

LIGHTCURVE ANALYSIS OF L₅ TROJAN ASTEROIDS AT THE CENTER FOR SOLAR SYSTEM STUDIES: 2018 APRIL TO MAY

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Lightcurves of four Jovian Trojan asteroids were obtained at the Center for Solar System Studies (CS3) from 2018 April to May. One of the Trojans observed was 617 Patroclus to time the start of mutual events in support of NASA's Lucy mission.

CCD Photometric observations of four 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 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 most 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. A special target selected this observing season was the Patroclus-Menoetius binary Trojan asteroid in support of NASA's Lucy mission.

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
0.35-m f/11 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). Night-to-night calibration (generally ± 0.05 mag) was done using field stars from the CMC-15 or APASS (Henden et al., 2009) catalogs. 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 V 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 $G = 0.15$. 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 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, and some data were found from the Palomar Transient Factory (Waszczak et al., 2015).

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 to determine how much more data might be needed, preliminary pole and shape models were created for some of these targets. These will be published at a later date. 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 Kassalinen 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.

617 Patroclus. The Patroclus-Menoetius system is the first known Jovian Trojan binary. It has a mutual orbit of 4.283 ± 0.004 days (Marchis et al. 2005). NASA's Lucy probe is planned for a visit to the Patroclus-Menoetius system in 2033, creating a desire to refine its orbital properties. The Lucy program put out a call for supporting observations (<https://lucybo.space.swri.edu/news/>) and a prediction of mutual event times was published (Grudy et al., 2018).

Observations were planned beyond the predicted mutual events to allow measurement of the primary lightcurve. With each mutual event lasting approximately 4 hours, it would be difficult for any single station to capture an entire mutual event given the unpredictable winter weather in the Northern Hemisphere. Indeed, from CS3, mutual events were only detected twice.

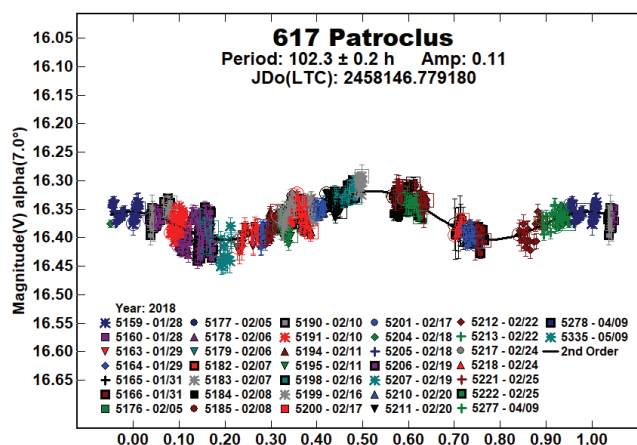


Figure 1. All observations of the Patroclus-Menoetius system without mutual events.

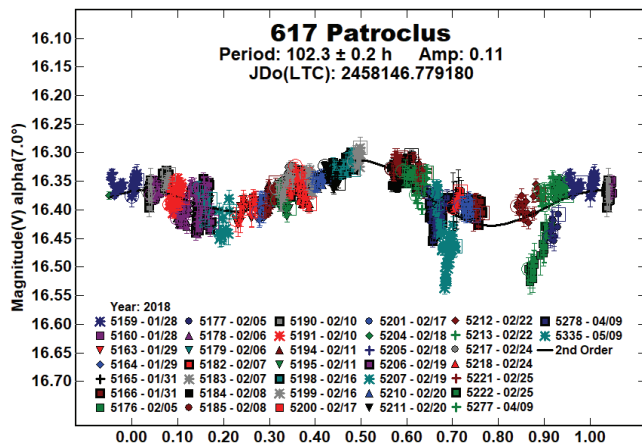


Figure 2. All observations of the Patroclus-Menoetius system including mutual events.

The purpose of the project was to measure the start and end of mutual events against their predicted times in order to reduce the orbital uncertainties. Precise predictions of the mutual events cannot be made due to the elapsed time from the original Marchis et al. (2005) predictions. In addition, the orbit could be changing over time due to perturbations.

Because of the 300 second exposures, it is unlikely the start of any single mutual event could be measured with an accuracy exceeding 10 minutes. An additional complication for the April 9 mutual event was that the German Equatorial mounted 0.35-meter SCT was crossing the meridian at the start of the mutual event, which caused further delay in the time sequence as the telescope reacquired the target field. This mutual event seemed to be about 60 minutes after its predicted start time, but this could be off by as much as 30 minutes due to the meridian flip. The session did not last long enough to reliably measure the end of the mutual event.

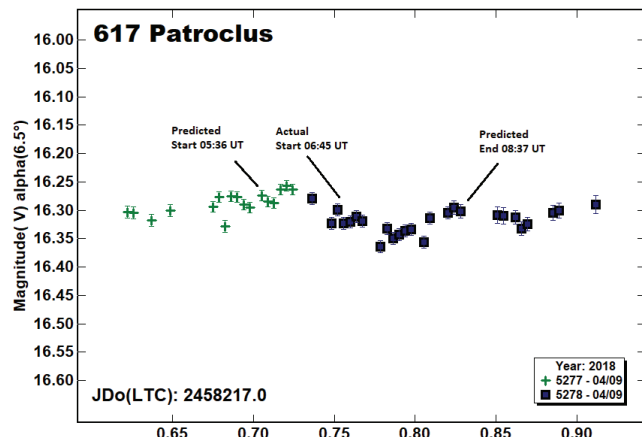


Figure 3. The mutual event on 2018 April 9. The actual start of the mutual event was about an hour after the predicted time.

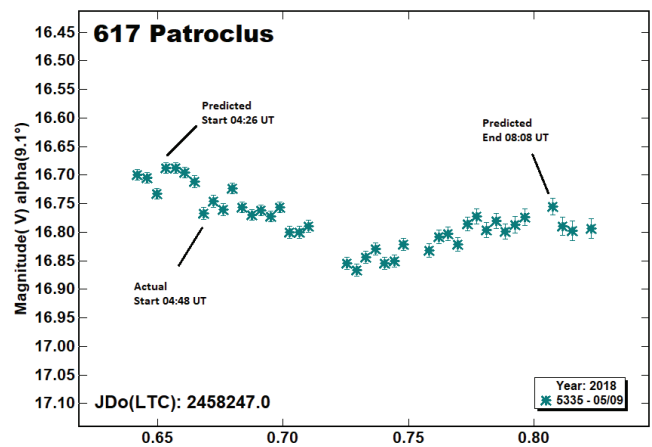


Figure 4. The mutual event on 2018 May 9. The actual start of the mutual event was about a half hour after the predicted time.

For the May 9 mutual event, the first drop in magnitude for the start of the mutual event was 22 minutes after the predicted time. However, that first data point might be an outlier, and the actual start of the mutual event could be about 30 minutes after the predicted time. Again, the session was not quite long enough to measure the end of the mutual event.

2895 Memnon. The synodic period we found this year agrees with previous synodic results (Binzel and Sauter, 1992; Mottola et al., 2011; French 2011; Stephens et al., 2015; 2016a; 2017). These data were combined with available sparse data to find a preliminary shape model with a sidereal rotational period of 7.51972 ± 0.00001 h.

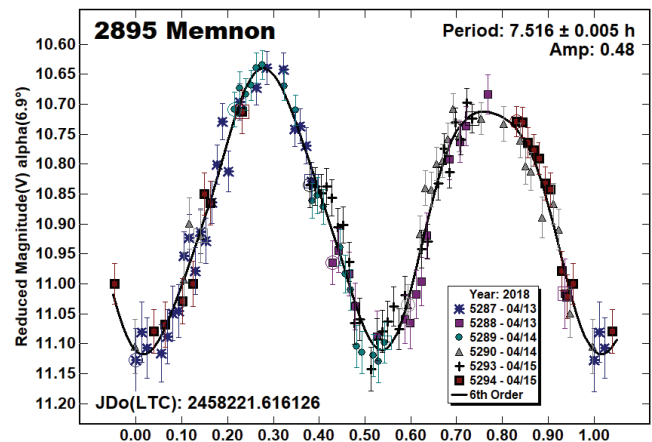


Figure 5. The lightcurve of 2895 Memnon for 2018.

4348 Poulydamas. Rotational periods have been determined five times in the past (Mottola et al., 2011; Stephens et al., 2015; 2016b; 2017; and Waszczak et al., 2015), each time finding a synodic period near 9.9 h. This year's result is in good agreement. The new and previous data were combined with available sparse data to find a preliminary shape model with a sidereal rotational period of 9.92006 ± 0.00001 h.

Number	Name	2018 mm/dd	Pts	Phase	L _{PAB}	B _{PAB}	Period(h)	P.E.	Amp	A.E.
617	Patroclus	01/28-05/11	920	7.0, 4.0, 9.3	166	21	102.8	0.1	0.05	0.01
2895	Memnon	04/13-04/15	123	7.0, 7.2	171	20	7.516	0.005	0.48	0.02
4348	Poulydamas	04/04-04/11	101	5.1, 6.2	167	-7	9.937	0.004	0.29	0.02
16070	1999 RB101	04/17-05/13	200	8.4, 10.4	160	-12	9.6	0.002	0.13	0.02

Table II. Observing circumstances and results. Pts is the number of data points. Phase is the solar phase angle for the first and last date. If there are three values, the middle value is the minimum phase angle. L_{PAB} and B_{PAB} are, respectively, the approximate phase angle bisector longitude and latitude at mid-date range (see Harris et al., 1984).

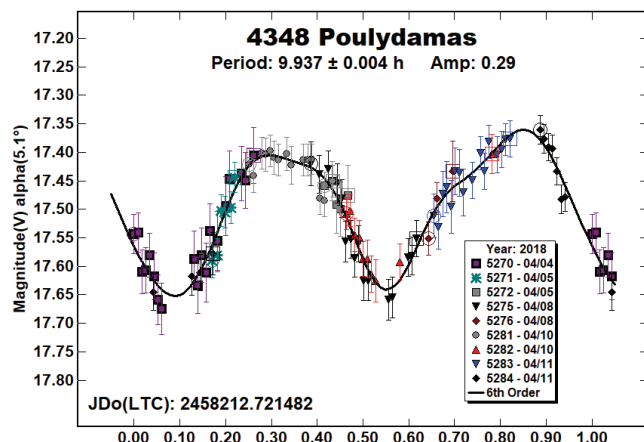


Figure 6. The synodic lightcurve of 4348 Poulydamas in 2018 April.

(16070) 1999 RB101. Due to its low amplitude and presumed spheroidal shape, this Trojan has always been a difficult case over the years. The tendency in evaluating rotational periods is to fit the Fourier curve to a bimodal solution. However, 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). We observed it four times in the past, first in 2011 (French et al., 2012) finding a synodic period of 31.74 h. In 2015, we observed it again finding a synodic period of 20.27 h while creating a very low amplitude single-modal lightcurve (Stephens et al., 2016a). In 2017, (Stephens et al., 2017) we again found a low amplitude lightcurve with a best fit synodic period of 20.205 h. However, the short runs each night and shape of the lightcurve did not by itself present a convincing case. In 2018, we were again presented with a low amplitude lightcurve, which, when phased to a period near 20 h, presented four extrema. However, the best fit in this range was just over 19 h. The data from the other years could not be phased to match this period.

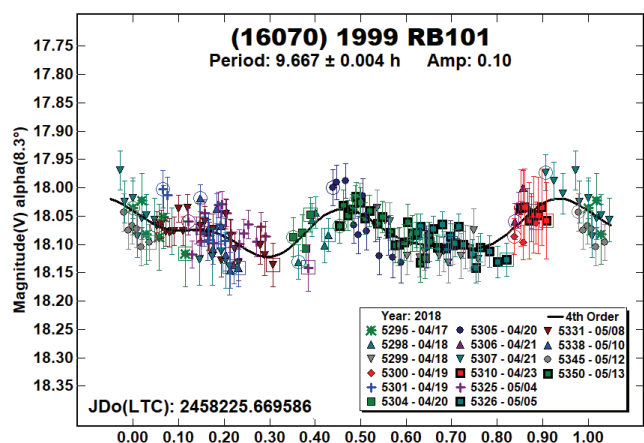


Figure 7. The lightcurve of (16070) 1999 RB101 in 2018 phased to 9.667 h.

The period spectrum for each year was reexamined to see if a common period presented itself. Each data set had several aliases present and minor zero point adjustments could make a difference. Like a Sherlock Holmes mystery, impossible solutions not present in all four datasets were eliminated leaving just one common solution near 9.7 h. Ultimately, this solution remains unsatisfactory since it is not a great fit to the 2011 dataset. It is possible some other physical process (e.g., tumbling) could be a factor contributing to the inability to find a repeatable rotation period.

Period Spectrum: (16070) 1999 RB101

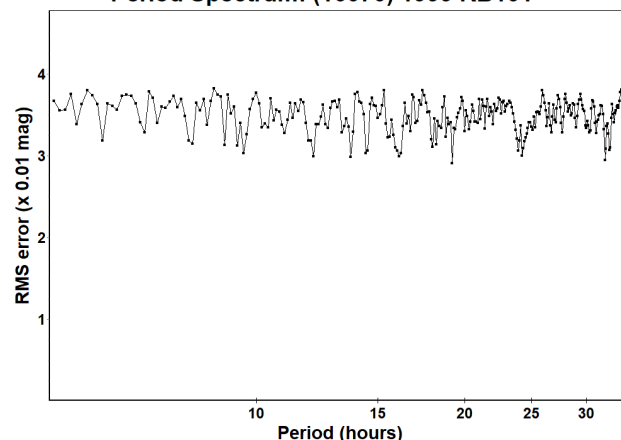


Figure 8. The period spectrum of (16070) 1999 RB101 in 2018 shows that no single period differentiates itself, but periods near 9.7 h, 19 h, and 24 h are possible.

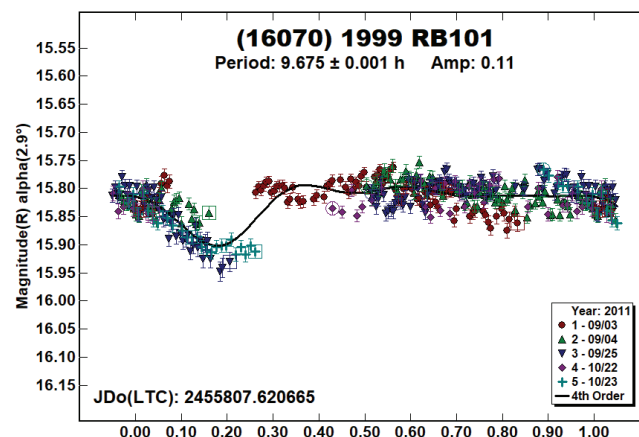


Figure 9. The dataset of (16070) 1999 RB101 in 2011 rephased to the 9.7 h period found in 2018. The dataset was originally fit to a period of 30.7 h, then to 19.06 h, both resulting in asymmetric bimodal lightcurves.

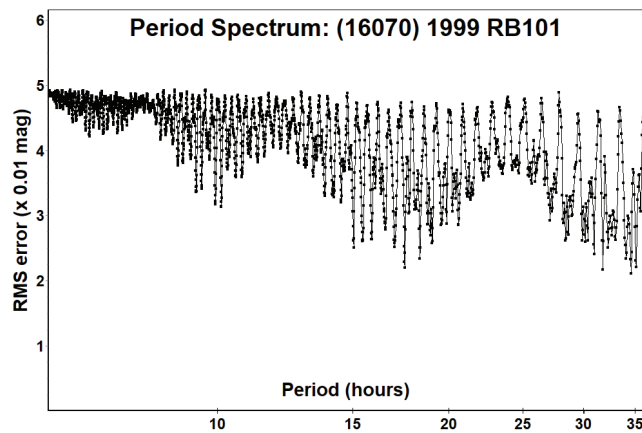


Figure 10. The Period Spectrum for the 2011 dataset of (16070) 1999 RB101 showing the 9.7 h, an 18 h, 19 h, and 34 h possible solutions.

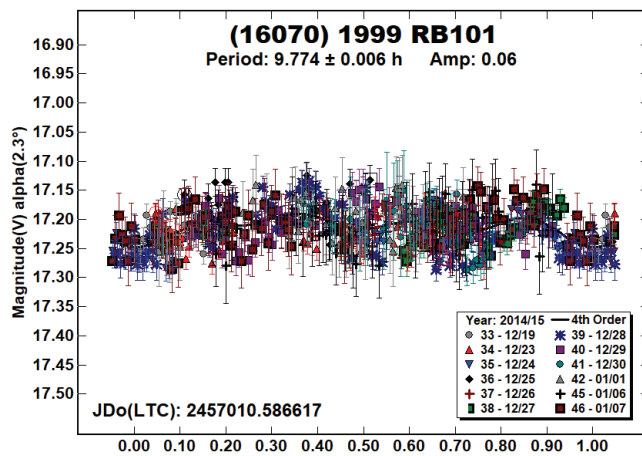


Figure 11. The dataset of (16070) 1999 RB101 in 2014/15 which has a very small amplitude. Combined with the noise in the observations almost equal to the amplitude, this dataset could fit a number of solutions.

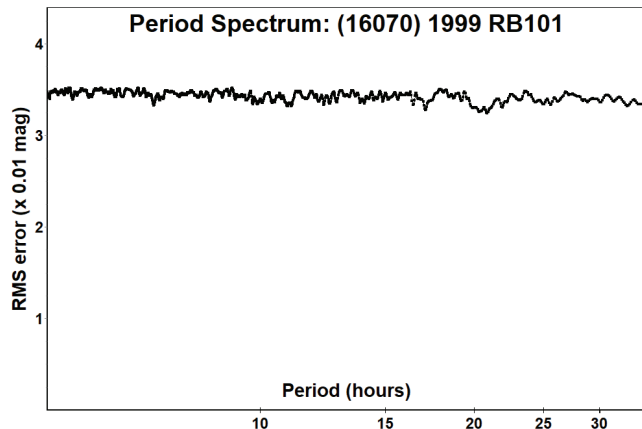


Figure 12. The Period Spectrum for the 2014/15 dataset which shows that no single solution stands out.

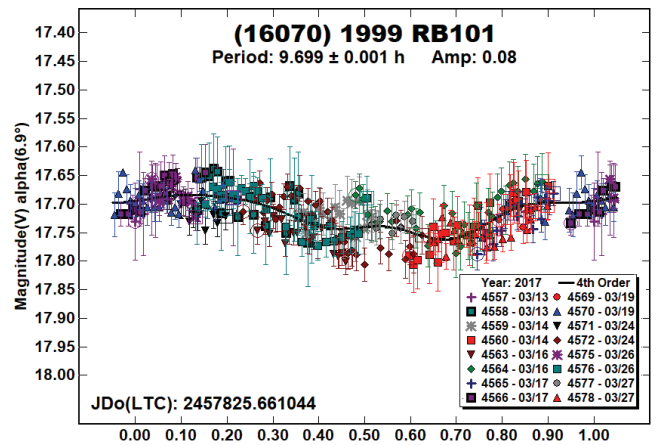


Figure 13. The dataset of (16070) 1999 RB101 in 2017 rephased to the 9.7 h period found in 2018. Originally the dataset was fitted to an asymmetric lightcurve with a 20.2 h period.

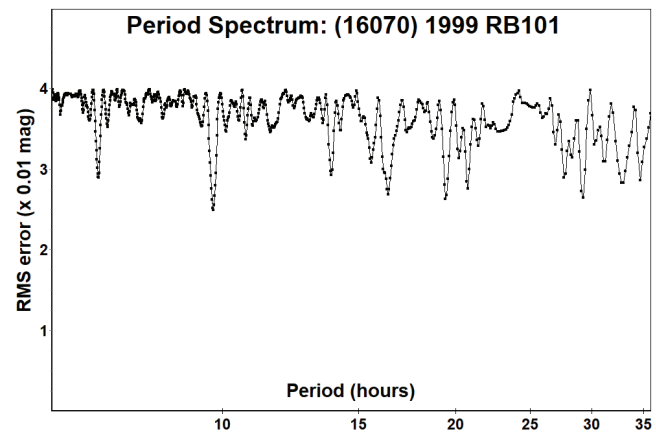


Figure 14. The Period Spectrum for the 2017 dataset of (16070) 1999 RB101 showing the 9.7 h, an 18 h, 20 h, and 30 h possible solutions.

Acknowledgements

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LIGHTCURVE ANALYSIS FOR FOURTEEN MAIN-BELT MINOR PLANETS

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Synodic rotation periods were determined for fourteen main-belt asteroids: 424 Gratia, 20.075 ± 0.008 h; 504 Cora, 7.58 ± 0.01 h; 791 Ani, 11.174 ± 0.004 h; 821 Fanny, 238.9 ± 0.8 h; 866 Fatme, 5.800 ± 0.002 h; 874 Rotraut, 14.297 ± 0.009 h; 896 Sphinx, 21.038 ± 0.008 h; 1097 Vicia, 100.5 ± 0.3 h; 1237 Genevieve, 16.48 ± 0.03 h; 1315 Bronislaw, 9.578 ± 0.002 h; 1329 Eliane, 137.8 ± 0.3 h; 1334 Lundmarka, 6.2497 ± 0.0008 h; 1793 Zoya, 5.750 ± 0.002 h; and 4142 Dersu-Uzala, 276.0 ± 1.0 h. All the data have been submitted to the ALCDEF database.

CCD photometric observations of fourteen main-belt asteroids were performed at Command Module Observatory (MPC V02) in Tempe. Images at V02 were taken using a 0.32-m $f/6.7$ Modified Dall-Kirkham telescope, SBIG STXL-6303 CCD camera, and a 'clear' glass filter. Exposure time for all the images was 2 minutes. The image scale after 2x2 binning was 1.76 arcsec/pixel. Table I shows the observing circumstances and results. All of the images for these fourteen asteroids were obtained during 2018 May and June, when southern Arizona enjoyed 35 photometric nights.

Images were calibrated using a dozen bias, dark, and flat frames. Flat-field images were made using an electroluminescent panel. Image calibration and alignment was performed using MaxIm DL software.

The data reduction and period analysis were done using *MPO Canopus* (Warner, 2017). The $45^\circ \times 30'$ field of the CCD typically enables the use of the same field center for three consecutive nights. In these fields, the asteroid and three to five comparison stars were measured. Comparison stars were selected with colors within the range of $0.5 < B-V < 0.95$ to correspond with color ranges of asteroids. In order to reduce the internal scatter in the data, the brightest stars of appropriate color that had peak ADU counts below the range where chip response becomes nonlinear were selected. The *MPO Canopus* internal star catalogue was useful in selecting comp stars of suitable color and brightness.

Comp star magnitudes were derived from a combination of CMC15 (Muñoz et al. 2014), APASS DR9 (Munari et al. 2015), and GAIA2 G (Sloan $r' = G$ for stars of asteroidal color) catalogues to set the zero-points each night. In most regions the Sloan r' data sources for brighter stars yielded very similar magnitudes (within about 0.05 mag total range), so mean values rounded to 0.01 mag precision were used.

This careful adjustment of the comp star magnitudes and color-indices allowed the separate nightly runs to be linked often with no zero-point offset required, or shifts of only a few hundredths of a magnitude in a series.

A 9-pixel (16 arcsec) diameter measuring aperture was used for asteroids and comp stars. It was typically necessary to employ star subtraction to remove contamination by field stars. For the