

LIGHTCURVE ANALYSIS OF L4 TROJAN ASTEROIDS AT THE CENTER FOR SOLAR SYSTEM STUDIES: 2019 JULY TO SEPTEMBER

Robert D. Stephens

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

Brian D. Warner

Center for Solar System Studies (CS3)/MoreData!
Eaton, CO

(Received: 2019 October 7)

Lightcurves for 11 L₄ Jovian Trojan asteroids were obtained at the Center for Solar System Studies (CS3) from 2019 July to September.

CCD Photometric observations of 11 Trojan asteroids from the L₄ (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 all 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 CMC-15 or the ATLAS catalog (Tonry et al., 2018), which has Sloan *griz* magnitudes that were derived from the GAIA and Pan-STARR catalogs, among others. The authors state that systematic errors are generally no larger than 0.005 mag, although they can reach 0.02 mag in small areas near the Galactic plane. BVRI magnitudes were derived by Warner using formulae from Kostov and Boney (2017). The overall errors for the BVRI magnitudes, when combining those in the ATLAS catalog and the conversion formulae, are on the order of 0.04-0.05 mag.

Even so, we found in most cases that nightly zero point adjustments for the ATLAS catalog to be on the order of only 0.02-0.03 mag were required during period analysis. There were

occasional exceptions that required up to 0.10 mag. These may have been related in part to using unfiltered observations, poor centroiding of the reference stars, and not correcting for second-order extinction terms. Regardless, the systematic errors seem to be considerably less than other catalogs, which reduces the uncertainty in the results when analysis involves data from extended periods or the asteroid is tumbling.

In the lightcurve plots, the Y-axis may be labeled “Reduced Magnitude” or “Magnitude.” Unless otherwise indicated, the values are Johnson V. The latter are sky (catalog-derived) magnitudes while “Reduced Magnitude” indicates that sky magnitudes were corrected to unity distances by applying $-5 \log(r\Delta)$ 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 $G = 0.15$. 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 L₄ observing campaign 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 lightcurve database (LCDB; Warner et al., 2009).

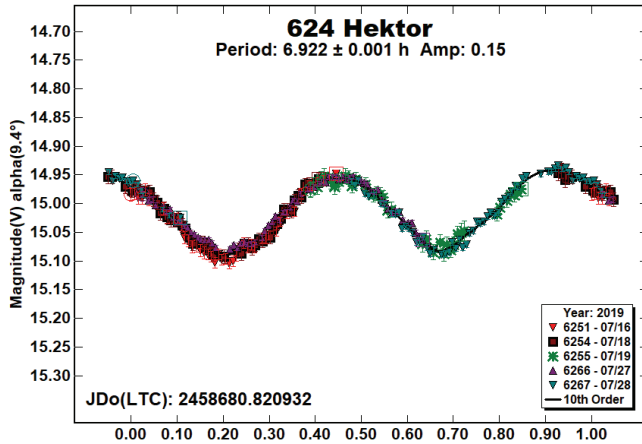
To evaluate the quality of the data obtained and to determine how much more data might be needed, preliminary pole and shape models were created for all of these targets. Sparse data observations were obtained from the Catalina Sky Survey and USNO-Flagstaff survey using the AstDyS-3 site (<http://hamilton.dm.unipi.it/asdys2/>). These sparse data were combined with our dense data as well as any other dense data found in the ALCDEF asteroid photometry database (<http://www.alcdef.org/>) using *MPO LCInvert*, (Bdw Publishing). This Windows-based program incorporates the algorithms developed by Kassalain et al (2001a, 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.

624 Hektor. Hektor has been previously found to be a binary asteroid (Marchis et al., 2006) with a primary that might have a bilobated shape approximately 350x210 km and a secondary estimated to be 15 km in size. They found a pole position with ecliptic coordinates of $\lambda_1 = 332^\circ$ and $\beta_1 = -32^\circ$. Pole positions have been independently found a number of times over the years, the latest by Hanus et al. (2015), which is similar to the Marchis et al solution. Both solutions reported a sidereal period of 6.920509 ± 0.000005 h.

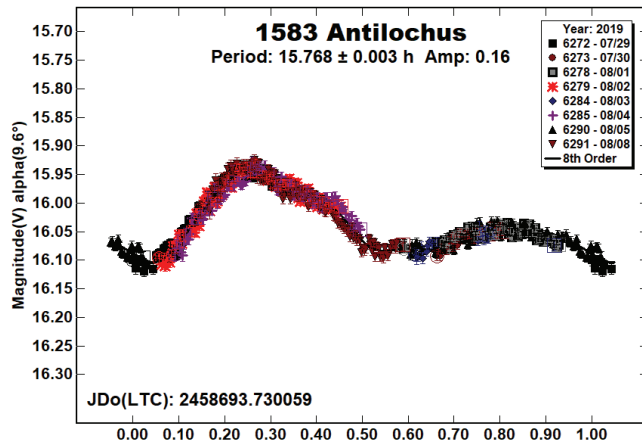
The synodic period found this year produced a classic bimodal lightcurve consistent with rotational periods found in previous years. We combined these data with our data from 2014 (Stephens et al., 2014) and available sparse data to create a preliminary shape model with a pole position of $\lambda_1 = 336^\circ$ and $\beta_1 = -22^\circ$ and a sidereal period of 6.92051 ± 0.00001 h, consistent with the prior findings.

Number	Name	2019 mm/dd	Phase	L _{PAB}	B _{PAB}	Period(h)	P.E.	Amp	A.E.
624	Hektor	07/16–07/28	9.4, 8.0	348	0	6.922	0.001	0.15	0.01
1583	Antilochus	07/29–08/08	9.6, 8.5	350	26	15.768	0.003	0.16	0.02
1868	Thersites	08/09–08/12	3.8, 3.7	317	16	10.492	0.004	0.27	0.02
2920	Automedon	08/17–08/21	5.2, 5.0	332	23	10.192	0.003	0.31	0.02
3709	Polypoites	08/10–08/13	3.7, 3.8	313	18	10.02	0.12	0.12	0.02
3793	Leonteus	08/28–08/30	3.4, 3.3	335	17	5.621	0.001	0.24	0.02
4060	Deipylos	08/17–08/22	2.0, 2.6	318	9	9.29	0.01	0.18	0.02
4501	Eurypylos	08/31–09/07	2.5, 2.0	344	9	6.941	0.002	0.23	0.02
5244	Amphilochos	08/23–08/27	3.0, 2.3	342	5	9.793	0.002	0.57	0.02
15436	1998 VU30	08/22–08/25	3.7, 3.8	325	17	8.970	0.002	0.33	0.02
15527	1999 YY2	08/27–08/29	3.4, 3.6	326	11	6.968	0.003	0.5	0.02

Table II. Observing circumstances and results. The phase angle is given for the first and last date. If preceded by an asterisk, the phase angle reached an extrema 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).

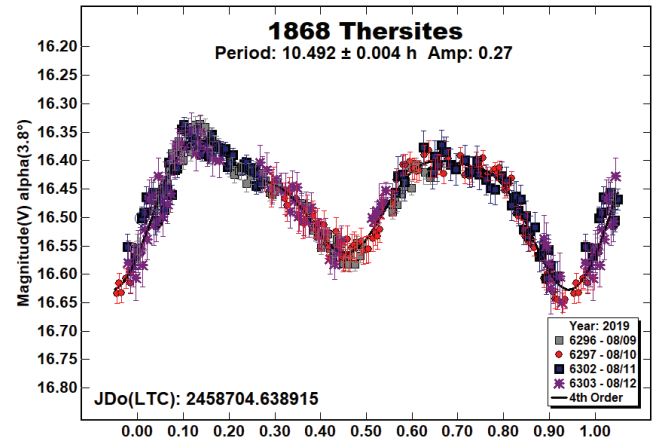


1583 Antilochus. We observed Antilochus four times in the past. Lightcurves obtained in 2009, 2016, 2017 and 2018 (Stephens 2010), Stephens et al. (2016b), Stephens and Warner (2018 and 2019). Over this timespan the amplitude increased from 0.05 to 0.31 mag. The 2009 and 2016 data produced a single modal lightcurve while the 2017 to 2019 observations resulted in bimodal lightcurves. 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 15.77132 ± 0.00001 h was created.

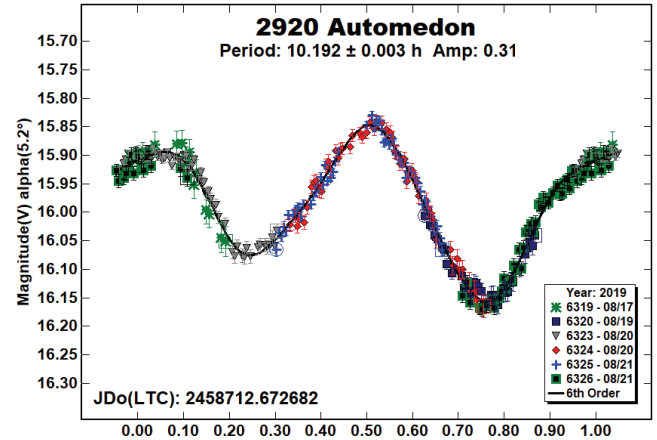


1868 Thersites. We have observed this L₄ Jovian Trojan twice in the past (Stephens et al. 2016b; Stephens and Warner 2018) reporting rotational periods near 10.4 h. Mottola et al. (2011) found a rotational period of 10.416 h. Using sparse data from the Asteroids – Dynamic Site, combined with our data, a preliminary

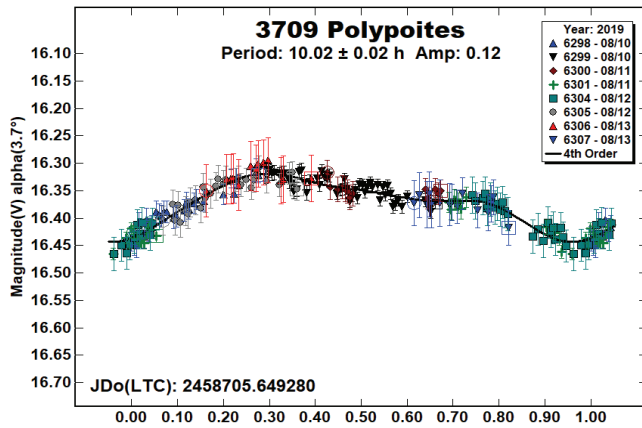
shape model with a sidereal rotational period of 10.47520 ± 0.00001 h was found.



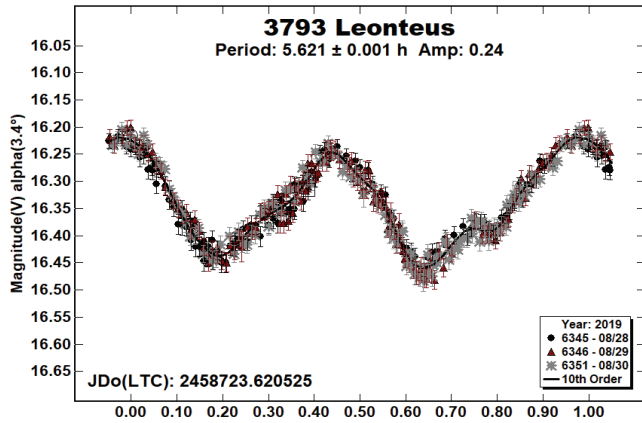
2920 Automedon. The synodic period found in 2019 using CS3 data agrees with previous synodic results (Molnar et al., 2008; Mottola et al., 2011; Stephens and Warner 2017 and 2019) near 10.2 h. The data analysis in 2019 is in good agreement and when combined with our previous data and available sparse data, were used to create a preliminary shape model with a sidereal rotational period of 10.20598 ± 0.00001 h.



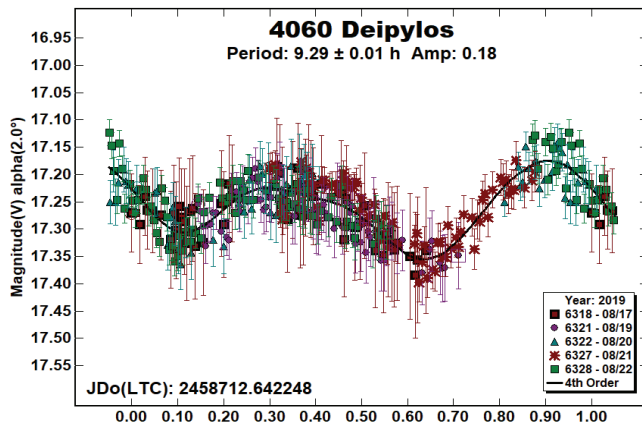
3709 Polypoites. We observed this Trojan five times in the past (French et al., 2011; Stephens et al., 2016a; 2016b; 2017; and 2019), each time finding a period near 10.04 h. The 2019 data resulted in a monomodal lightcurve that in good agreement with those prior results. We were able to create a preliminary shape model with a sidereal rotational period of 10.03705 ± 0.00001 h.



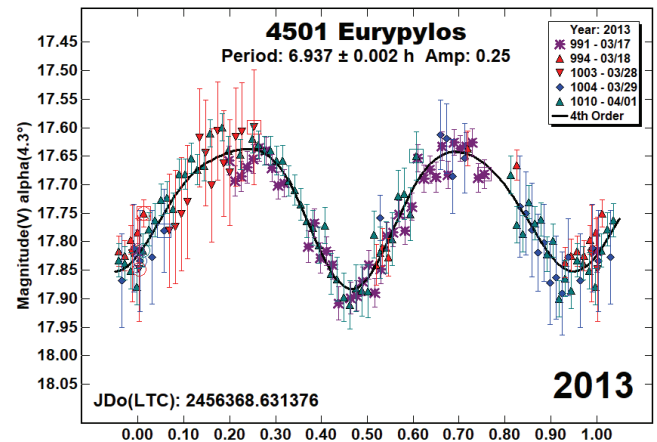
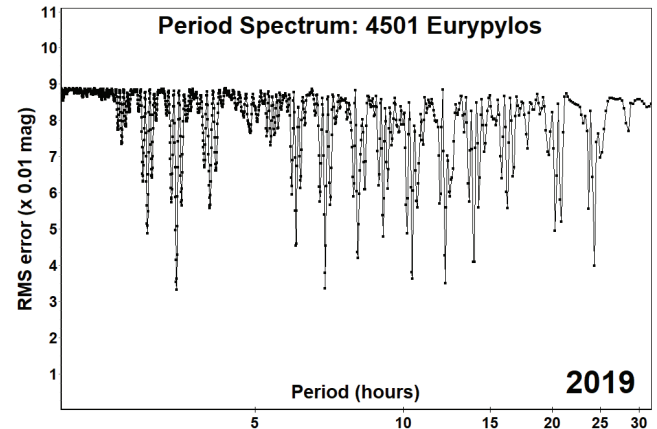
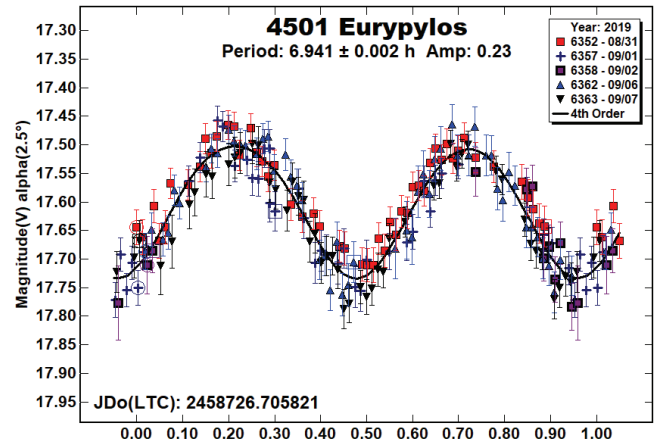
3793 Leonteus. This large Trojan has been well studied in the past. Mottola et al., (2011) observed it in 1994 and 1997. We found periods in 2009, 2015, 2016 and 2018 (Stephens et al., 2016a; 2016b; and 2019). Each of these periods was found to be close to 5.62 h. This year's data analysis result is in good agreement. We were able to create a preliminary shape model with a sidereal rotational period of 5.62192 ± 0.00001 h.

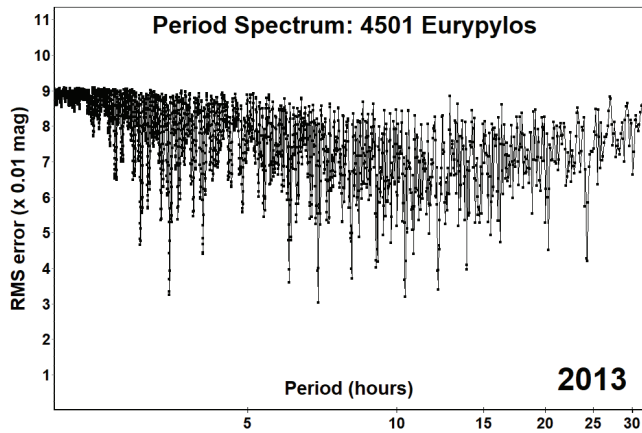


4060 Deipylos. Using sparse photometry from the Palomar Transient Factory, Waszczak et al. (2015) reported a period of 11.4905 h for Deipylos. We observed it four times (Stephens et al 2016a; 2016b; 2017; and 2019) finding periods near 9.3 h. That period appears to be a 5:4 alias of the Waszczak et al. period. The data from 2019 are noisy but the result of 9.29 h, but in good agreement with our prior results. We were able to create a preliminary shape model with a sidereal rotational period of 9.30836 ± 0.00001 h.

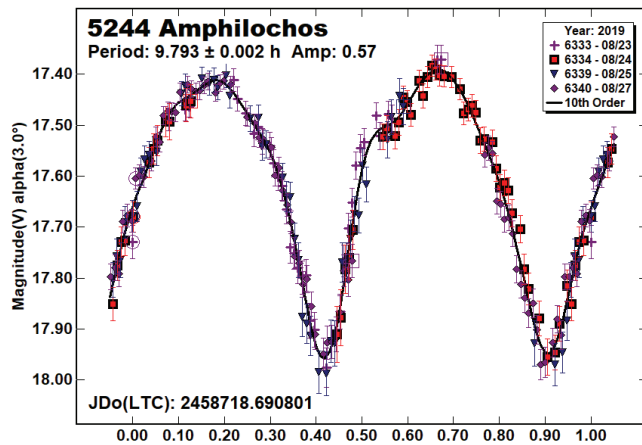


4501 Eurypylos. Only one prior rotational period is reported in the lightcurve database (LCDB; Warner et al., 2009), which is from our data in 2013 (French et al. 2013) when we reported a rotational period of 6.054 h. The data we collected in 2019 were not a good fit to that rotational period. The period spectrum for the 2019 data shows the half period near 3.5 h, the preferred period of 6.9 h, and an 8:7 alias near 6 h. Rephasing the 2013 data to the 6.9 h period shows a good fit after eliminating a couple of outlier data points. The new period spectrum for the 2013 data now shows the preferred period to be 6.937 h. Using sparse data from the Asteroids – Dynamic Site, we were able to create a preliminary shape model with a sidereal rotational period of 6.93545 ± 0.00001 h.

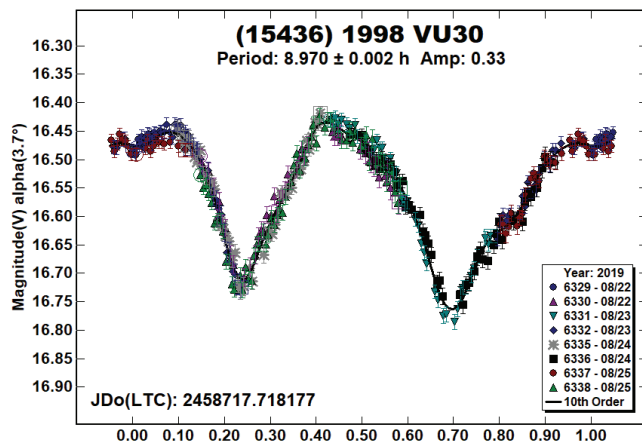




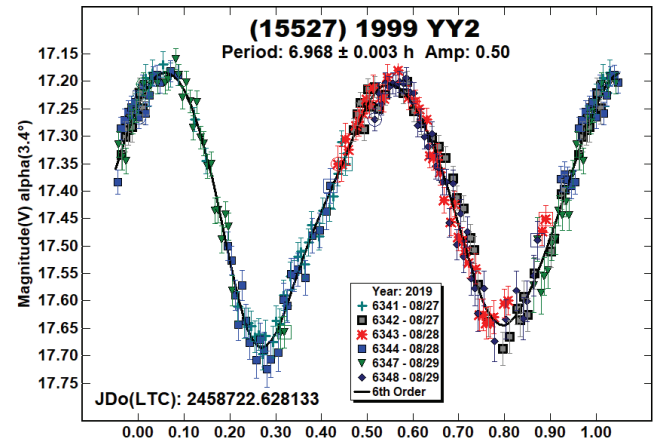
5244 Amphilochois. We observed this L₄ Trojan once before (Stephens et al., 2016b) and found a rotational period of 9.768 h. This year's result is in good agreement. The lightcurves from both oppositions had relatively large amplitudes. The shoulders present in the 2019 data are suggestive of being a bilobed object. Using sparse data from the Asteroids – Dynamic Site, we were able to create a preliminary shape model with a sidereal rotational period of 9.78572 ± 0.00001 h.



(15436) 1998 VU30. We observed this Trojan twice in the past (French et al. 2013 and Stephens et al. 2016b) and both times found a rotational period of 8.97 h. This year's result agrees with those periods. Using sparse data from the Asteroids – Dynamic Site, we were able to create a preliminary shape model with a sidereal rotational period of 8.96657 ± 0.00001 h.



(15527) 1999 YY2. We observed this Trojan once before (Stephens and Warner, 2017) and found a rotational period of 6.9903 h. This year's result is in good agreement. Using sparse data from the Asteroids – Dynamic Site, we were able to create a preliminary shape model with a sidereal rotational period of 6.99181 ± 0.00001 h.



Acknowledgements

Observations at CS3 and continued support of the asteroid lightcurve database (LCDB; Warner et al., 2009) are supported by NASA grant 80NSSC18K0851. Work on the asteroid lightcurve database (LCDB) was also partially funded by National Science Foundation grant AST-1507535. This research was made possible in part based on data from CMC15 Data Access Service at CAB (INTA-CSIC) (<http://svo2.cab.inta-csic.es/vocats/cmc15/>). 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 Grants from the Planetary Society.

References

- Asteroids – Dynamic Site. <https://newton.spacedys.com/astdys/>
- Asteroid Lightcurve Photometry Database. <http://www.alcdef.org/>
- 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**, 116-120.
- French, L.M.; Stephens, R.D.; Coley, D.R.; Wasserman, L.H.; Vilas, F.; La Rocca, D. (2013). "A Troop of Trojans: Photometry of 24 Jovian Trojan Asteroids." *Minor Planet Bull.* **40**, 198-203.
- Harris, A.W.; Young, J.W.; Scaltriti, F.; Zappala, V. (1984). "Lightcurves and phase relations of the asteroids 82 Alkmene and 444 Geytis." *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.

Hanuš, J.; Delbo', M.; Ďurech, J.; Alí-Lagoa, V. (2015). "Thermophysical modeling of asteroids from WISE thermal infrared data - Significance of the shape model and the pole orientation uncertainties." *Icarus* **256**, 101-116.

Kassalinen, M.; Torppa J. (2001a). "Optimization Methods for Asteroid Lightcurve Inversion. I. Shape Determination." *Icarus* **153**, 24-36.

Kassalinen, M.; Torppa J.; Muinonen, K. (2001b). "Optimization Methods for Asteroid Lightcurve Inversion. II. The Complete Inverse Problem." *Icarus* **153**, 37-51.

Kostov, A.; Bonev, T. (2017). "Transformation of Pan-STARRS1 gri to Stetson BVRI magnitudes. Photometry of small bodies observations." *Bulgarian Astron. J.* **28**, 3 (AriXiv:1706.06147v2).

Marchis, F.; Wong, M. H.; Berthier, J.; Descamps, P.; Hestroffer, D.; Vachier, F.; Le Mignant, D.; Keck Observatory, W.M.; de Pater, I. (2006). "S/2006 (624) 1." *IAU Circ.*, No. **8732**, #1.

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.

Stephens, R.D. (2010). "Trojan Asteroids Observed from GMARS and Santana Observatories: 2009 October - December." *Minor Planet Bull.* **37**, 47-48.

Stephens, R.D.; Coley, D.R.; French, L.M. (2014). "Trojan Asteroids Observed from CS3: 2014 January-May." *Minor Planet Bull.* **41**, 210-212.

Stephens, R.D.; Coley, D.R.; French, L.M., (2016a). "Large L5 Jovian Trojan Asteroid Lightcurves from the Center for Solar System Studies." *Minor Planet Bull.* **43**, 15-22.

Stephens, R.D.; Coley, D.R.; Warner, B.D.; French, L.M. (2016b). "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.; Warner B.W. (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 L4 Trojan Asteroids at the Center for Solar System Studies 2017 July - September." *Minor Planet Bull.* **45**, 48-50.

Stephens, R.D.; Warner, B.D. (2019). "Lightcurve Analysis of L4 Trojan Asteroids at the Center for Solar System Studies 2018 July - September." *Minor Planet Bull.* **46**, 73-75.

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 2019 July. <http://www.minorplanet.info/lightcurvedatabase.html>

Waszczak, A.; Chang, C.; Ofek, E.O.; Laher, R.; Masci, F.; Levitan, D.; Surace, J.; Cheng, Y.; Ip, W.; Kinoshita, D.; Helou, G.; Prince, T.A.; Kulkarni, S. (2015). "Asteroid lightcurves from the Palomar Transient Factory survey: Rotation periods and phase functions from sparse photometry." *Astron. J.* **150**, A75.

MINOR PLANETS AT UNUSUALLY FAVORABLE ELONGATIONS IN 2020

Frederick Pilcher
4438 Organ Mesa Loop
Las Cruces, NM 88011 USA
fpilcher35@gmail.com

A list is presented of minor planets which are much brighter than usual at their 2020 apparitions.

The minor planets in the lists which follow will be much brighter at their 2020 apparitions than at their average distances at maximum elongation. Many years may pass before these planets will be again as bright as in 2020. Observers are encouraged to give special attention to those which lie near the limit of their equipment.

These lists have been prepared by an examination of the maximum elongation circumstances of minor planets computed by the author for all years through 2060 with a full perturbation program written by Dr. John Reed, and to whom he expresses his thanks. Elements are from EMP 1992, except that for all planets for which new or improved elements have been published subsequently in the Minor Planet Circulars or in electronic form, the newer elements have been used. Planetary positions are from the JPL DE-200 ephemeris, courtesy of Dr. E. Myles Standish.

Any planets whose brightest magnitudes near the time of maximum elongation vary by at least 2.0 in this interval and in 2020 will be within 0.3 of the brightest occurring, or vary by at least 3.0 and in 2020 will be within 0.5 of the brightest occurring; and which are visual magnitude 14.5 or brighter, are included. For planets brighter than visual magnitude 13.5, which are within the range of a large number of observers, these standards have been relaxed somewhat to include a larger number of planets. Magnitudes have been computed from the updated magnitude parameters published in MPC28104-28116, on 1996 Nov. 25, or more recently in the Minor Planet Circulars.

Oppositions may be in right ascension or in celestial longitude. Here we use still a third representation, maximum elongation from the Sun, instead of opposition. Though unconventional, it has the advantage that many close approaches do not involve actual opposition to the Sun near the time of minimum distance and greatest brightness and are missed by an opposition-based program. Other data are also provided according to the following tabular listings: Minor planet number, date of maximum elongation from the Sun in format yyyy/mm/dd, maximum elongation in degrees, right ascension on date of maximum elongation, declination on date of maximum elongation, both in J2000 coordinates, date of brightest magnitude in format yyyy/mm/dd, brightest magnitude, date of minimum distance in format yyyy/mm/dd, and minimum distance in AU.

Users should note that when the maximum elongation is about 177° or greater, the brightest magnitude is sharply peaked due to enhanced brightening near zero phase angle. Even as near as 10 days before or after minimum magnitude the magnitude is generally about 0.4 greater. This effect takes place in greater time interval for smaller maximum elongations. There is some interest in very small minimum phase angles. For maximum elongations E near 180° at Earth distance Δ , an approximate formula for the minimum phase angle ϕ is $\phi = (180^\circ - E)/(\Delta + 1)$.