

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.

Koff, R.A. (2000). "Rotation Periods and Lightcurves of 536 Merapi and 760 Massinga." *Minor Planet Bull.* **27**, 26-27.

Koff, R.A. (2006). "Lightcurves of asteroids 141 Lumen, 259 Alatheia, 363 Padua, 455 Bruchsalia 514 Armida, 524 Fidelio, and 1139 Atami." *Minor Planet Bull.* **33**, 31-33.

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 Souther Survey." *Ap. J. Suppl. Ser.* **247**, id. 26.

Percy, S.C. (2019). "Rotation Period for 2326 Tololo." *Minor Planet Bull.* **46**, 13-14.

Polakis, T. (2020). "Photometric Observations of Thirty Minor Planets." *Minor Planet Bull.* **47**, 177-186.

Stephens, R.D. (2012). "Asteroids Observed from Santana, CS3 and GMARS Observatories: 2012 April - June." *Minor Planet Bull.* **39**, 226-228.

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." *Ap. J.* **867**, A105.

Warner, B.D.; Harris, A.W.; Pravec, P. (2009). "The Asteroid Lightcurve Database." *Icarus* **202**, 134-146. Updated 2020 Aug. <http://www.minorplanet.info/lightcurvedatabase.html>

Warner, B.D. (2011). Collaborative Asteroid Lightcurve Link website. <http://www.minorplanet.info/call.html>

Warner, B.D. (2020). MPO Canopus software. <http://bdwpublishing.com>

LIGHTCURVE ANALYSIS OF L4 AND L5 TROJAN ASTEROIDS AT THE CENTER FOR SOLAR SYSTEM STUDIES: 2021 APRIL TO JUNE

Robert D. Stephens
Center for Solar System Studies (CS3) / MoreData!
11355 Mount Johnson Ct., Rancho Cucamonga, CA 91737 USA
rstephens@foxandstephens.com

Daniel R. Coley
Center for Solar System Studies
Corona, CA

Brian D. Warner
Center for Solar System Studies (CS3) / MoreData!
Eaton, CO

(Received: 2021 July 13, Revised: 2021 August 22)

Lightcurves for two L5 Jovian Trojan asteroids were obtained at the Center for Solar System Studies (CS3) from 2021 April to June. In addition, recovered data from 2017 to 2019 allowed finding nine previously unreported periods and restating three previously reported Trojan rotational periods.

For several years, the Center for Solar System Studies (CS3, MPC U81) has been conducting a study of Jovian Trojan asteroids. This paper reports CCD photometric observations of two Trojan asteroids from the L₅ (Trojan) Lagrange point from 2021. In addition, a substantial dataset was recovered with unpublished observations from both the L₄ and L₅ Lagrange points from 2017 to 2019. That recovered dataset also allowed us to reevaluate previous published results for (11395) 1998 XN77 for 2015, 2016, and 2017.

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.

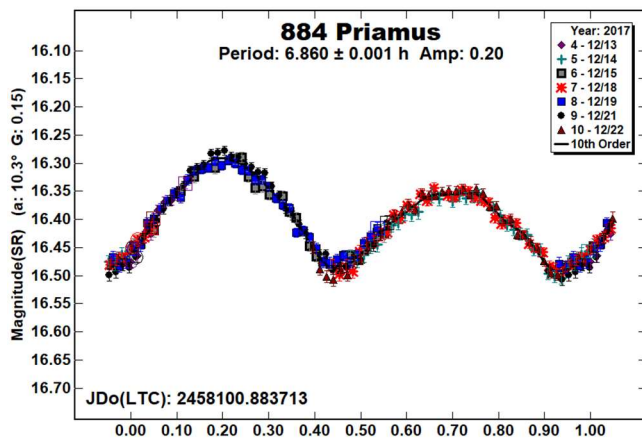
Image processing, measurement, and period analysis were done using *MPO Canopus* (Bdw Publishing), which incorporates the Fourier analysis algorithm (FALC) developed by Harris (Harris et al., 1989). The Comp Star Selector feature in *MPO Canopus* was used to limit the comparison stars to near solar color. 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.

Unless otherwise indicated, the Y-axis of lightcurves gives ATLAS SR “sky” (catalog) magnitudes. Some of the older recovered datasets used Johnson V or R (catalog) magnitudes. During period analysis, the magnitudes were normalized to the phase angle and value for G given in the parentheses. The X-axis rotational phase ranges from -0.05 to 1.05 .

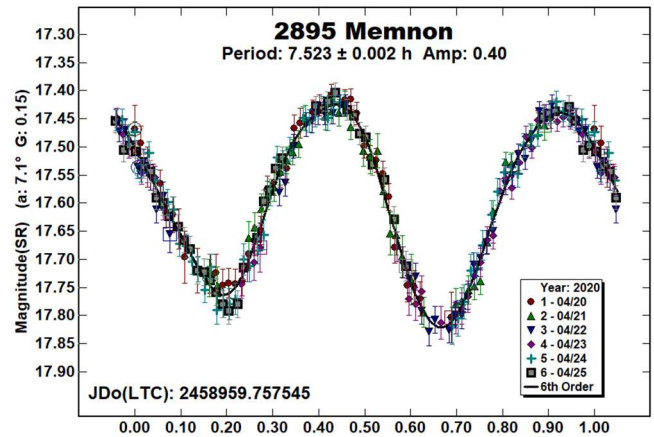
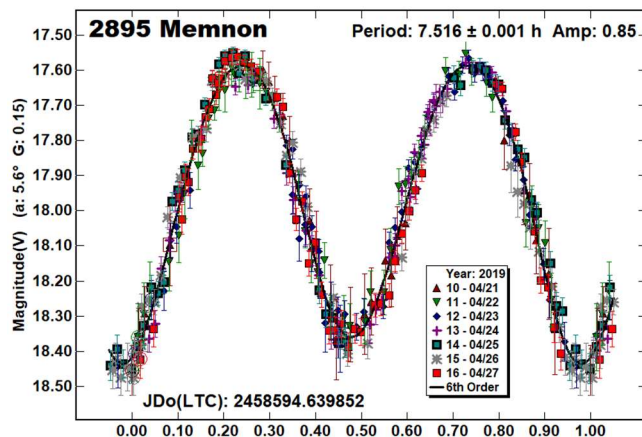
The amplitude indicated in the plots (e.g., Amp. 0.23) is the amplitude of the Fourier model curve and not necessarily the adopted amplitude of the lightcurve.

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

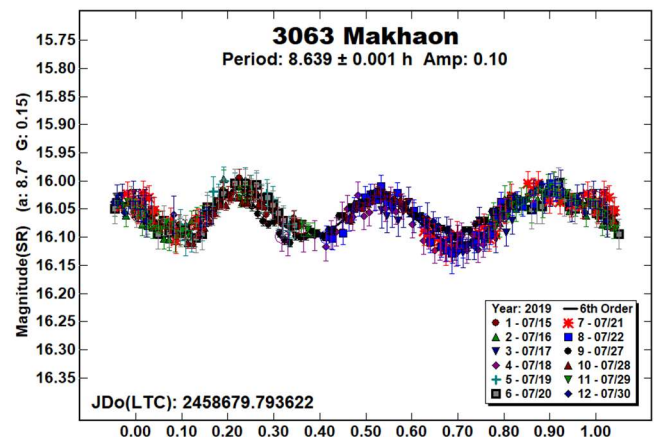
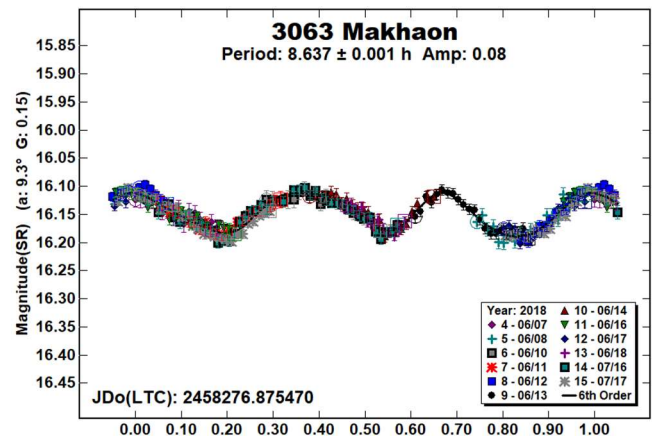
884 Priamus. Mottola et al. (2011) reported two periods for this L₅ Trojan. Stephens (2017, and references therein) also observed it four times in the past, each time finding a period near 6.86 h. The period from the 2017 recovered dataset is in good agreement with the past results.



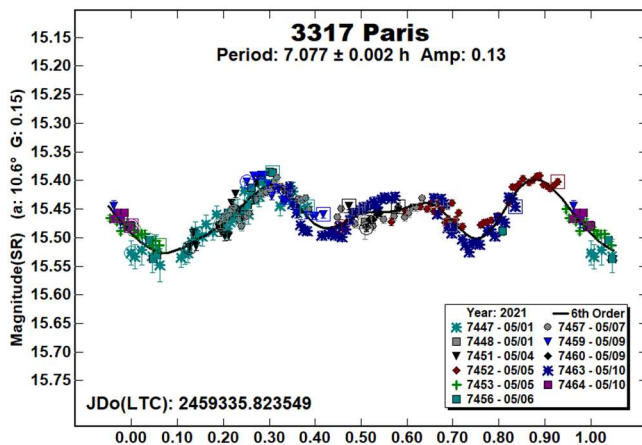
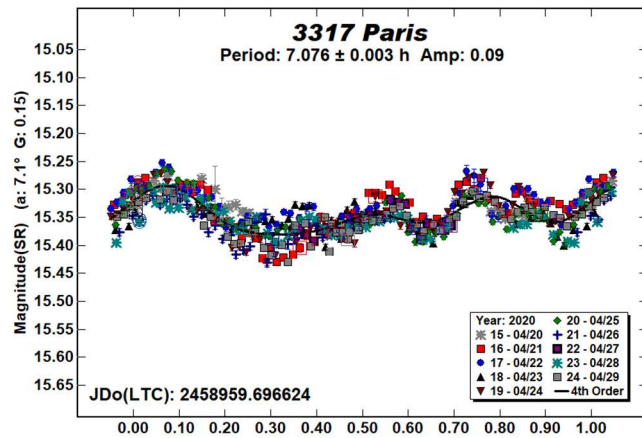
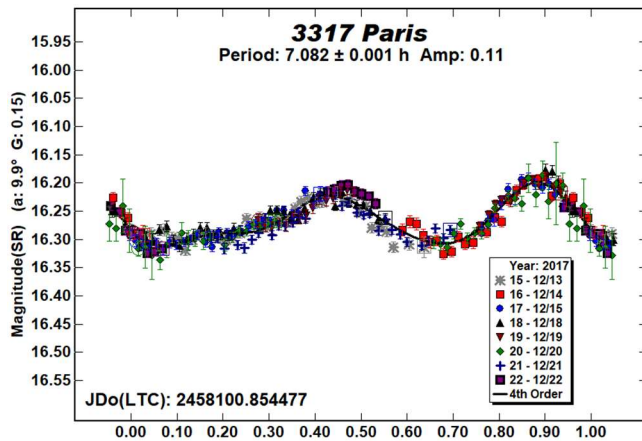
2895 Memnon. Stephens and Warner (2020a, and references therein) obtained rotational periods for this Trojan five times in the past, each time finding a period near 7.52 h. Two recovered datasets, one from 2019 and the other obtained a month before the previous 2020 data, produced periods that are in good agreement with the prior results.



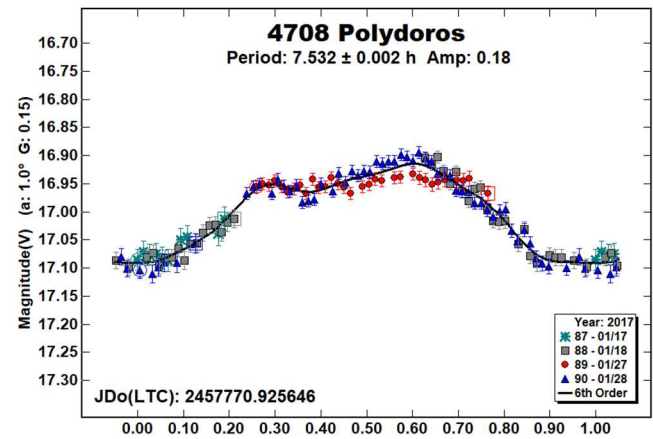
3063 Makhaon. Stephens and Warner (2020b, and references therein) observed this L₄ Trojan three times in the past. Mottola et al. (2011) also observed it twice. The results using the recovered datasets from 2018 and 2019 are in good agreement with those prior findings.



3317 Paris. This L₅ Trojan has been observed many times in the past (Mottola et al., 2011; Stephens and Warner, 2020a, and references therein). All of these previous periods were near 7.08 h. We recovered datasets from 2017 and 2020 and observed it again in 2021 May. The results from these three datasets are in good agreement with the prior results.

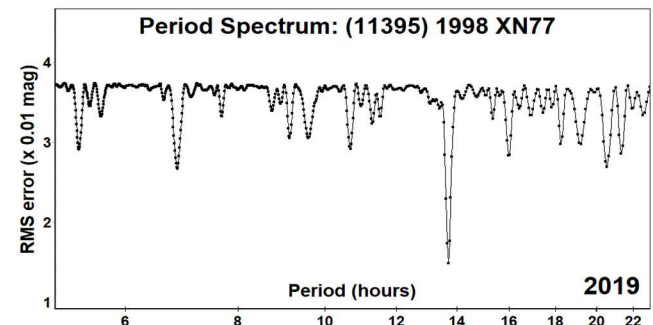
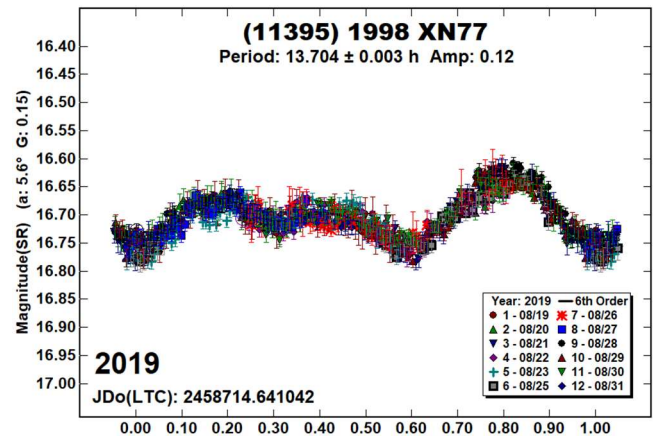


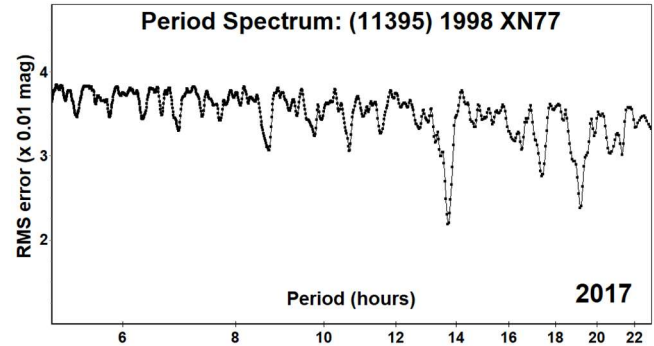
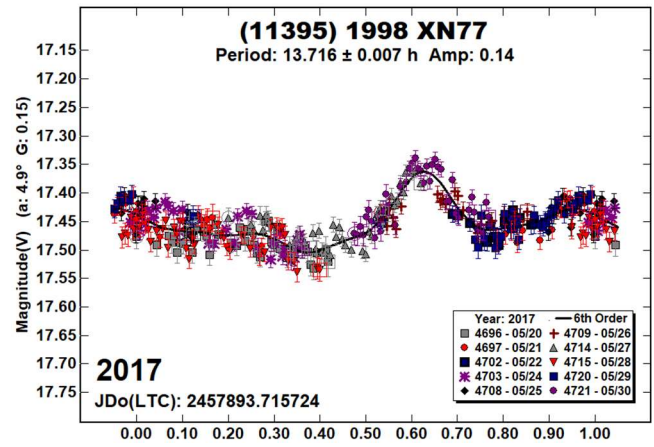
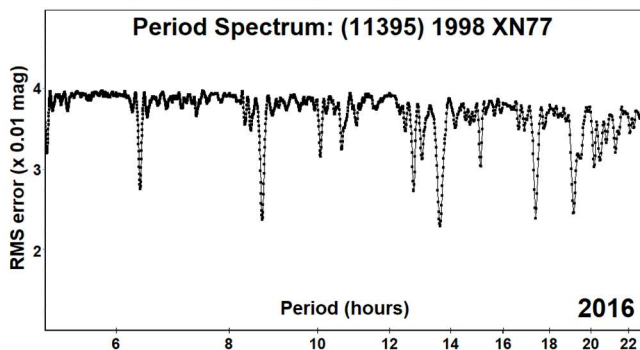
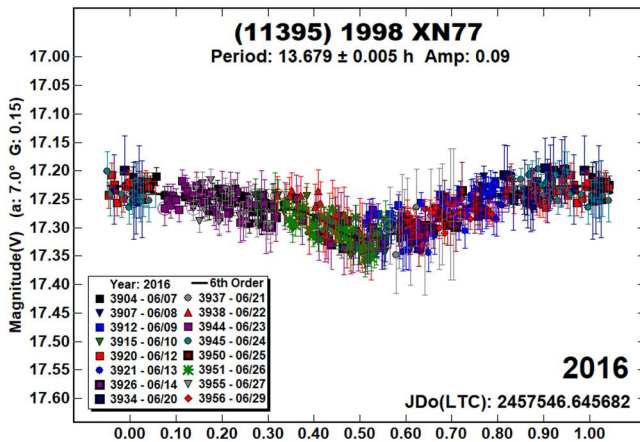
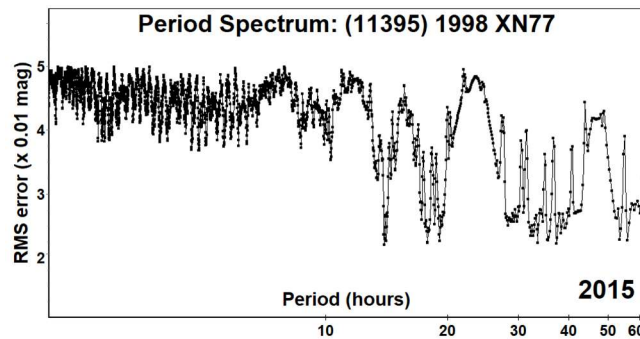
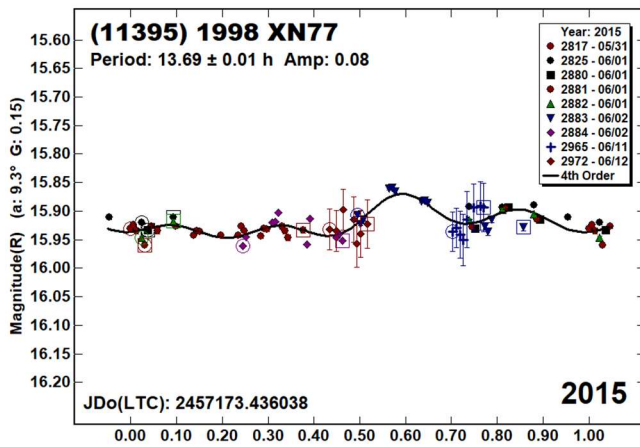
4708 Polydorus. Stephens and Warner (2018, and references therein) observed Polydorus four times in the past finding a common period near 7.5 h for all of the datasets. Using data from the TESS spacecraft, Pál et al. (2020) found a period of 7.51411 h. The results using recovered data from 2017 are in good agreement with the prior results.



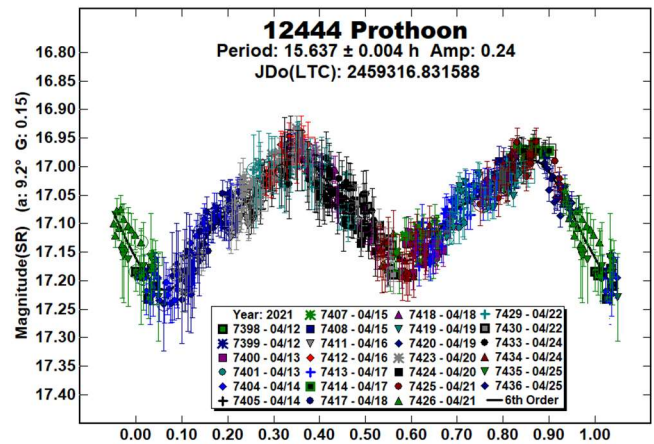
(11395) 1998 XN77. Determining a rotational period for this L₄ Trojan has always been difficult due to its low amplitude. It has been observed five times in the past, with the amplitude never exceeding 0.14 mag. Mottola et al. (2011) observed this Trojan in 2009 and 2010, finding periods of 13.70 h and 13.696 h, respectively. Stephens et al. (2016) and Stephens and Warner (2017) observed it three times. Our initial analysis found periods near 17.9 h with low amplitude asymmetric lightcurves.

A recovered dataset from 2019 had a 13.704 h period, ruled out the longer 17.9 h period, and confirmed the earlier Mottola rotational periods. We corrected some zero-point adjustments and rephase the 2015, 2016, and 2017 data to this period.





12444 Prothoon. This L₅ Trojan has been observed twice in the past (French et al., 2012; Stephens and Warner 2020a). Our results from 2021 are in good agreement with those findings. Using data from the TESS spacecraft, Pál et al. (2020) found a period of 23.1005 h, a 2:3 alias of our period. The period spectra for all three of our dense datasets show periods near 23 h. However, the 2011 lightcurve rephased to approximately 23 h has a bad fit and the 2020 and 2021 rephased lightcurves have an unlikely shape with the extrema being only 0.3 phase apart. This causes us to reject 23 h as a plausible period.



Number	Name	yy/mm/dd	Phase	L _{PAB}	B _{PAB}	Period(h)	P.E.	Amp	A.E.
884	Priamus	17/12/13-12/22	10.3,10.0	159	-5	6.860	0.001	0.20	0.02
2895	Memnon	19/04/21-04/27	5.6,5.7	203	29	7.516	0.001	0.85	0.02
2895	Memnon	20/04/20-04/25	7.1,6.7	238	29	7.523	0.002	0.40	0.01
3063	Makhaon	18/06/07-07/17	9.3,3.8	313	5	8.637	0.001	0.08	0.01
3063	Makhaon	19/07/15-07/30	8.7,6.9	342	10	8.639	0.001	0.10	0.01
3317	Paris	17/12/13-12/22	9.9,9.5	155	8	7.082	0.001	0.11	0.01
3317	Paris	20/04/20-04/29	7.1,6.8	222	31	7.076	0.003	0.09	0.01
3317	Paris	21/05/01-05/10	10.6,9.6	268	25	7.077	0.002	0.13	0.02
4708	Polydoros	17/01/17-01/28	*0.9,1.7	121	-3	7.532	0.002	0.18	0.01
11395	1998 XN77	15/05/31-06/12	9.3,10.2	194	-7	*13.69	0.01	0.08	0.01
11395	1998 XN77	16/06/07-06/29	7.0,9.7	222	6	*13.679	0.005	0.09	0.01
11395	1998 XN77	17/05/20-05/30	4.9,4.0	254	18	*13.716	0.007	0.14	0.02
11395	1998 XN77	19/08/19-08/31	*5.6,5.4	333	24	13.704	0.003	0.12	0.01
12444	Prothoon	21/04/12-04/25	9.2,7.5	247	18	15.637	0.004	0.24	0.02

Table II. Observing circumstances and results. *Restated previous period. The phase angle is given for the first and last dates. If preceded by an asterisk, the phase angle reached an extremum during the period. L_{PAB} and B_{PAB} are the approximate phase angle bisector longitude/latitude at mid-date range (see Harris et al., 1984).

Acknowledgements

Observations at CS3 and continued support of the asteroid lightcurve database (LCDB; Warner et al., 2009) are supported by NASA grant 80NSSC18K0851. This work includes data from the Asteroid Terrestrial-impact Last Alert System (ATLAS) project. ATLAS is primarily funded to search for near earth asteroids through NASA grants NN12AR55G, 80NSSC18K0284, and 80NSSC18K1575; byproducts of the NEO search include images and catalogs from the survey area. The ATLAS science products have been made possible through the contributions of the University of Hawaii Institute for Astronomy, the Queen's University Belfast, the Space Telescope Science Institute, and the South African Astronomical Observatory. The purchase of a FLI-1001E CCD camera was made possible by a 2013 Gene Shoemaker NEO Grant from the Planetary Society.

References

- 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**, 183-187.
- 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.
- Mottola, S.; Di Martino, M.; Anders, E.; Gonano-Beurer, M.; Carbognani, A.; Carsenty, U.; Hahn, G.; Schober, H.-J.; Lahulla, F.; Delbò, M.; Lagerskvist, C.-I. (2011). "Rotational Properties of Jupiter Trojans. I. Light Curves of 80 Objects." *Astron. J.* **141**, A170.
- 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.
- Stephens, R.D.; Coley, D.R.; Warner, B.D.; French, L.M. (2016). "Lightcurves of Jovian Trojan Asteroids from the Center for Solar System Studies: L4 Greek Camp and Spies." *Minor Planet Bull.* **43**, 323-331.
- Stephens, R.D. (2017). "Lightcurve Analysis of Trojan Asteroids at the Center for Solar System Studies 2016 October - December." *Minor Planet Bull.* **44**, 123-125.
- Stephens, R.D.; Warner, B.D., (2017). "Lightcurve Analysis of L4 Trojan Asteroids at the Center for Solar System Studies 2017 April - June." *Minor Planet Bull.* **44**, 312-316.
- Stephens, R.D.; Warner, B.D. (2018). "Lightcurve Analysis of L5 Trojan Asteroids at the Center for Solar System Studies: 2018 January to March." *Minor Planet Bull.* **45**, 301-304.
- Stephens, R.D.; Warner, B.D. (2020a). "Lightcurve Analysis of L5 Trojan Asteroids at the Center for Solar System Studies: 2020 April to June." *Minor Planet Bull.* **47**, 285-289.
- Stephens, R.D.; Warner, B.D. (2020b). "Lightcurve Analysis of L4 Trojan Asteroids at the Center for Solar System Studies: 2020 October to December." *Minor Planet Bull.* **48**, 167-170.
- 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." *Ap. J.* **867**, A105.
- Warner, B.D.; Harris, A.W.; Pravec, P. (2009). "The Asteroid Lightcurve Database." *Icarus* **202**, 134-146. Updated 2020 Oct. <http://www.minorplanet.info/lightcurvedatabase.html>