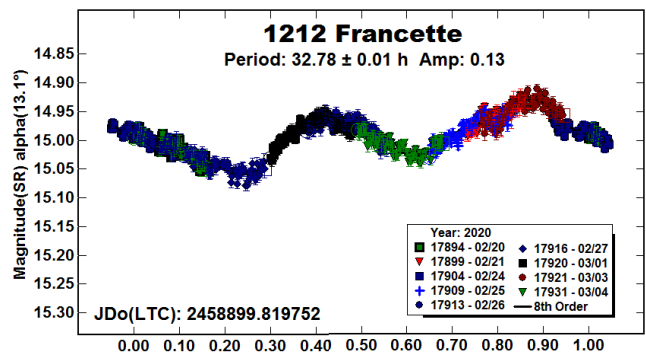
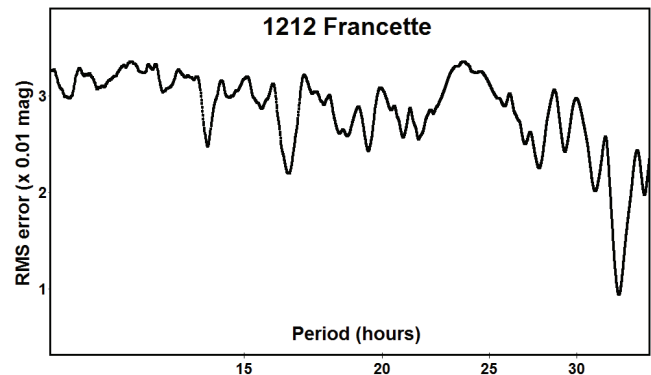
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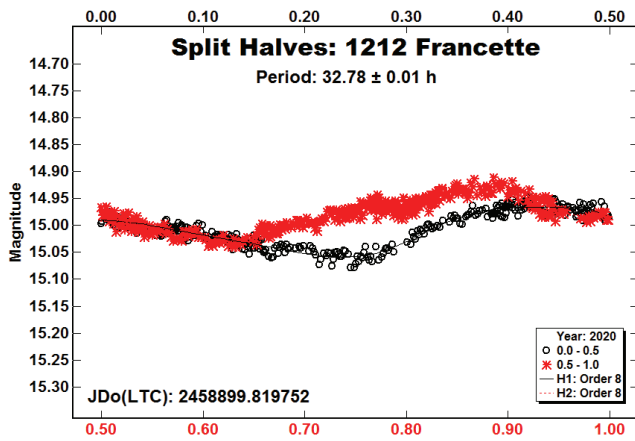
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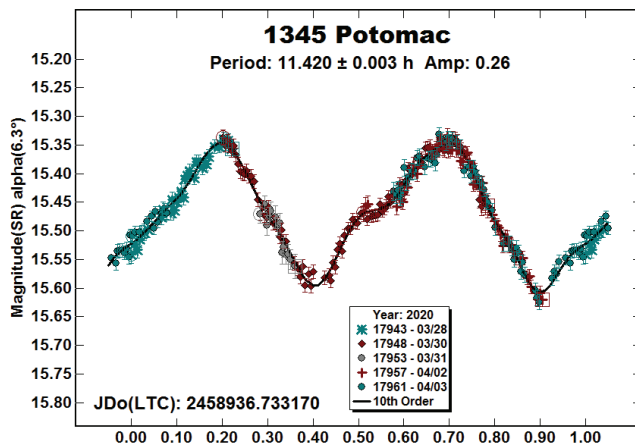
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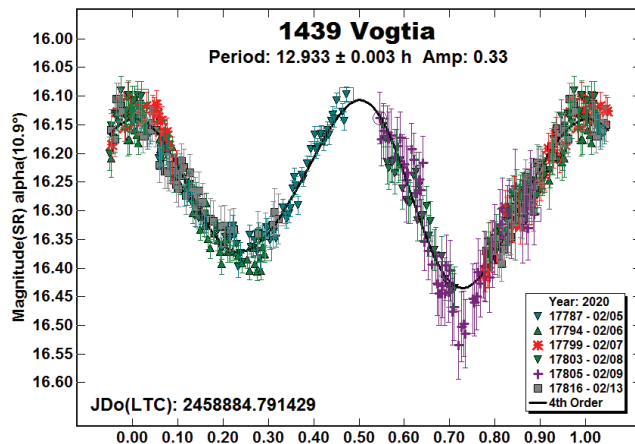


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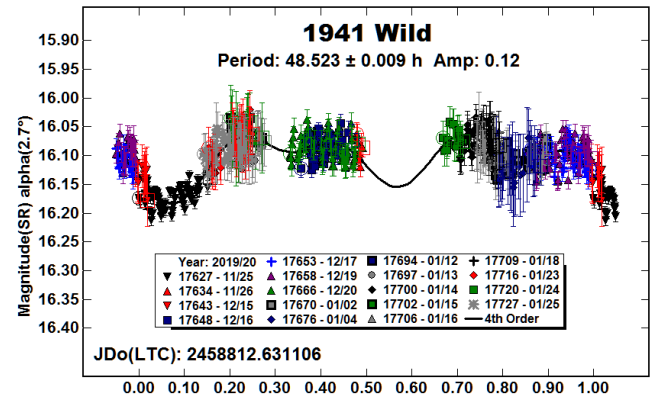
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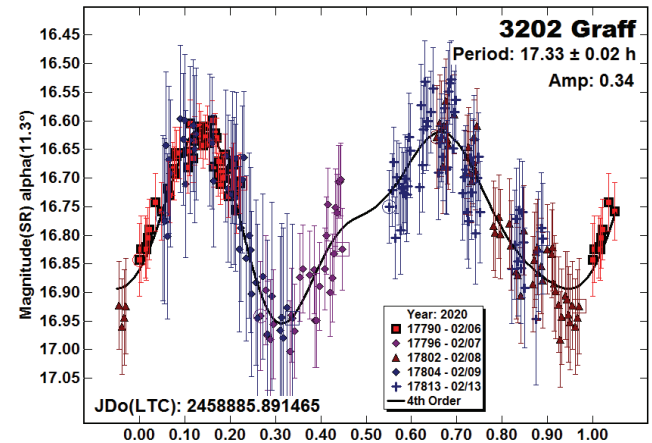
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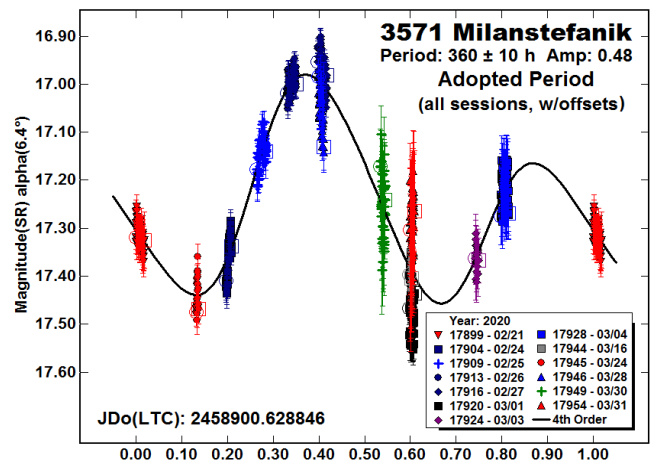
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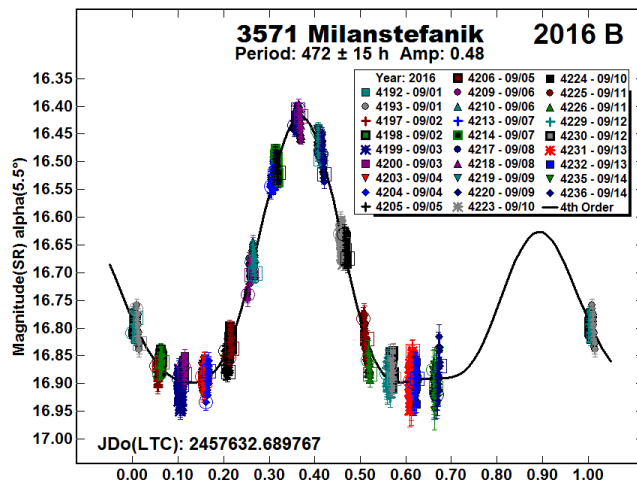
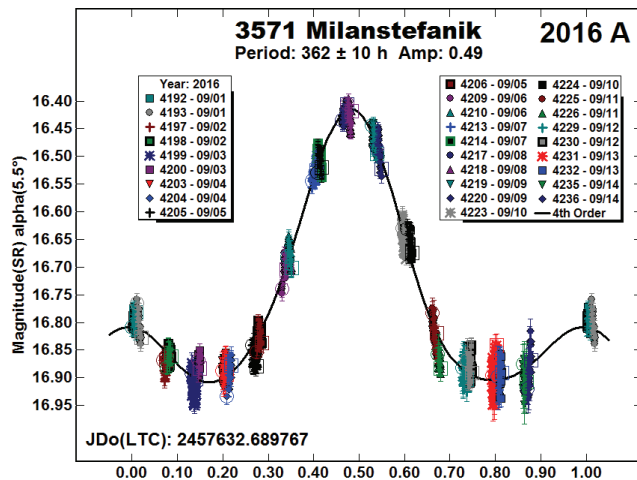
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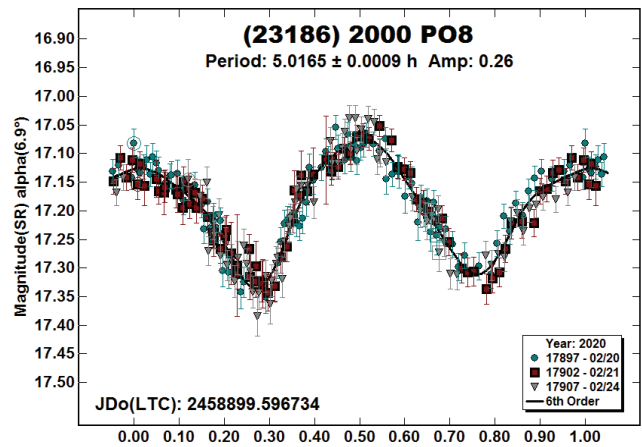
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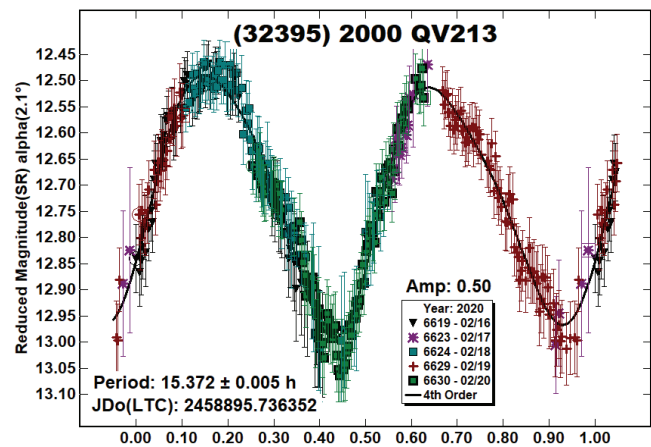


To solve the ambiguity will likely require a collaboration among individual or groups of observers who are well-separated in longitude.

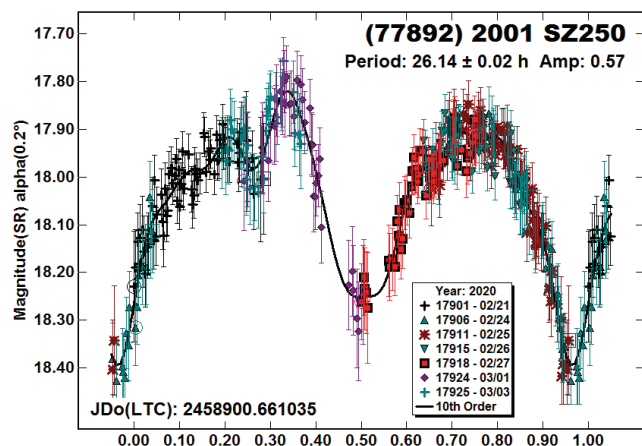
(23186) 2000 PO8. We observed this asteroid in 2017 (Warner and Stephens, 2018). Analysis of the data found a period of 5.003 h. Our 2020 data set led to $P = 5.0165$ h, which is in good agreement with our earlier result.



(32395) 2000 QV213. Waszczak et al. (2015) reported a period of 15.349h. Analysis of our denser data set found $P = 15.372$ h.



(77892) 2001 SZ250. This appears to be the first reported period for 2001 SZ250, which has an estimated diameter of 13 km. The “notch” at 0.25 rotation phase was seen on several occasions and so appears to have a physical cause.



Acknowledgements

Funding for observations at CS3 and work on the asteroid lightcurve database (Warner et al., 2009) and ALCDEF database (*alcdef.org*) are supported by NASA grant 80NSSC18K0851.

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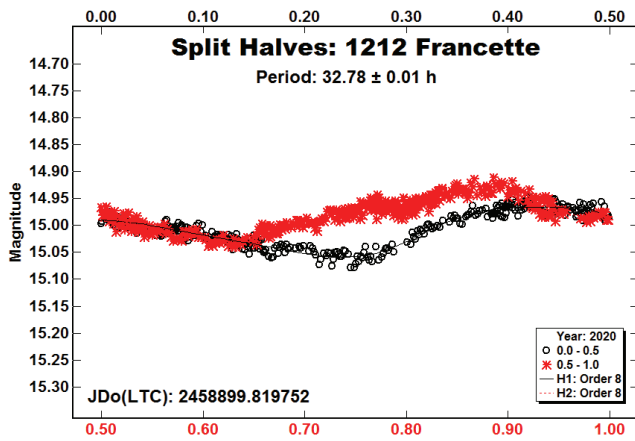
The authors gratefully acknowledge Shoemaker NEO Grants from the Planetary Society (2007, 2013). These were used to purchase some of the telescopes and CCD cameras used in this research.

References

- Brinsfield, J.W. (2010). "Asteroid Lightcurve Analysis at Via Capote Observatory: 4th Quarter 2009." *Minor Planet Bull.* **37**, 50-53.
- 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.
- Harris, A.W.; Young, J.W.; Scaltriti, F.; Zappala, V. (1984). "Lightcurves and phase relations of the asteroids 82 Alkmene and 444 Gytis." *Icarus* **57**, 251-258.
- 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>
- Pál, A.; Szakáts, R.; Kiss, C.; Bódi, A.; Bognár, Z.; Kalup, C.; Kiss, L.L.; Marton, G.; Molnár, L.; Plachy, E.; Sárneczky, K.; Szabó, G.M.; Szabó, R. (2020). "Solar System Objects Observed with TESS—First Data Release: Bright Main-belt and Trojan Asteroids from the Southern Survey." *Ap. J. Supl. Ser.* **247**, id.26.
- 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.
- Rubincam, D.P. (2000). "Relative Spin-up and Spin-down of Small Asteroids." *Icarus* **148**, 2-11.
- Stephens, R.D. (2016). "Asteroids Observed from CS3: 2015 July - September." *Minor Planet Bull.* **43**, 52-56.
- Tonry, J.L.; Denneau, L.; Flewelling, H.; Heinze, A.N.; Onken, C.A.; Smartt, S.J.; Stalder, B.; Weiland, H.J.; Wolf, C. (2018). "The ATLAS All-Sky Stellar Reference Catalog." *Astrophys. J.* **867**, A105.
- Warner, B.D.; Harris, A.W.; Pravec, P. (2009). "The Asteroid Lightcurve Database." *Icarus* **202**, 134-146. Updated 2020 March. <http://www.minorplanet.info/lightcurvedatabase.html>
- Warner, B.D.; Stephens, R.D. (2017). "Lightcurve Analysis of Hilda Asteroids at the Center for Solar System Studies: 2016 June-September." *Minor Planet Bull.* **44**, 36-41.
- Warner, B.D.; Stephens, R.D. (2018). "Lightcurve Analysis of Hilda Asteroids at the Center for Solar System Studies: 2017 July through September." *Minor Planet Bull.* **45**, 35-39.
- Warner, B.D.; Stephens, R.D.; Coley, D.R. (2017). "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.; Coley, D.R. (2018). "Lightcurve Analysis of Hilda Asteroids at the Center for Solar System Studies: 2017 October-December." *Minor Planet Bull.* **45**, 147-161.
- Waszczak, A.; Chang, C.-K.; Ofek, E.O.; Laher, R.; Masci, F.; Levitan, D.; Surace, J.; Cheng, Y.-C.; Ip, W.-H.; Kinoshita, D.; Helou, G.; Prince, T.A.; Kulkarni, S. (2015). "Asteroid Light Curves from the Palomar Transient Factory Survey: Rotation Periods and Phase Functions from Sparse Photometry." *Astron. J.* **150**, A75.

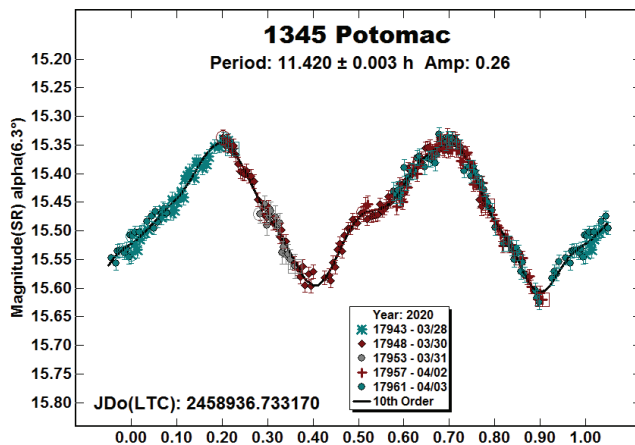
Number	Name	2020/mm/dd	Phase	L _{PAB}	B _{PAB}	Period(h)	P.E.	Amp	A.E.
1202	Marina	02/09-02/13	8.2, 9.0	107	3	9.558	0.005	0.30	0.03
1212	Francette	02/20-03/04	13.1, 10.2	196	6	32.78	0.01	0.13	0.01
1345	Potomac	03/28-04/03	6.3, 5.1	207	12	11.420	0.003	0.26	0.02
1439	Vogtia	02/05-02/13	10.9, 9.0	174	4	12.933	0.003	0.37	0.03
1941	Wild	11/25-01/25	2.7, 17.0	58	0	48.523	0.009	0.12	0.02
3202	Graff	02/06-02/13	11.4, 9.9	178	-7	17.33	0.02	0.34	0.04
3571	Milanstefanik	2016/09/01-09/14	5.5, 2.6	356	9	362	10	0.49	0.05
						^A 472	15	0.48	0.05
3571	Milanstefanik	2020/02/21-03/31	6.4, 12.7	128	-8	360	10	0.50	0.05
23186	2000 PO8	02/20-02/24	6.9, 7.9	129	9	5.0165	0.0009	0.26	0.03
32395	2000 QV213	02/16-02/20	2.1, 1.0	153	2	15.372	0.005	0.50	0.03
77892	2001 SZ250	02/21-03/03	0.2, 3.9	152	0	26.14	0.02	0.57	0.04

Table II. Observing circumstances. ^AAlternate period. The phase angle (α) is given at the start and end of each date range. L_{PAB} and B_{PAB} are the average phase angle bisector longitude and latitude (see Harris *et al.*, 1984). An amplitude in italics overrides the value in the plot.

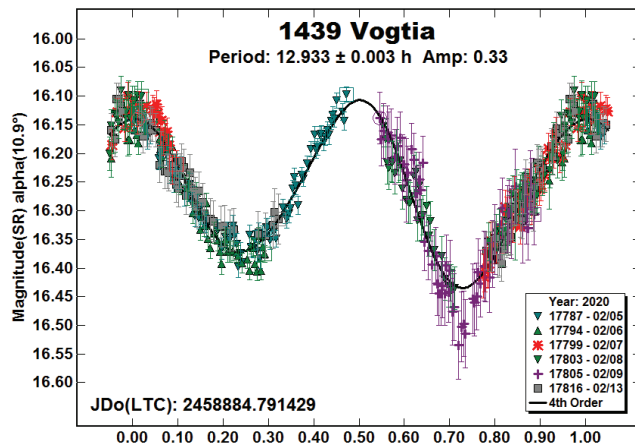


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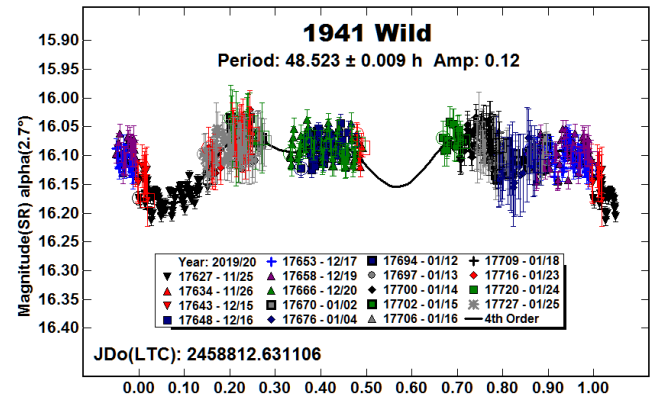
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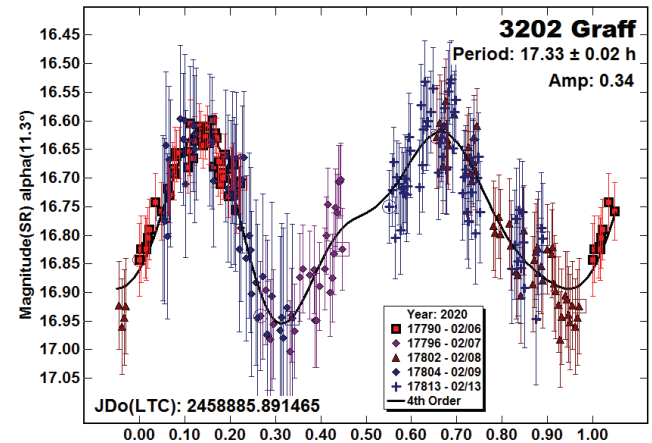
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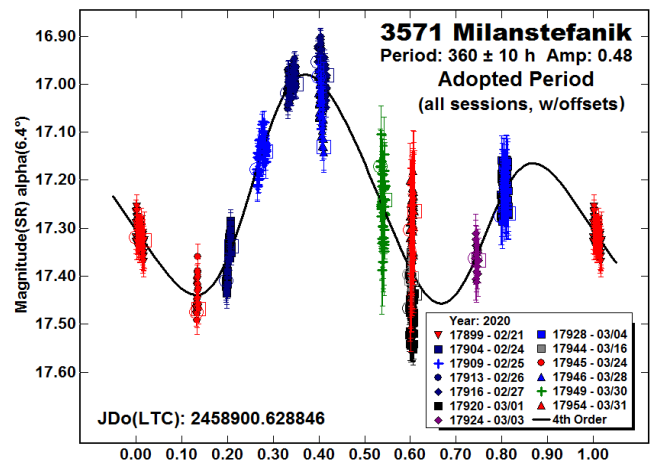
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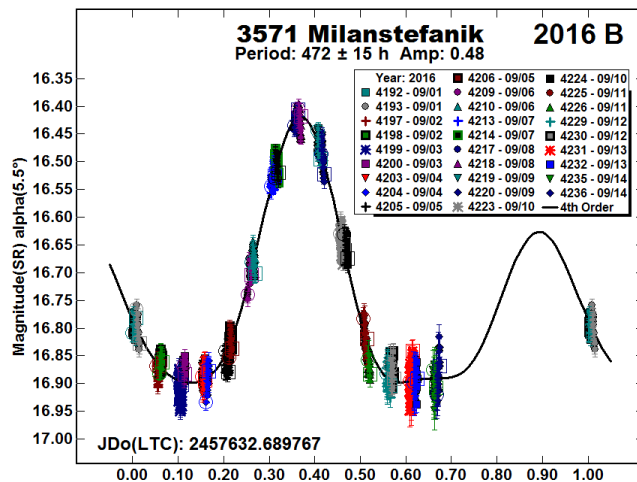
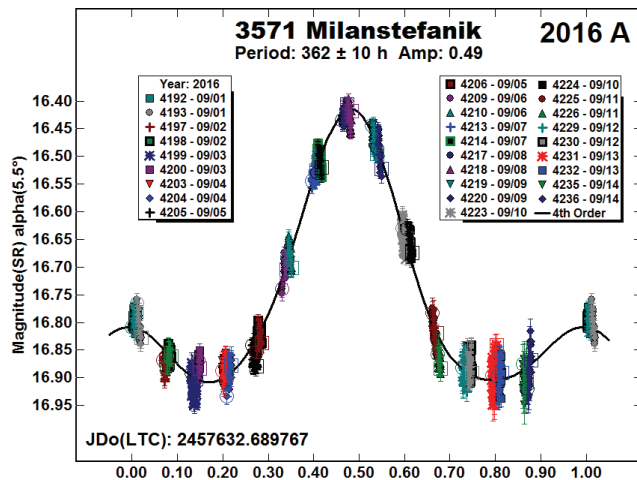
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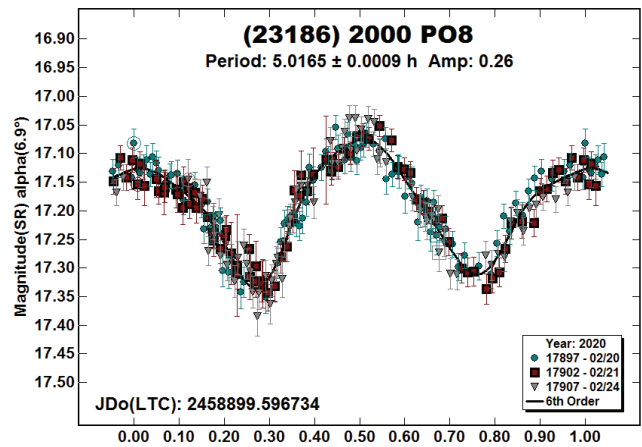
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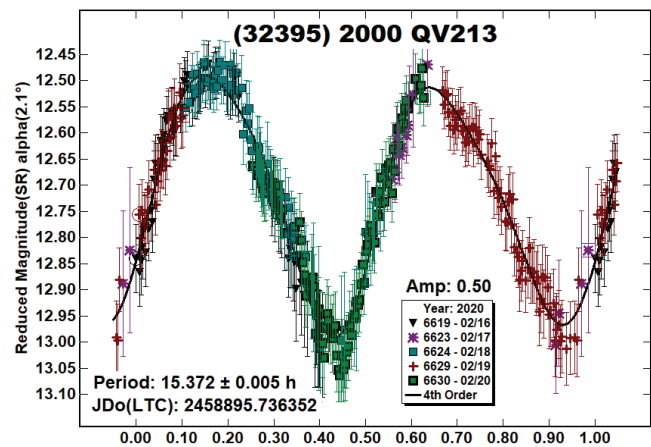


To solve the ambiguity will likely require a collaboration among individual or groups of observers who are well-separated in longitude.

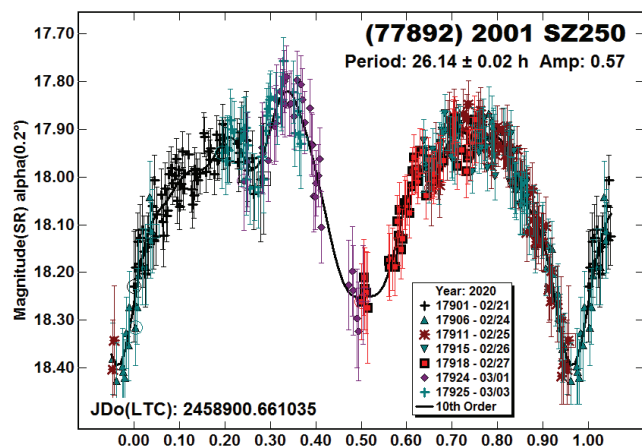
(23186) 2000 PO8. We observed this asteroid in 2017 (Warner and Stephens, 2018). Analysis of the data found a period of 5.003 h. Our 2020 data set led to $P = 5.0165$ h, which is in good agreement with our earlier result.



(32395) 2000 QV213. Waszczak et al. (2015) reported a period of 15.349h. Analysis of our denser data set found $P = 15.372$ h.



(77892) 2001 SZ250. This appears to be the first reported period for 2001 SZ250, which has an estimated diameter of 13 km. The “notch” at 0.25 rotation phase was seen on several occasions and so appears to have a physical cause.



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