

LIGHTCURVE ANALYSIS OF L5 TROJAN ASTEROIDS AT THE CENTER FOR SOLAR SYSTEM STUDIES: 2020 APRIL TO JUNE

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Lightcurves for nine L5 Jovian Trojan asteroids were obtained at the Center for Solar System Studies (CS3) from 2020 April to June.

CCD Photometric observations of nine Trojan asteroids from the L₅ (Trojan) Lagrange point were obtained at the Center for Solar System Studies (CS3, MPC U81). For several years, CS3 has been conducting a study of Jovian Trojan asteroids. This is another in a series of papers reporting data analysis being accumulated for family pole and shape model studies. It is anticipated that for most Jovian Trojans, two to five dense lightcurves per target at oppositions well distributed in ecliptic longitudes will be needed and can be supplemented with reliable sparse data for the brighter Trojan asteroids. For six of these targets we were able to get preliminary pole positions and create shape models from sparse data and the dense lightcurves obtained to date. These preliminary models will be improved as more data are acquired at future oppositions and will be published at a later date.

Table I lists the telescopes and CCD cameras that were used to make the observations. Images were unbinned with no filter and had master flats and darks applied. The exposures depended upon various factors including magnitude of the target, sky motion, and Moon illumination.

Telescope	Camera
0.40-m f/10 Schmidt-Cass	FLI Proline 1001E
0.40-m f/10 Schmidt-Cass	Fli Microline 1001E
0.35-m f/10 Schmidt-Cass	Fli Microline 1001E

Table I. List of telescopes and CCD cameras used at CS3.

Image processing, measurement, and period analysis were done using *MPO Canopus* (Bdw Publishing), which incorporates the Fourier analysis algorithm (FALC) developed by Harris (Harris et al., 1989). The Comp Star Selector feature in *MPO Canopus* was used to limit the comparison stars to near solar color. Night-to-night calibration was done using field stars from the ATLAS catalog (Tonry et al., 2018), which has Sloan *griz* magnitudes that were derived from the GAIA and Pan-STARR catalogs and are the “native” magnitudes of the catalog.

To reduce the number of times and amount of resetting nightly zero points, we use the ATLAS *r'* (SR) magnitudes. Those adjustments are mostly ≤ 0.03 mag. The occasions where larger corrections were required may have been related in part to using unfiltered observations, poor centroiding of the reference stars, and not correcting for second-order extinction terms.

Unless otherwise indicated, the Y-axis of lightcurves are ATLAS SR “sky” (catalog) magnitudes. During period analysis, the magnitudes were normalized to the phase angle given in parentheses using $G = 0.15$. The X-axis rotational phase ranges from -0.05 to 1.05 .

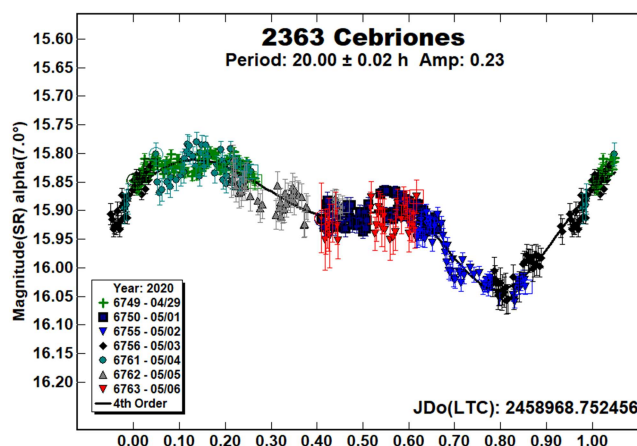
The amplitude indicated in the plots (e.g. Amp. 0.23) is the amplitude of the Fourier model curve and not necessarily the adopted amplitude of the lightcurve.

Targets were selected for this L₅ observing campaign were mostly based upon the availability of dense lightcurves acquired in previous years. We obtained two to four lightcurves for most of these Trojans at previous oppositions.

For brevity, only some of the previously reported rotational periods may be referenced. A complete list is available at the asteroid lightcurve database (LCDB; Warner et al., 2009).

To evaluate the quality of the data obtained and to determine how much more data might be needed, preliminary pole and shape models were created for all of these targets. Sparse data observations were obtained from the Catalina Sky Survey and USNO-Flagstaff survey using the AstDyS-2 site (2020). These sparse data were combined with our dense data as well as any other dense data found in the Asteroid Lightcurve Data Exchange Format database (ALCDEF, 2020) using *MPO LCInvert*, (Bdw Publishing). This Windows-based program incorporates the algorithms developed by Kaasalainen and Torppa (2001a) and Kaasalainen et al. (2001b) and converted by Josef Durech from the original FORTRAN to C. A period search was made over a sufficiently wide range to assure finding a global minimum in χ^2 values.

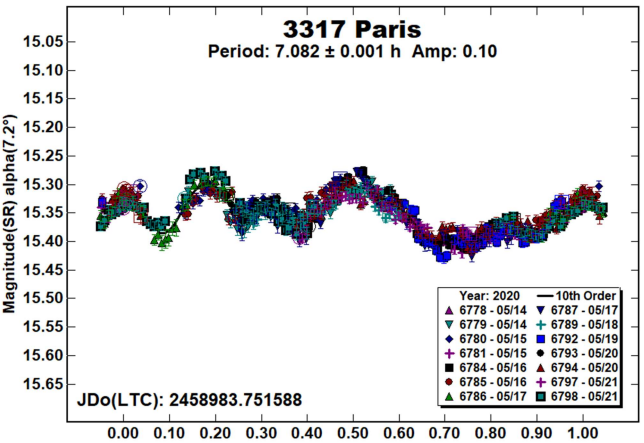
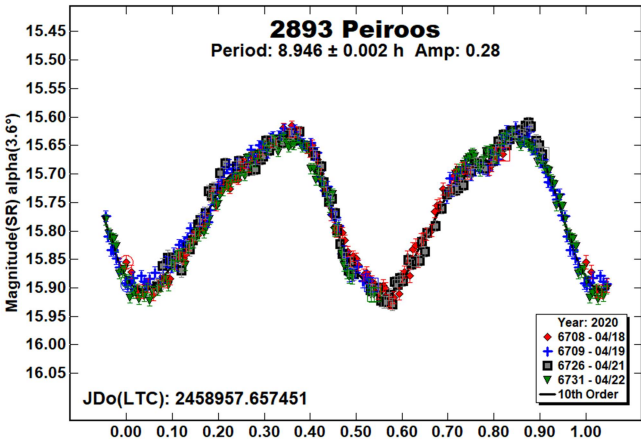
2363 Cebiriones. Reliable rotational rates for this Trojan were obtained four times in the past (Galad and Kornos, 2008; Mottola et al., 2011; Skiff et al., 2019; Stephens and Warner 2019b), each time finding a period near 20.1 h. The 2020 results are in good agreement. Using sparse data from the AstDys-2 (2020) and ALCDEF (2020) sites, a preliminary shape model with a sidereal rotational period of 20.118791 ± 0.00001 h was created.



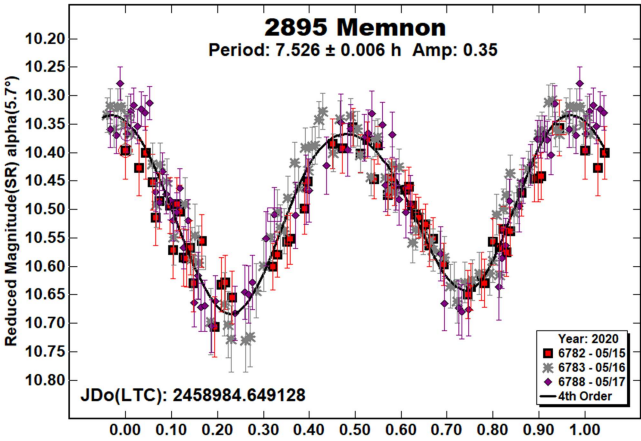
2893 Peiroos. We observed Peiroos four times in the past. Lightcurves were obtained in 2015, 2016, 2017 and 2019 (Stephens and Warner, 2019a and references therein). The data collected this year, when combined with our previous data and available sparse data, were used to create a preliminary shape model with a sidereal rotational period of 8.94893 ± 0.00001 h.

Number	Name	2020 mm/dd	Phase	L _{PAB}	B _{PAB}	Period(h)	P.E.	Amp	A.E.
2363	Cebriones	04/29-05/06	7.1, 6.2	247	21	20.00	0.02	0.23	0.03
2893	Peiroos	04/18-04/22	3.6, 3.6	211	16	8.946	0.002	0.28	0.02
2895	Memnon	05/15-05/17	5.7, 5.6	237	29	7.526	0.006	0.35	0.03
3317	Paris	05/14-05/21	7.2, 7.6	222	31	7.082	0.001	0.10	0.01
3451	Mentor	04/23-04/28	8.2, 7.6	247	25	7.695	0.002	0.11	0.01
5144	Achates	04/12-04/18	4.9, 5.9	178	-6	5.959	0.001	0.21	0.02
5476	1989 TO11	05/01-05/04	2.2, 1.9	227	7	5.759	0.003	0.31	0.03
12444	Prothoon	05/22-06/10	6.1, 9.1	213	2	15.676	0.004	0.33	0.03
12929	1999 TZ1	04/19-04/29	7.6, 6.8	236	30	9.272	0.004	0.15	0.03
		2019/05/26-06/02	7.3, 8.3	208	11	9.27	0.01	0.08	0.02

Table II. Observing circumstances and results. The phase angle is given for the first and last date. L_{PAB} and B_{PAB} are the approximate phase angle bisector longitude/latitude at mid-date range (see Harris et al., 1984).

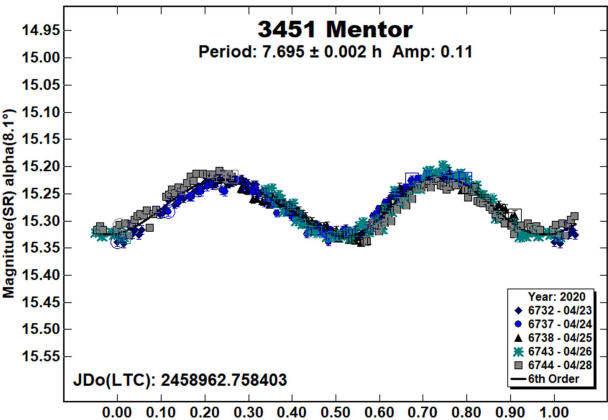


2895 Memnon. The synodic period we found this year agrees with previous synodic results (Binzel and Sauter, 1992; Mottola et al., 2011; French et al., 2011; Stephens et al., 2015, 2016; Stephens and Coley, 2017; Stephens and Warner, 2018). These data were combined with available sparse data to find a preliminary shape model with a sidereal rotational period of 7.519252 ± 0.00001 h.

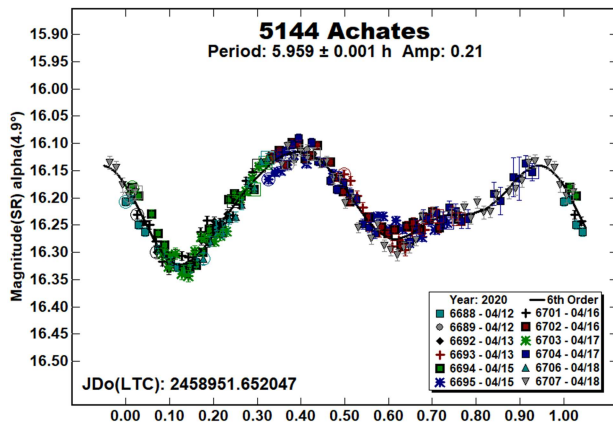


3317 Paris. The synodic period found in 2020 agrees with previous synodic results (Mottola et al., 2011; Stephens and Warner, 2019a and references therein). All of these previous periods were near 7.08 h. The results in 2020 are in good agreement and, when combined with our previous data and available sparse data, were used to create a preliminary shape model with a sidereal rotational period of 7.08100 ± 0.00001 h.

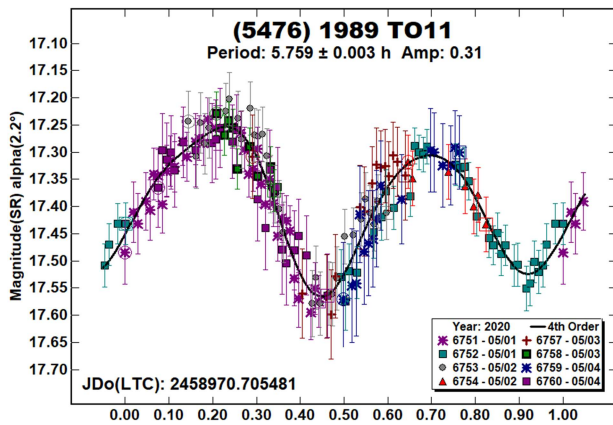
3451 Mentor. We observed this Trojan four times in the past (Stephens and Coley, 2017 and references therein), each time finding a period near 7.69 h. The 2020 data resulted in a bimodal lightcurve with a period that in good agreement with those prior results. We were able to create a preliminary shape model with a sidereal rotational period of 7.6966367 ± 0.000001 h and an ecliptic longitude/latitude of $84^\circ/10^\circ$. In the Database of Asteroid Models from Inversion Techniques (DAMIT, 2020) website, Durech reports an ecliptic longitude/latitude of $81^\circ/18^\circ$, close to our preliminary model.



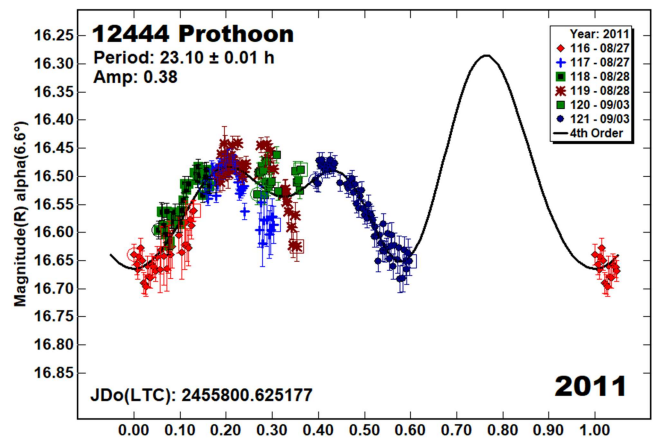
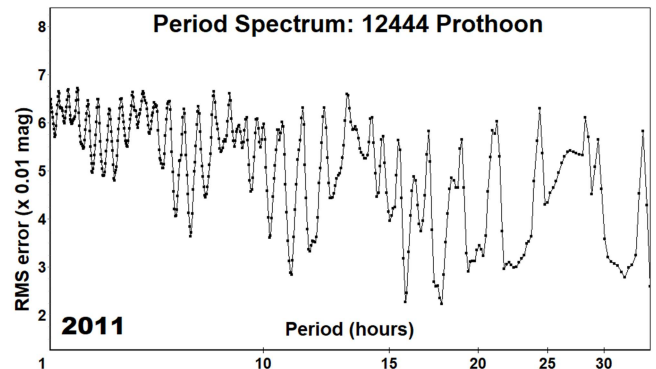
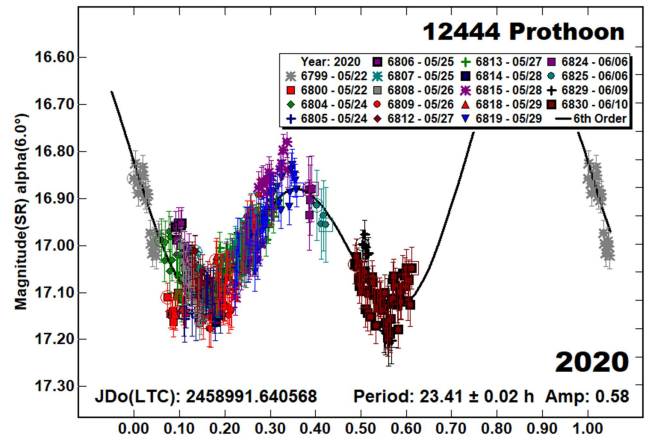
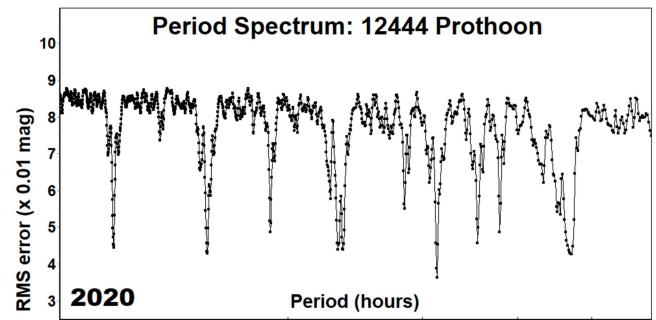
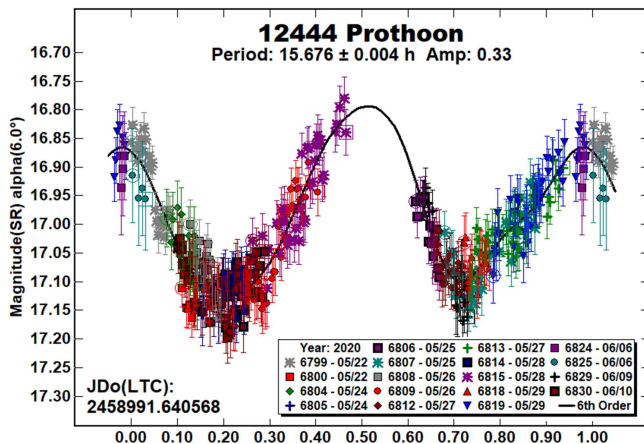
5144 Achates. This Trojan was observed five times in the past (Molnar et al., 2008; Mottola et al., 2011; Stephens et al., 2015; Stephens and Warner, 2018, 2019a), each time finding a period near 5.95 h. The 2019 results are in good agreement and were used to create a preliminary shape model with a sidereal rotational period of 5.95392 ± 0.00001 h.



(5476) 1989 TO11. Only one prior rotational period is reported in the lightcurve database (LCDB; Warner et al., 2009). Mottola et al. (2011) reported a rotational period of 5.780 h from observations obtained in 1994. Our result this year of 5.759 h has a denser dataset over four consecutive nights and is in good agreement.



12444 Prothoon. From our data in 2011 (French et al., 2012) we reported a rotational period of 15.82 h. The data we collected in 2020 were a reasonable fit to that rotational period. Using data from the Transiting Exoplanet Survey Satellite (TESS), Pál et al. (2020) found a rotational period of 23.10 h, a 2:3 alias of our period. The period spectrums for both the 2011 and 2019 data show periods near 23 h. The 2011 lightcurve rephased to approximately 23 h has a bad fit and the 2020 rephased lightcurve has an unlikely shape with the extrema being only 0.3 phase apart.

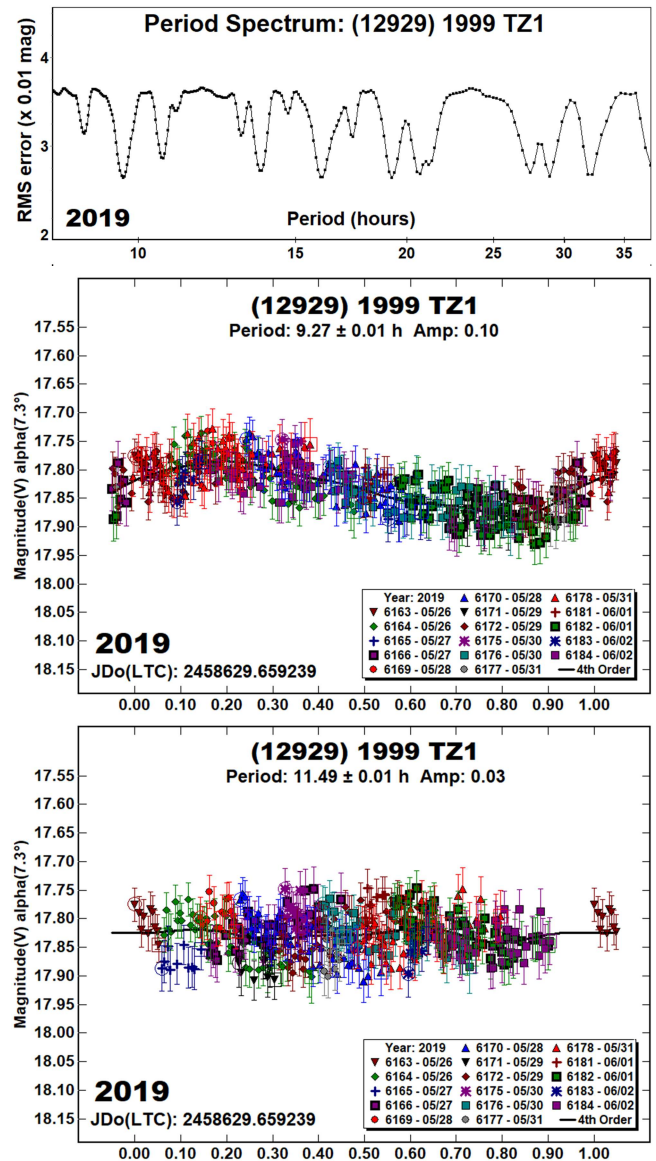
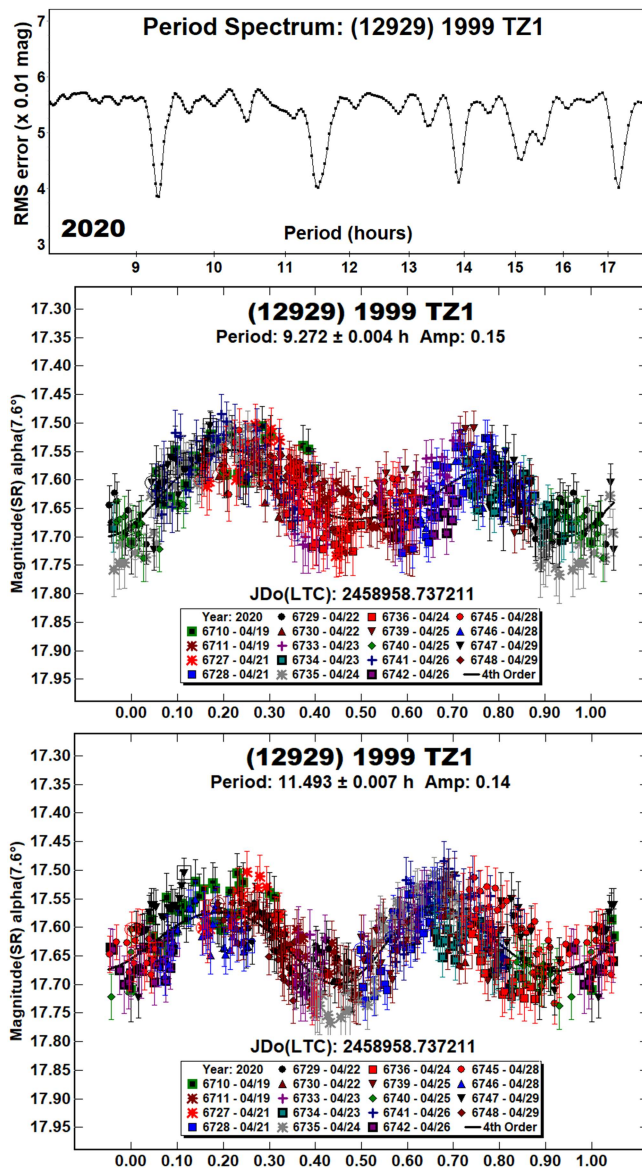


(12929) 1999 TZ1. This L₅ Jovian Trojan has been observed several times in the past. Moullet et al. (2008) observed it in 2007 reporting a rotational period of 10.4 h from sparse data over 12 nights. The resulting lightcurve was a poor fit. Over seven nights in 2009, Mottola et al. (2011) used sparse data and found a rotational period of 9.2749 h with a single extremum. Thirouin et

al. (2010) used sparse data over six nights in 2007 to find two ambiguous periods, a bimodal 5.211 h period and a 10.422 h period with four extrema. Both lightcurves show scatter equal to the 0.07 mag. amplitude. Our period of 13.73 h from our 2019 data (Stephens and Warner, 2019b) is based on a much denser dataset but still had an ambiguous solution.

The period spectrum for our 2020 data shows possible solutions near 9.3 h, 11.5 h, and 13.8 h. Those latter periods being 4:5 and 2:3 aliases of the 9.3 h period. Phasing the 2020 data to a 13.8 h period resulted in a noisy and improbable three extrema lightcurve. Phasing the 2020 data to either 9.27 h or 11.49 h resulted in bimodal lightcurves, with the 9.27 h solution being slightly asymmetric. To break the tie, we rephased the 2019 data to both the 9.27 h and 11.49 h periods. The 9.27 h 2019 period resulted in a single modal lightcurve. No reasonable period could be found near 11.5 h for the 2019 data.

Our preferred solution, and the one adopted for this paper, is 9.272 h for the 2020 data and 9.27 h for the 2019 data. Both are in good agreement with the Mottola result which had a 0.17 mag amplitude, per the LCDB, the highest reported for any opposition.



Acknowledgements

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References

- AstDys-2 (2020). Asteroids – Dynamic web site.
<https://newton.spacedys.com/astdys/>
- ALCDEF (2020). Asteroid Lightcurve Data Exchange Format database. <http://www.alcdef.org/>
- DAMIT (2020). Database of Asteroid Models from Inversion Techniques (DAMIT).
<https://astro.troja.mff.cuni.cz/projects/damit/>
- Binzel, R.P.; Sauter, L.M. (1992). “Trojan, Hilda, and Cybele asteroids - New lightcurve observations and analysis.” *Icarus* **95**, 222-238.
- French, L.M.; Stephens, R.D.; Lederer, S.M.; Coley, D.R.; Rhol, D.A. (2011). “Preliminary Results from a Study of Trojan Asteroids.” *Minor Planet Bull.* **38**, 183-187.
- French, L.M.; Stephens, R.D.; Coley, D.R.; Megna, R.; Wasserman, L.H. (2012). “Photometry of 17 Jovian Trojan Asteroids.” *Minor Planet Bull.* **39**, 116-120.
- Galad, A.; Kornos, L. (2008). “A Collection of Lightcurves from Modra: 2007 December - 2008 June.” *Minor Planet Bull.* **35**, 114-146.
- 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.; 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.
- Kaasalainen, M.; Torppa, J. (2001a). “Optimization Methods for Asteroid Lightcurve Inversion. I. Shape Determination.” *Icarus* **153**, 24-36.
- Kaasalainen, M.; Torppa, J.; Muinonen, K. (2001b). “Optimization Methods for Asteroid Lightcurve Inversion. II. The Complete Inverse Problem.” *Icarus* **153**, 37-51.
- Molnar, L.A.; Jaegert, M.J.; Hoogetboom, K.M. (2008). “Lightcurve Analysis of an Unbiased Sample of Trojan Asteroids.” *Minor Planet Bull.* **35**, 82-84.
- Mottola, S.; Di Martino, M.; Erikson, A.; Gonano-Beurer, M.; Carbognani, A.; Carsenty, U.; Hahn, G.; Schober, H.; Lahulla, F.; Delbò, M.; Lagerkvist, C. (2011). “Rotational Properties of Jupiter Trojans. I. Light Curves of 80 Objects.” *Astron. J.* **141**, A170.
- Moulet, A.; Lellouch, E.; Doressoundiram, A.; Ortiz, J.L.; Duffard, R.; Morbidelli, A.; Vernazza, P.; Moreno, R. (2008). “Physical and dynamical properties of (12929) 1999 TZ1 suggest that it is a Trojan.” *Astron. and Astrophys.* **483**, L17-L20.
- Pál, A.; Szakáts, R.; Kiss, C.; Bódi, A.; Bognár, Z.; Kalup, C.; Kiss, L.; Marton, G.; Molnár, L.; Plachy, E.; Sárneczky, K.; Szabó, G.; Szabó, R. (2020). “Solar System Objects Observed with TESS - First Data Release: Bright Main-belt and Trojan Asteroids from the Southern Survey.” *Astron. J.* **247**, id 26.
- Skiff, B.A.; McLelland, K.P.; Sanborn, J.J.; Pravec, P.; Koehn, B.W. (2019). “Lowell Observatory Near-Earth Asteroid Photometric Survey (NEAPS): Paper 3.” *Minor Planet Bull.* **46**, 238-265.
- Stephens, R.D.; Coley, D.R.; French, L.M. (2015). “Dispatches from the Trojan Camp - Jovian Trojan L5 Asteroids Observed from CS3: 2014 October - 2015 January.” *Minor Planet Bull.* **42**, 216-224.
- Stephens, R.D.; Coley, D.R.; French, L.M. (2016). “A Report from the L5 Trojan Camp - Lightcurves of Jovian Trojan Asteroids from the Center for Solar System Studies.” *Minor Planet Bull.* **43**, 265-270.
- Stephens, R.D.; Coley, D.R. (2017). “Lightcurve Analysis of Trojan Asteroids at the Center for Solar System Studies 2017 January - March.” *Minor Planet Bull.* **44**, 252-257.
- Stephens, R.D.; Warner, B.D. (2018). “Lightcurve Analysis of L5 Trojan Asteroids at the Center for Solar System Studies 2018 April to May.” *Minor Planet Bull.* **45**, 343-347.
- Stephens, R.D.; Warner, B.D. (2019a). “Lightcurve Analysis of L5 Trojan Asteroids at the Center for Solar System Studies: 2019 January to March.” *Minor Planet Bull.* **46**, 315-317.
- Stephens, R.D.; Warner, B.D. (2019b). “Lightcurve Analysis of L5 Trojan Asteroids at the Center for Solar System Studies: 2019 April to June.” *Minor Planet Bull.* **46**, 389-392.
- Thirouin, A.; Ortiz, J.L.; Duffard, R.; Santos-Sanz, P.; Aceituno, F.J.; Morales, N. (2010). “Short-term variability of a sample of 29 trans-Neptunian objects and Centaurs.” *Astron. and Astrophys.* **522**, A93.
- 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 June.
<http://www.minorplanet.info/lightcurvedatabase.html>