

LIGHTCURVES OF JOVIAN TROJAN ASTEROIDS FROM THE CENTER FOR SOLAR SYSTEM STUDIES: L4 GREEK CAMP AND SPIES

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(Received: 11 July 2016)

Jovian Trojan asteroids larger than ~ 30 km were studied from the Center for Solar System Studies (CS3, MPC U81). Lightcurves for 30 Trojan asteroids in the L4 (Greek) cloud were between May and June 2016. These were mostly from the L4 “Greek” cloud, but several were L5 “Trojan” cloud lightcurves not previously published.

For three years, CS3 has been conducting a study of Jovian Trojan asteroids. As part of this study, data are being accumulated for family rotational and future shape model studies. It is anticipated that for most Jovian Trojans, up to five dense lightcurves per target at oppositions well distributed in ecliptic longitudes will be needed since reliable sparse data probably do not exist for Trojan asteroids at 5 AU and a low albedo. To date, CS3 has obtained three or more dense lightcurves for several dozen Jovian Trojans.

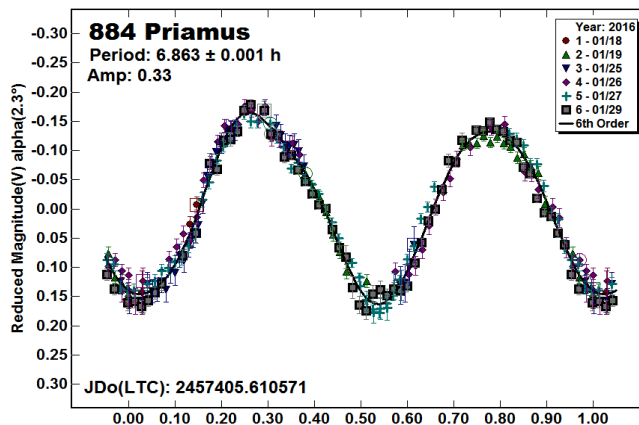
With the exception of the 2015 observations of (11395) 1998 XN77 and the 2016 observations of 5012 Eurymedon, all images were made with a 0.4-m or a 0.35-m SCT using an FLI-1001E or a SBIG STL-1001E CCD camera. Images were unbinned with no filter and had master flats and darks applied to the science frames prior to measurement. The 2015 observations of (11395) 1998 XN77 were made with the 0.9-m SMARTS telescope at CTIO (Cerro Tololo Inter-American Observation, MPC 807). The observations of 5012 Eurymedon were obtained with the 4-m Blanco telescope and the Dark Energy Camera at CTIO.

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). Night-to-night calibration of the data (generally $< \pm 0.05$ mag) was done using field stars converted to approximate Cousins V magnitudes based on 2MASS J-K colors (Warner 2007). The Comp Star Selector feature in *MPO Canopus* was used to limit the comparison stars to near solar color.

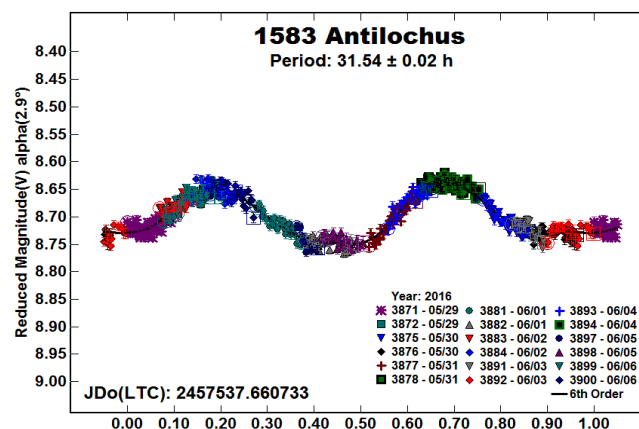
In the lightcurve plots, the “Reduced Magnitude” is Johnson R corrected to a unity distance by applying $-5 \cdot \log(r\Delta)$ to the measured sky magnitudes with r and Δ being respectively, the Sun-asteroid and the Earth-asteroid distances in AU. The magnitudes

were normalized to the phase angle given in parentheses using $G = 0.15$.

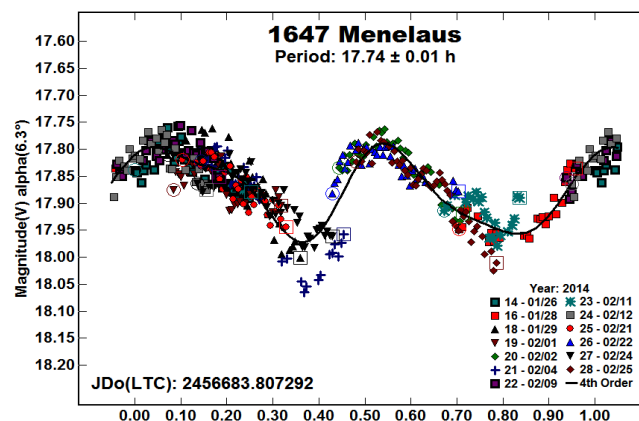
884 Priamus. Mottola *et al.* (2011) observed this Trojan in 1995 and again in 2002, reporting periods of 6.866 h and 6.894 h, respectively. We observed it in 2010 (French *et al.*, 2011) and 2015 (Stephens *et al.*, 2015), finding periods of 6.8605 h and 6.854 h. The results from the observations in 2016 agree with those previous findings.



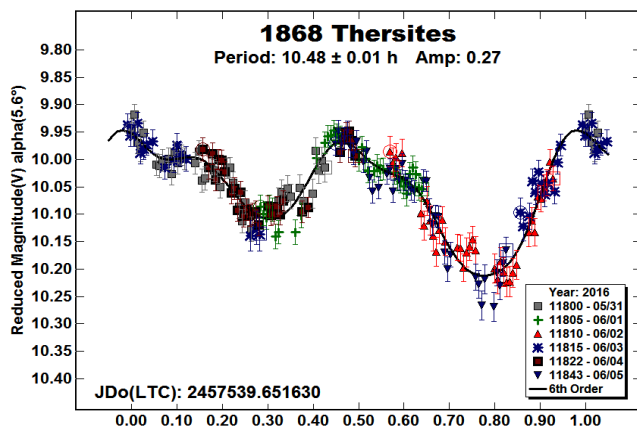
1583 Antilochus. We observed this Trojan in 2009 (Stephens, 2010), finding a rotation period of 31.52 h. Our results from 2016 agree with the 2009 period.



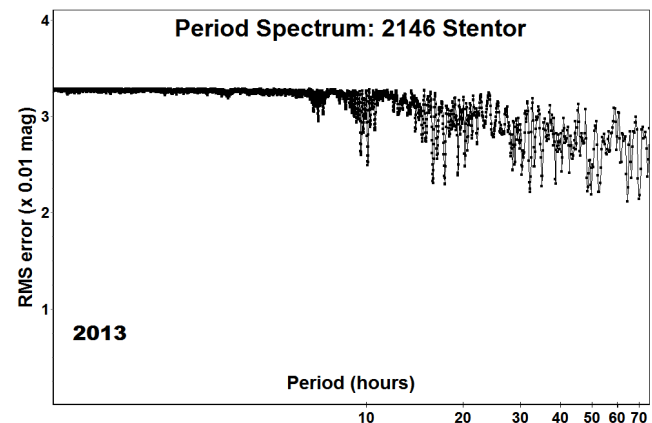
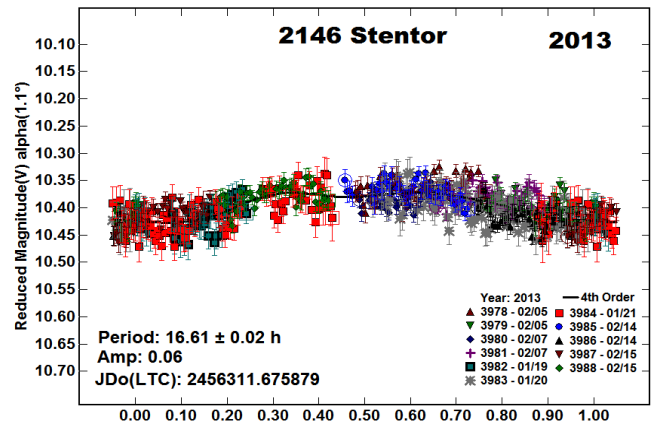
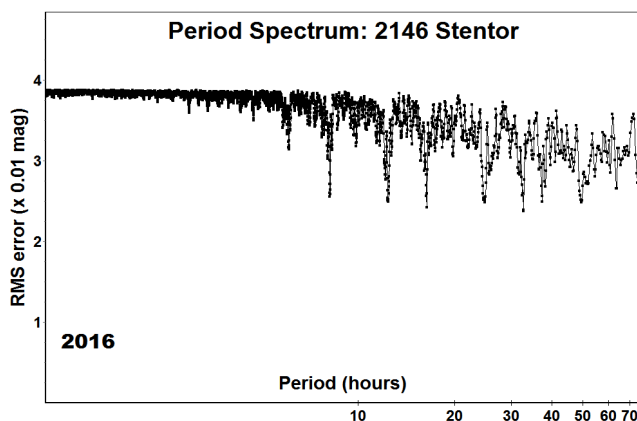
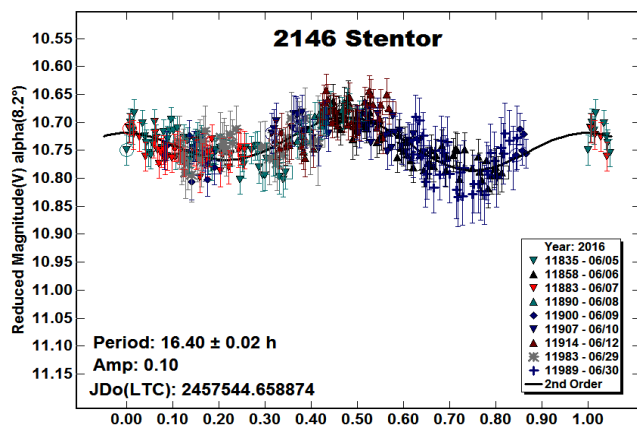
1647 Menelaus. Using sparse photometry from the Palomar Transient Factory, Waszczak *et al.* (2015) reported a period of 17.7390 h. Our period of 17.74 h agrees with that result.



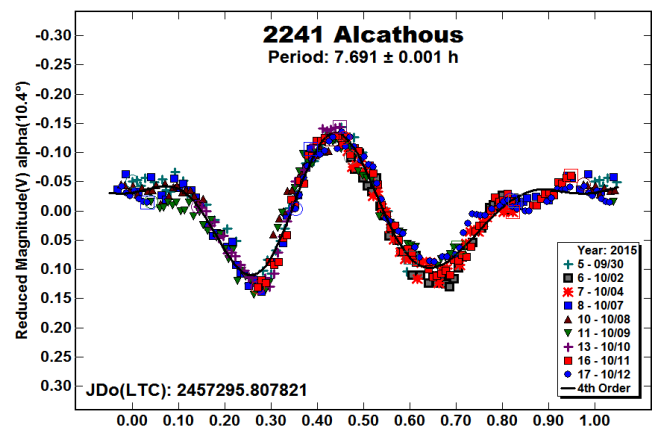
1868 Thersites. Mottola *et al.* (2011) studied this Trojan in 1994, reporting a period of 10.416 h. The result from 2016 of 10.48 h is in good agreement with the Mottola finding.



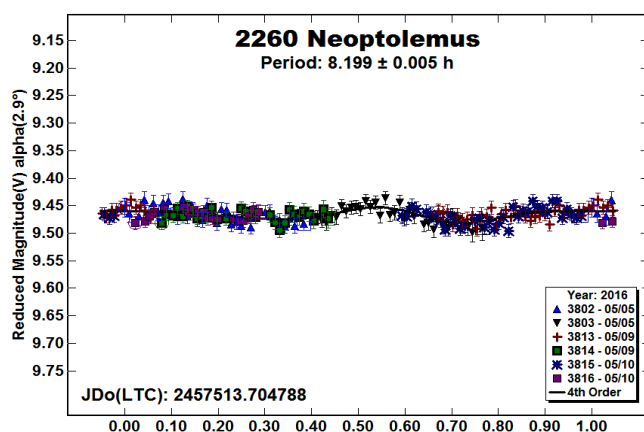
2146 Stentor. We observed Stentor in 2013 (French *et al.*, 2013) finding a period of 35.14 h with an amplitude of 0.08 magnitudes. This produced a bimodal lightcurve. However, as mentioned in the 2013 analysis, with an amplitude under 0.1 magnitudes, it is possible that a lightcurve could have only a single extremum, or three or more extrema (Harris *et al.* 2014). The data obtained in 2016 resulted in a bimodal lightcurve at about a 1:2 alias of the 2013 period and amplitude of 0.1 mag. We were able to make the 2013 data fit a single modal lightcurve with a period of 16.61 h. Given the bimodal features present in the 2016 data, we now prefer the 16.40 h period. This is another example of the need to reobserve low amplitude asteroids at several oppositions.



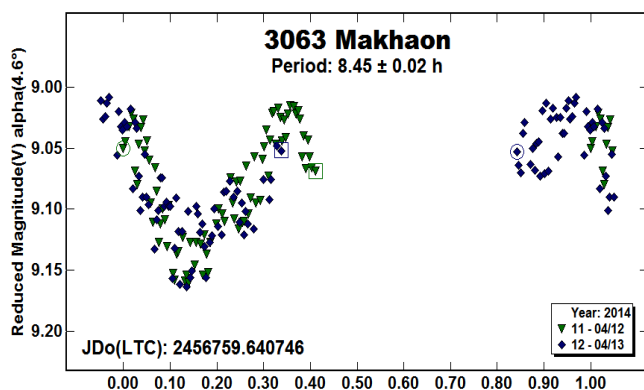
2241 Alcahous. We observed Alcahous three times before (French *et al.*, 2011b, Stephens *et al.*, 2014; 2015), finding rotation periods of 7.695 h, 7.690 h, and 7.689 h. Mottola *et al.* (2011) found a similar period of 7.687 h. The result we found at this year's opposition is in good agreement with those previous findings.



2260 Neoptolemus. Mottola *et al.* (2011) observed this Trojan in 1995 and again in 2002, reporting a period of 8.180 h. Our observations in 2016 result in a flat, almost featureless lightcurve with an amplitude of about 0.05 mag. The observations by themselves would not be sufficient to derive the rotation period with any confidence. However, the rotation period derived in 2016 is consistent with the Mottola results and perhaps useful for shape modeling.

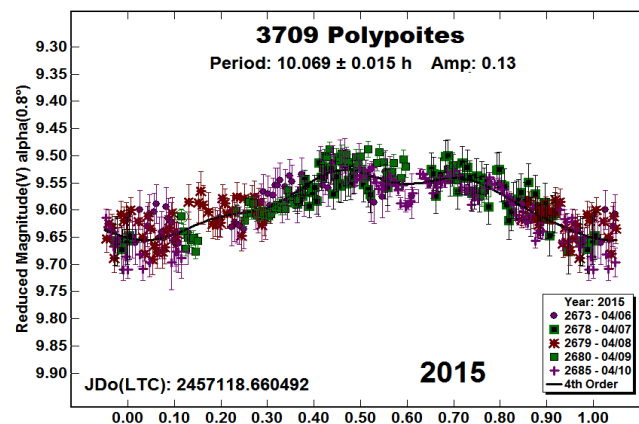
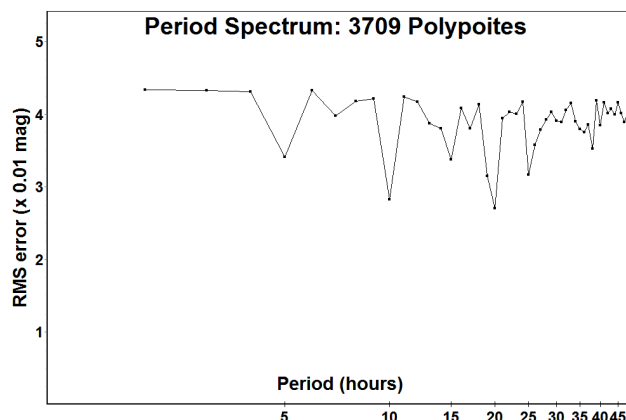
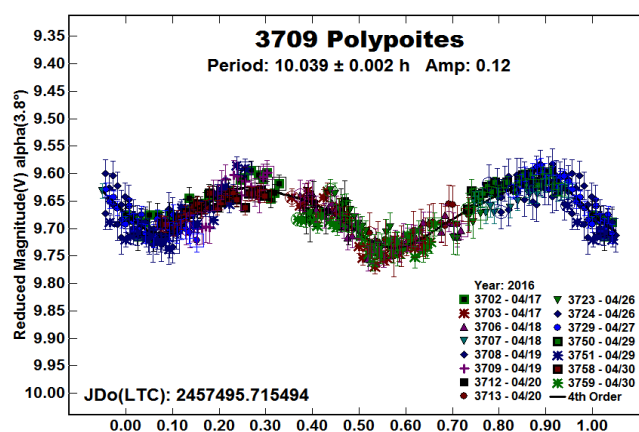


3063 Makhaon. We observed this Trojan in 2010 (French *et al.*, 2011) finding a period of 8.64 h. Binzel (1992) reported a period of 17.3 h based upon two consecutive nights of observations. This appears to be an alias of our 8.64 ± 0.01 h period. Mottola *et al.* (2011) observed this Trojan in 1994 and again in 2009, reporting periods of 8.648 h and 8.6354 h, respectively. Our previously unreported observations from 2014 covered only half the phased lightcurve on two nights, but the period is consistent with previous results.

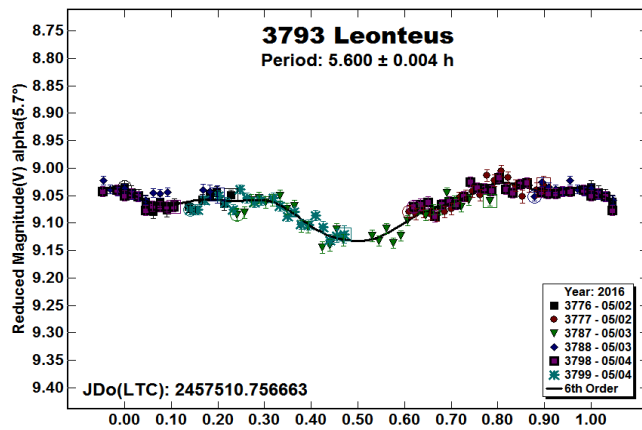


3709 Polypoites. This Trojan illustrates the need to reobserve asteroids, sometimes multiple times. In 2010 we observed Polypoites on two nights, obtaining what appeared to be a very reasonable, if asymmetric, lightcurve with a 5.71 h period (French *et al.*, 2011). However, with an amplitude of about 0.12 magnitudes, it is possible that it could have only a single extremum, or three or more extrema (Harris *et al.*, 2014). In 2015 our lightcurve had a slightly larger amplitude and a dramatically different appearance, which is inconsistent with a 5.71 h period. The phased lightcurve was still asymmetric and likely dominated by surface features. It has a rotation period 2.5 times that of the 2010 result. We rephased the 2010 data, producing a lightcurve that has almost no overlap for the two nights and rejecting the 5.71 h period in favor of the 14.19 h period.

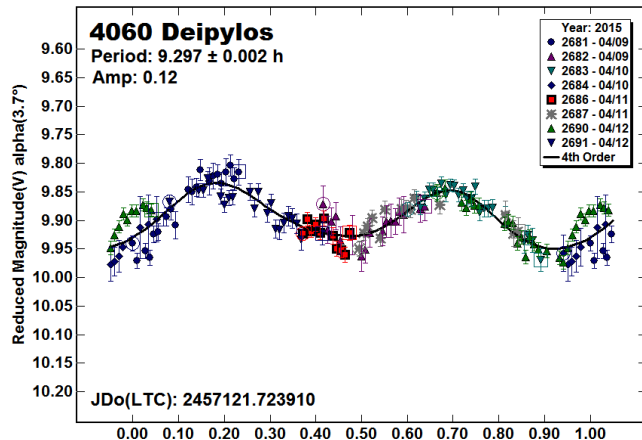
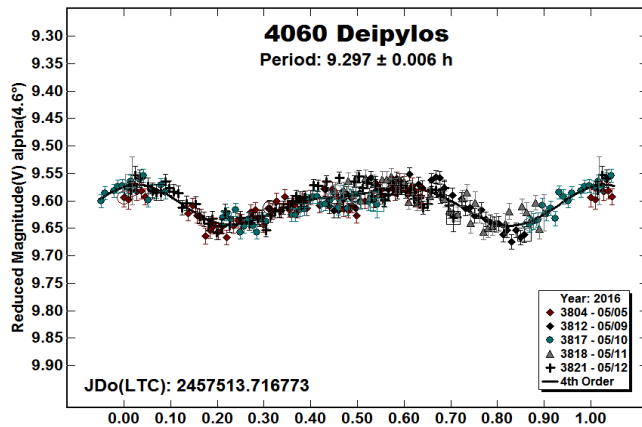
In 2016 the data favored a 10.039 h period with bimodal lightcurve and amplitude of only 0.12 mag. The period spectrum shows the 14.2 hour period to be a weak alias and the lightcurve has several inconsistencies. We were able to rephase the 2015 data to a monomodal lightcurve with an amplitude of 0.13 mag. Based on the 2015 and 2016 data, we now favor the 10.039 h period.



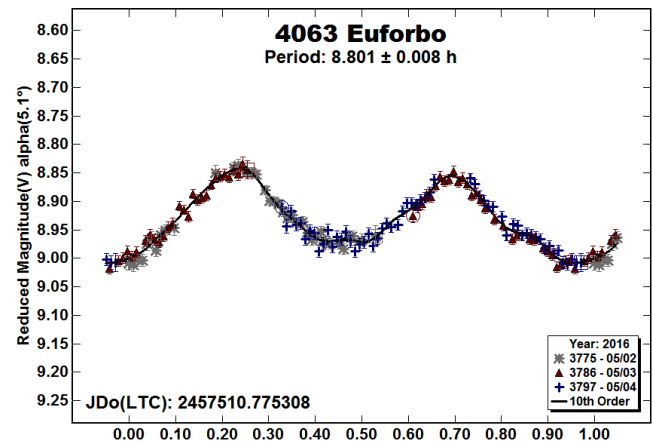
3793 Leonteus. Leonteus is another example where a low amplitude lightcurve can produce alias results when forced to a bimodal solution. We observed this Trojan in 2009 and 2015, showing asymmetric lightcurves reporting a period of 5.62 h and a small amplitude of 0.05 mag. Mottola *et al.* (2011) reported a period of 5.6225 h from observations obtained in 1994 and 1997. The largest amplitude in the Mottola observations was 0.24 magnitudes, which suggested that our 2009 observations were nearly pole on. Our observations in 2016 still show an asymmetric lightcurve with a period of 5.60 h but a larger amplitude of 0.11 mag.



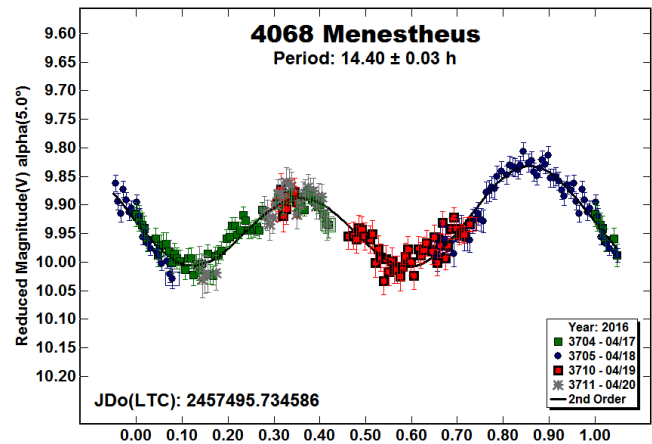
4060 Deipylos. Using sparse photometry from the Palomar Transient Factory, Waszczak *et al.* (2015) reported a period of 11.4905 h for Deipylos. That period appears to be a 5:4 alias of the period of 9.19 h that we found in 2015 (Stephens *et al.*, 2016), when the asteroid was observed over four consecutive nights. We observed Deipylos again in 2016 for five nights spanning a week. Analysis found a slightly different rotation period of 9.297 h. By making slight zero point adjustments to the 2015 data, we were able to phase the lightcurve to a reasonable match to the 2016 period, which we now adopt as the correct period.



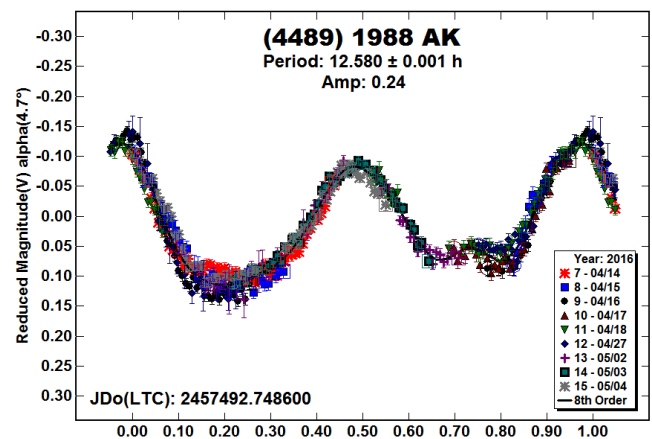
4063 Euforbo. This Trojan has been well observed over the years. Brinsfield (2011), Mottola *et al.* (2011), and Waszczak *et al.*, (2015) each reported periods near 8.84 h, which were in agreement with our findings. In 2015, we again found a period of 8.84 h (Stephens *et al.*, 2016). The period of 8.801 h we found in 2016 is in good agreement with the earlier results.



4068 Menestheus. We studied this asteroid on two previous occasions: French *et al.* (2011) and Stephens *et al.* (2016), finding a period of 14.341 h and 14.45 h. The result this year of 14.40 h is in good agreement with those findings.

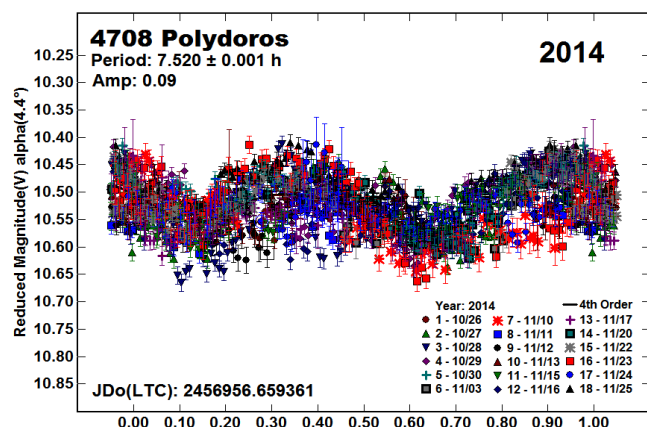
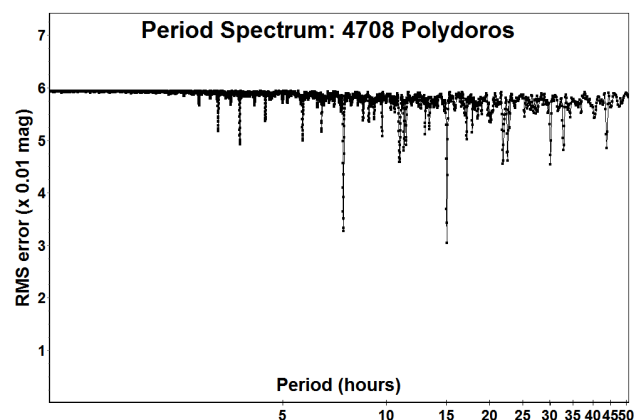
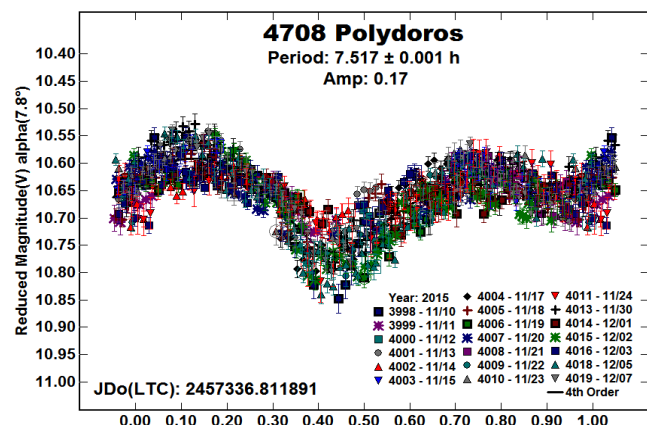


(4489) 1988 AK. Mottola *et al.* (2011) observed this Trojan in 1995, finding a period of 16.25 h. We observed it in 2009 and 2010 (French *et al.*, 2011) and 2015 (Stephens *et al.*, 2016). Each time we found a period near 12.58 h. The period from based on the 2016 agrees with our previous results.

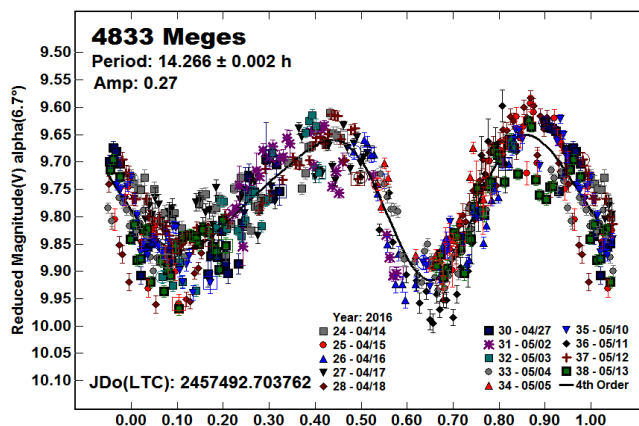


4708 Polydoros. We previously observed this Trojan in 2011 (French *et al.*, 2012) and 2014 (Stephens *et al.*, 2015), finding periods of 20.03 h and 20.24 h, respectively. We obtained a much denser dataset in 2016. Analysis of the new data favored 7.517 h

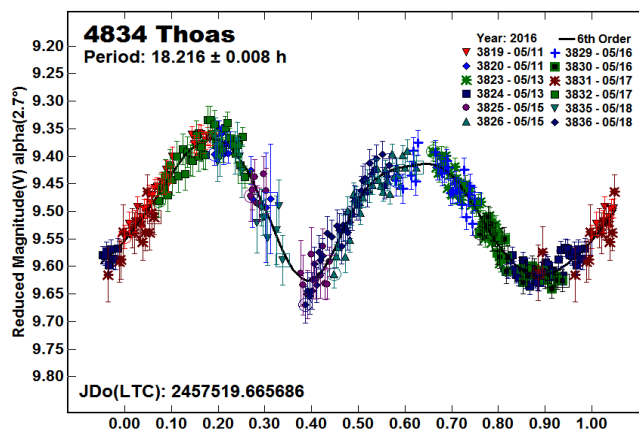
and 15.037 h, with an alias around 23 h. We adopted the 7.517 h solution because it produces a bimodal lightcurve. The 15.037 h solution creates a lightcurve with four extrema, and although possible with a lightcurve with a 0.21 mag. amplitude, the 7.517 h solution is more likely. We rephased the 2014 lightcurve to 7.520 h with a result of an asymmetric bimodal lightcurve with an amplitude of 0.09 mag. We also rephased the 2011 data, forcing a monomodal fit to 7.52 h on the assumption that the ending data on Aug 3 were the result of observational errors.



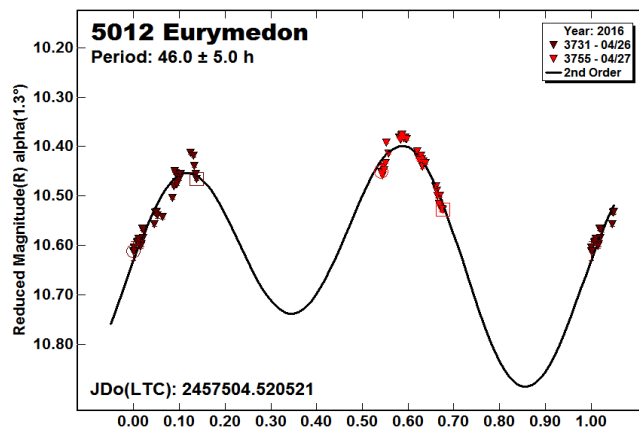
4833 Meges. Mottola *et al.* (2011) observed Meges in 1995, finding a period of 14.250 h. Our period derived from the 2016 data is in good agreement.



4834 Thoas. Mottola *et al.* (2011) observed Thoas in 1996, finding a period of 18.22 h. We observed it in 2010 (French *et al.*, 2011), finding a period of 18.192 h, and again in 2015 (Stephens *et al.*, 2016) when we found a period of 18.14 h. Our period of 18.216 h based on the 2016 data is in good agreement with those results.



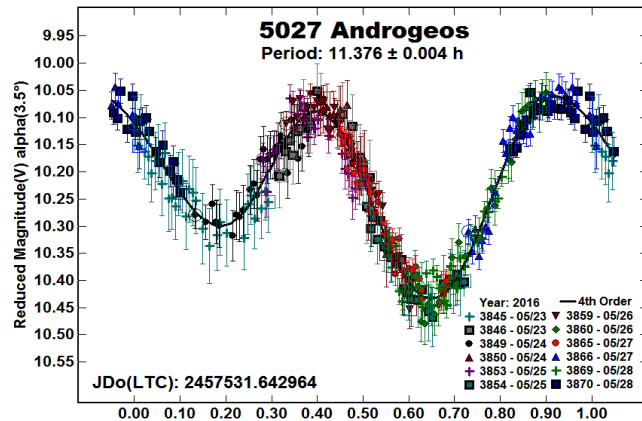
5012 Eurymedon. There were no previously reported rotation periods in the asteroid lightcurve database (LCDB; Warner *et al.*, 2009) for this Trojan, which was observed with the 4-m Blanco Telescope at CTIO as part of a survey of small ($D < 30$ km) Jovian Trojan asteroids.



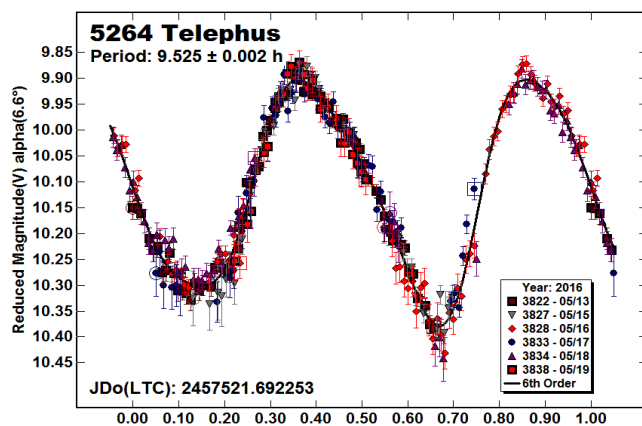
The WISE/NEOWISE program (Grav *et al.*, 2012) estimates the size of Eurymedon to be 36 km, so it was excluded from the small Trojan survey. For our observing run in 2016, the Trojan L4 cloud could be observed for only two nights which is insufficient to determine a rotation period exceeding 20 hours. However, based

on the maxima and slopes of the lightcurve segments that were observed, we estimate that the period is probably near 46 h.

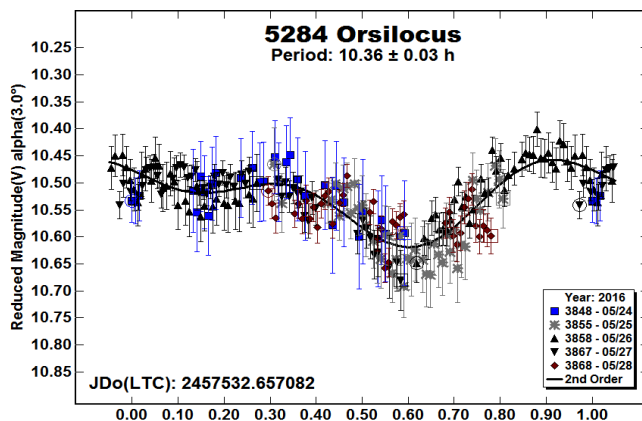
5027 Androgeos. Mottola *et al.* (2011) observed Androgeos in 1992, finding a period of 11.355 h. We observed it in 2015 (Stephens *et al.*, 2016), finding a period of 11.301 h. The period of 11.376 h found from the 2016 data agrees with those prior results.



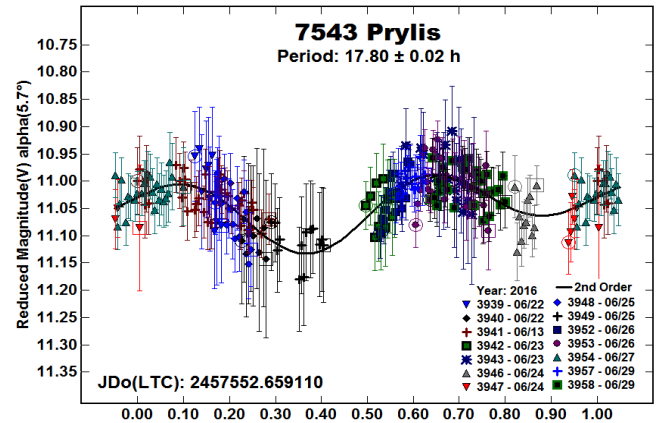
5264 Telephus. Telephus was observed by Mottola *et al.* (2011) in 1994, who reported a period of 9.518 h. We found a period of 9.540 h in 2015 (Stephens *et al.*, 2016). The 2016 result of 9.525 h agrees with those previous findings.



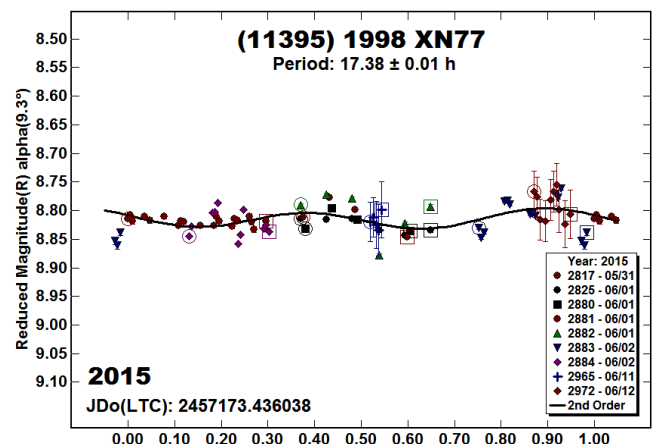
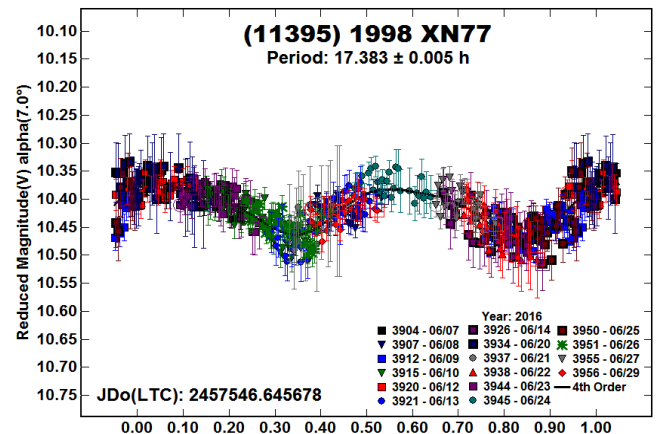
5284 Orsilocus. We studied Orsilocus in 2013 (French *et al.*, 2013) and 2015 (Stephens *et al.*, 2016), finding periods of 10.31 h and 10.28 h, respectively. The period of 10.36 h found from the 2016 data agrees with those findings.

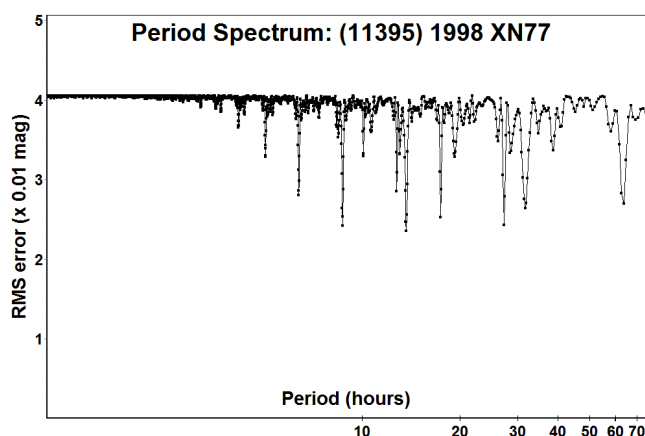


7543 Prylis. This Trojan did not have a previously reported rotation period in the LCDB (Warner *et al.*, 2009).

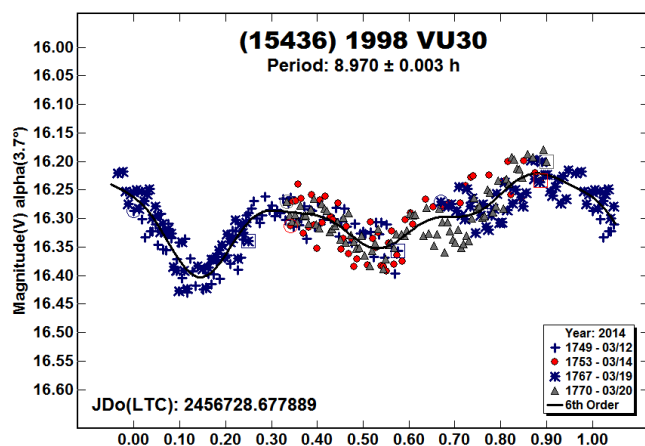


(11395) 1998 XN77. Mottola *et al.* (2011) observed this Trojan in 2009 and 2010, finding periods of 13.70 h and 13.696 h, respectively. We first observed the asteroid in 2015 using the 0.9-m SMARTS telescope at CTIO and then in a follow-up session using the 0.35-m telescope at CS3 (Stephens *et al.*, 2016), finding a period of 17.89 h. We observed it again in 2016 from CS3, obtaining a much denser data set, and found a period of 17.383 h. Determining a rotation period proved difficult because of the low amplitude and strong aliases. We were able to rephase the 2015 data to this period, but because of the low amplitude, many rotation periods were possible.

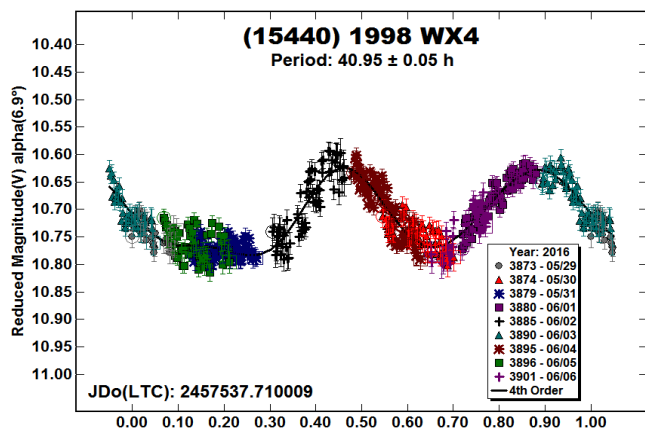




(15436) 1998 VU30. We observed this Trojan in 2013 (French *et al.*, 2013) finding a rotational period of 8.97 h. The period we found in 2016 is identical to that result.

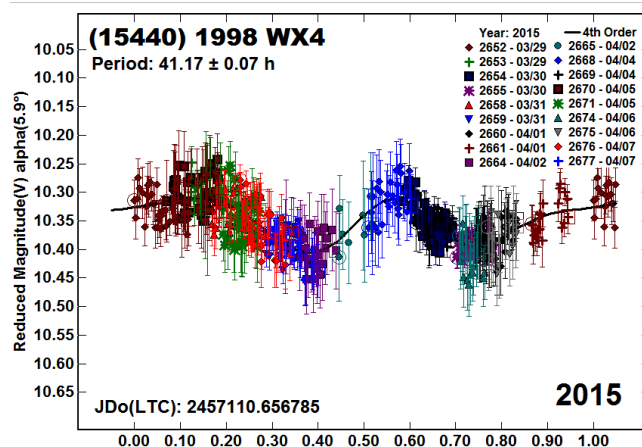
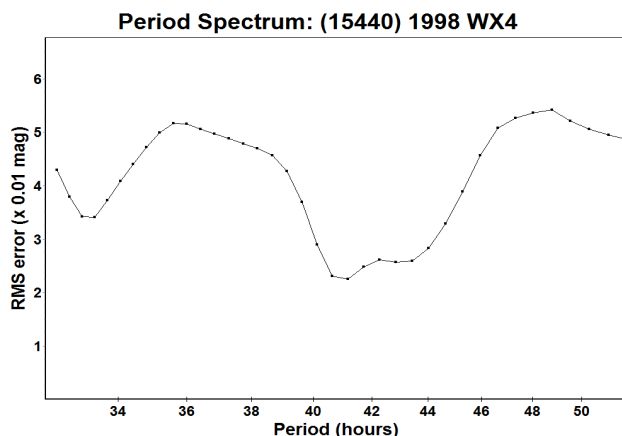


(15440) 1998 WX4. We observed this Trojan in 2013 (French *et al.*, 2013) and 2014 (Stephens *et al.*, 2014). In both cases, the raw lightcurves spanning multiple nights were featureless. We observed it again in 2015 (Stephens *et al.*, 2016) and found a rotation period of 43.08 h and an amplitude of 0.11 magnitudes based on an asymmetric bimodal shape. However, with such a low amplitude, it is possible that a lightcurve could have only a single extremum, or three or more extrema (Harris *et al.*, 2014).

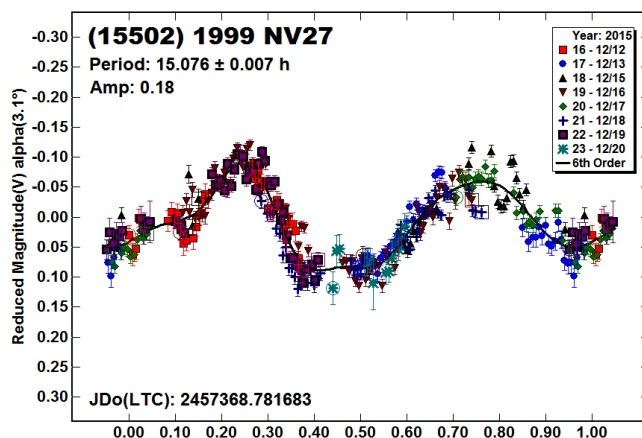


We observed (15440) 1998 WX4 again in 2016, this time finding a rotation period of 40.95 h with an amplitude of 0.16 mag. The data

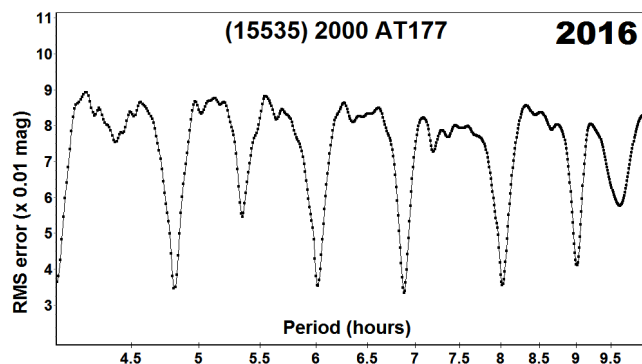
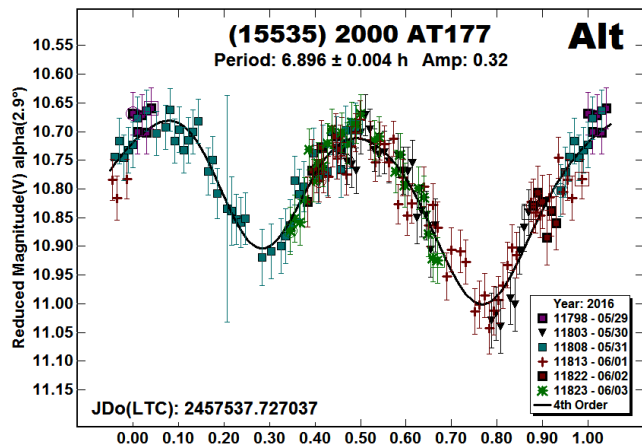
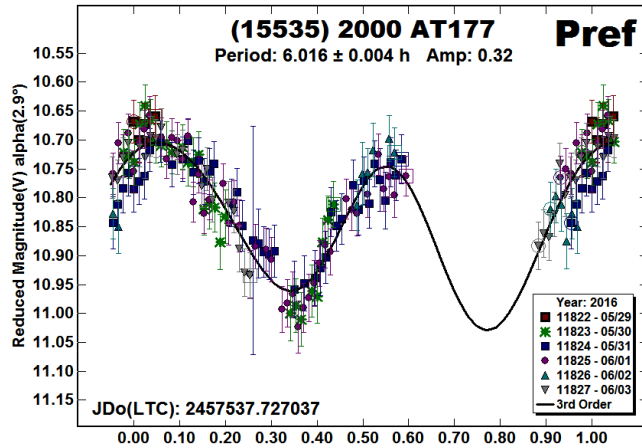
were much cleaner in 2016. We attempted to reconcile the differences between the 2015 and 2016 results. We rephased the 2015 results after making slight zero point adjustments and were able to find a period of 41.17 h, which is close to the 2016 result considering the formal error of ± 0.07 h. A period spectrum of the 2016 data shows a slight dip for the 43 h solution. Given the quality of the 2016 data, we are adopting 40.95 h as the rotation period.



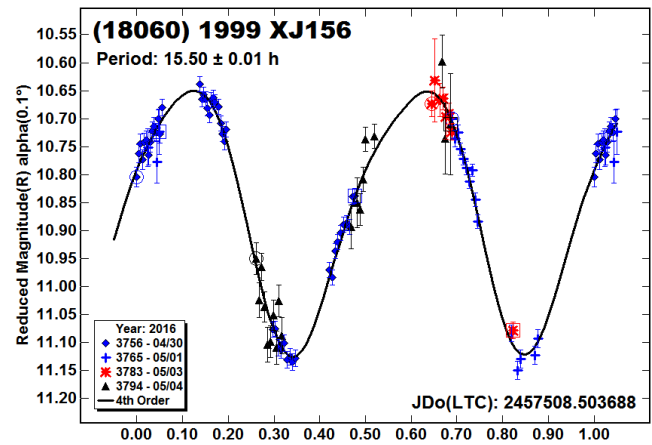
(15502) 1999 NV27. We observed this Trojan three times in the past: in 2012 (French *et al.*, 2013), in 2013 Stephens *et al.*, 2014), and in 2014 (Stephens *et al.*, 2015). Each time we found periods near 15.1 h. This results from 2016 are in good agreement with those previous findings.



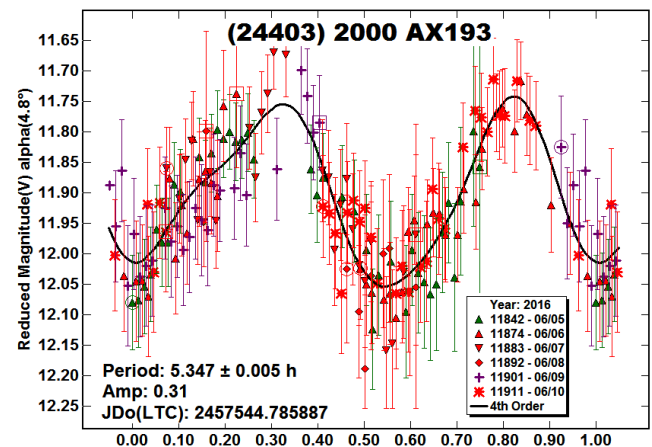
(15535) 2000 AT177. We observed this Trojan in 2013 (French *et al.*, 2013), finding a rotational period of 6.01 h. Analysis of the 2016 observations led to aliases at 6.016 h and 6.896 h. The shorter solution covered only three quarters of the lightcurve. To break the tie, we reanalyzed the 2013 data, which did not show a strong alias near 6.9 h. Therefore we are adopting the 6.016 h solution as the most likely.



(18060) 1999 XJ156. This Trojan is a member of the Eurybates family. We observed it with the 0.9-m SMARTS telescope at CTIO. Using sparse photometry from the Palomar Transient Factory, Waszczak *et al.* (2015) reported a period of 15.4542 h. Our denser dataset was used to find a period of 15.50 h, which is in good agreement with the Waszczak *et al.* results.



(24403) 2000 AX193. We could not find a previously reported rotation period in the LCDB (Warner *et al.*, 2009).



Acknowledgements

This research was supported by National Science Foundation grant AST-1212115. The purchase of two FLI-1001E CCD cameras was made possible by a 2013 and 2015 Gene Shoemaker NEO Grants from the Planetary Society.

French and Stephens were visiting astronomers at Cerro Tololo Inter-American Observatory, National Optical Astronomy Observatory, operated by the Association of Universities for Research in Astronomy, under contract with the NSF.

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Numbe	Name	2016 mm/dd	Pts	Phase	L _{PAB}	B _{PAB}	Period	P.E.	Amp	A.E.	Gr
884	Priamus	01/18-01/29	234	2.2,4.0	105	3	6.863	0.001	0.33	0.02	L5
1583	Antilochus	05/29-06/06	533	2.9,3.7	244	14	31.54	0.02	0.11	0.02	L4
1647	Menelaus	¹ 01/26-02/25	437	6.3,1.4	157	-6	17.74	0.01	0.17	0.03	L4
1868	Thersites	05/31-06/05	213	5.6,6.3	220	8	10.48	0.01	0.27	0.02	L4
2146	Stentor	06/05-06/30	335	8.2,9.5	226	42	16.40	0.02	0.1	0.01	L4
2241	Alcathous	² 09/30-10/12	427	10.4,9.7	78	5	7.691	0.001	0.24	0.02	L4
2260	Neoptolemus	05/05-05/10	188	2.9,2.4	234	11	8.199	0.005	0.03	0.01	L4
3063	Makhaon	¹ 04/12-04/13	607	4.6,6.4	185	-13	8.45	0.02	0.15	0.01	L4
3709	Polypoites	04/17-04/30	403	3.8,2.6	222	12	10.039	0.002	0.12	0.02	L4
3793	Leonteus	05/03-05/04	135	5.6,5.5	248	17	5.600	0.004	0.11	0.02	L4
4060	Deipylus	05/09-05/12	264	4.1,3.8	242	17	9.297	0.006	0.07	0.02	L4
4063	Euforbo	05/02-05/04	155	5.1,4.8	245	16	8.801	0.008	0.17	0.01	L4
4068	Menestheus	04/17-04/20	205	5.0,4.5	227	14	14.40	0.03	0.18	0.03	L4
4489	1988 AK	04/14-05/04	444	4.7,3.9	218	19	12.58	0.001	0.24	0.02	L4
4833	Meges	04/14-05/13	537	6.6,6.1,6.3	221	34	14.266	0.002	0.27	0.03	L4
4708	Polydorus	² 11/10-12/07	850	7.9, 3.3	88	3	7.517	0.001	0.17	0.02	L4
4834	Thoas	05/11-05/18	316	2.7,3.0	230	14	18.216	0.008	0.26	0.02	L4
5012	Eurymedon	⁴ 04/26-04/27	69	1.3,1.1	223	-1	46	5	0.3	0.07	L4
5027	Androgeos	05/23-05/28	337	1.3,0.0,1.1	233	+15	11.376	0.004	0.37	0.02	L4
5264	Telephus	05/13-05/19	305	6.6,6.2	250	31	9.525	0.002	0.48	0.02	L4
5284	Orsilocus	05/24-05/28	233	3.0,3.2	242	18	10.36	0.03	0.16	0.02	L4
7543	Prylis	06/13-06/29	245	4.3,6.7	244	12	17.80	0.02	0.14	0.0	L4
11395	1998 XN77	^{2,3} 05/31-	94	9.3,10.2	194	-7	17.383	0.01	0.03	0.02	L4
11395	1998 XN77	06/07-06/29	477	7.0,9.7	222	6	17.383	0.005	0.1	0.01	L4
15436	1998 VU30	¹ 03/12-03/20	316	3.7,4.0	172	-18	8.970	0.003	0.18	0.02	L4
15440	1998 WX4	05/29-06/06	477	6.9,7.5	227	30	40.95	0.05	0.16	0.02	L4
15502	1999 NV27	² 12/12-12/20	334	3.1,2.7	86	13	15.076	0.007	0.18	0.02	L5
15535	2000 AT177	05/29-06/03	160	2.9,3.0	249	15	6.016	0.004	0.32	0.03	L4
18060	1999 XJ156	³ 04/30-05/04	92	0.1,0.8	220	-1	15.50	0.01	0.48	0.03	L4
24403	2000 AX193	06/05-06/10	176	4.8,4.9	254	24	5.347	0.005	0.31	0.03	L4

Table 1. Observing circumstances. ^{1,2}Observations in 2014, 2015. ³Observations made with 0.9-m SMARTS Telescope at CTIO. ⁴Observations made with 4-m Blanco Telescope at CTIO. Pts is the number of data points used in the analysis. The phase angle (α) is given at the start and end of each date range, unless it reaches a minimum, which is then the second of the three values. L_{PAB} and B_{PAB} are, respectively the average phase angle bisector longitude and latitude. Grp is the Trojan family, L4 (Greeks) and L5 (Trojans).

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