

CCD PHOTOMETRIC OBSERVATIONS OF 617 PATROCLUS-MENOETIUS MUTUAL EVENTS

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In response to a call for photometric observations of the Jupiter Trojan binary asteroid, 617 Patroclus-Menoetius, we formed a collaboration of observers in the United States, Italy, Brazil, and Australia. The observations were to coincide with the 2024-2025 mutual events season, which would allow refining the parameters of the system in preparation for NASA's Lucy fly-by mission in 2033 March. We recorded parts of nine different events from 2024 September 12 through October 23. Analysis found a period of 102.873 ± 0.006 h for the pair when including the events. The period without events was found to be 103.09 ± 0.04 h with an amplitude of 0.12 ± 0.01 mag. While we present analysis of our data for period and event details, we offer no interpretation regarding the parameters of the system beyond the rotation/orbital period. Additional observations will continue for as long as possible.

In 2033 March, NASA's Lucy mission will fly by the Jupiter Trojan 617 Patroclus and its binary companion, Menoetius. Mission planning requires having an accurate determination of the orbital

period, the rotation period of the system (slightly different if excluding events from analysis), and the orbital parameters. A call was put out for photometric observations of the system during the mutual events season in mid-2024 to mid-2025 (e.g., Binzel, 2024). The timing, depths, and shapes of the events would provide critical information needed for mission planning.

Brozovic et al. (2024) published a list of predictions for superior and inferior events. The former is when Patroclus is in front of Menoetius and the later when the positions are reversed. We used those predictions to plan observations of events visible from each observatory. Warner observed every clear night between 2024 Sep 13 and Oct 23, except two (it seems that it is important to remember to start the automation script), so that a period could be found when excluding event data. We produced more than 3,800 data points used for analysis.

Lead	Observatory	Tel	MPC	Dates (mm/dd)
Durkee	Shed of Science	0.50	V61	09/30
Fauerbach	Roque de los Muchachos	0.60	950	10/10
	Cerro Tololo Inter-Am.	0.60	807	10/15
Gebauer	McCarthy	0.43	932	10/10
Nastasi	Galhassin Robotic Telescope	0.40	L34	09/12, 09/15 09/24, 10/10
	Wide-field Mufara Telescope	1.0	M57	09/20
Oey	Blue Mountains	0.40	Q68	09/20
Tedesco	Remote Observatory Campos dos Goytacazes	0.28	Y16	09/26-09/28 10/07, 10/08
Stephens	CS3-U81	0.40	U81	09/30
Warner	CS3-U82	0.25	U82	09/13-10/23

Table I. List of observers and dates of contributed data. The "Tel" column gives the telescope aperture, in meters.

Superior Events

PO Partial Occultation
PE Partial Eclipse
PO+PE Partial Occultation and Partial
Eclipse with overlap
PO_PE Partial Occultation and Partial Eclipse
without overlap
TO Total Occultation
TE Total Eclipse

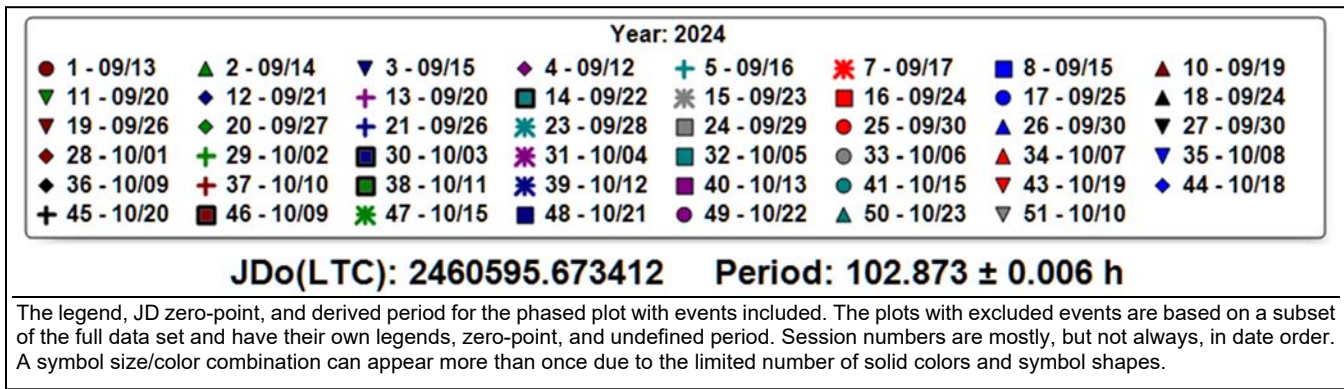
Inferior Events

PO Partial Occultation
PE Partial Eclipse
PO+PE Partial Occultation and Partial Eclipse
with overlap
PO_PE Partial Occultation and Partial Eclipse
without overlap
AO Annular Occultation
AO+PE Annular Occultation and Partial Eclipse
with overlap
AE Annular Eclipse

Table II. List of abbreviations for superior and inferior mutual events as defined by Brozovic et al. (2024).

Observing and Reduction Methodology

In order to avoid working with differences among systems as much as possible, all observers used either a clear or Sloan r' filter in the optical train of the telescope and CCD camera. Differential photometry used ATLAS refcat2 (Tonry et al., 2018) magnitudes of the comp stars. The magnitudes (r') are on the Pan-STARRS



photometric system, which closely follows the older Sloan (SDSS) system. The two do not have a simple linear conversion between them but, for these purposes, they are “close enough.” The response of the CCD cameras favored the red-end of the visible spectrum, and so, by selecting comp stars of near solar/asteroid color, it was possible to merge the data with minimal adjustments to the zero-point. Also helpful was having all images measured by one person using the same software. Only occasional tweaks of < 0.03 mag matched all but two sessions. Those two were provided as pre-measured data using *MPO Canopus* v10 with different filter/catalog settings. Even so, they were easily fitted before analysis began.

Exposures varied from observatory to observatory. Warner, for example, used 2-minute exposures on a 0.3-meter telescope and SBIG STL-1001E (Kodak KAF-1001E 1024×1024×24-micron chip) to get a high SNR (several hundred) for the asteroid and enough for the comps in the field. The asteroid was moving through relatively sparse fields, meaning that there was a limited need to reject images when the asteroid merged with a star, but this also meant not always finding the maximum allowed number of comp stars that met the requirements for color and not being too near saturation or too faint.

In other cases, especially when using modern CMOS or similar cameras, it was harder to keep the asteroid from saturating (going into the non-linear response of the ADU) while using sufficiently long exposures to avoid problems with scintillation noise. Some trial-and-error imaging led to the correct exposure length.

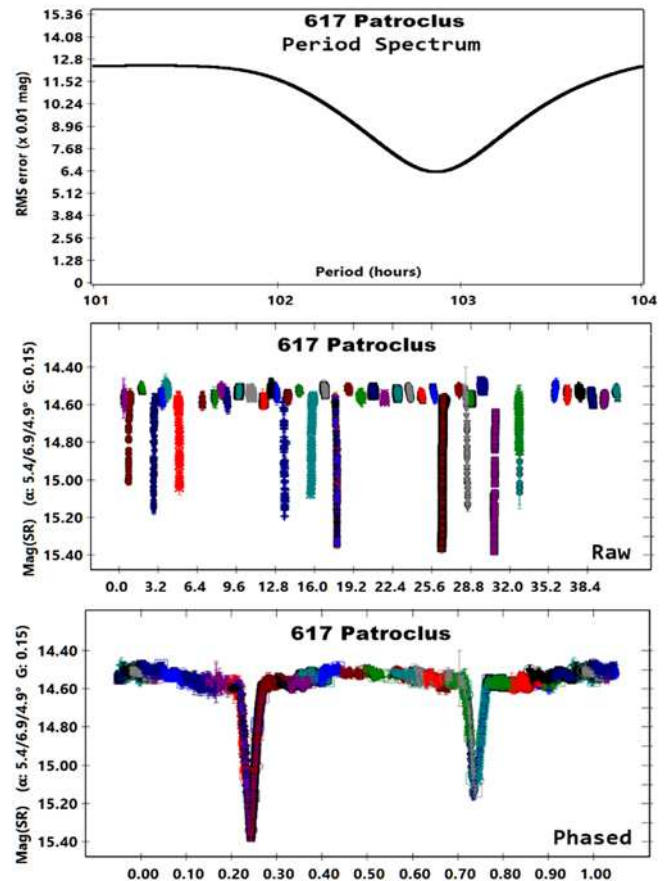
All observers made their original images available to Warner via a cloud account. This included light, flat, dark, and bias frames. Using *MPO Canopus* v12, Warner created a master dark, flat, and bias images when only submasters were available. These *master processing frames* were applied on-the-fly during measuring so that the original images were not altered.

The images were all measured using *MPO Canopus* v12 which allows using the r' (PR) magnitudes from the ATLAS refcat2 catalog for the up to 15 comp stars used for differential photometry. As noted above, the comp stars were restricted to those of near solar and asteroid color to minimize errors due to color differences.

Period analysis was done with *MPO Canopus* v12 which incorporates the FALC Fourier analysis algorithm written by Alan Harris (Harris et al., 1989). Once events were included in the data set, the period search used 15th-order analysis because of the very deep and sharp minimums. The original period search was confined to 100-106 hours based on the 102.8-hour period on the summary line of the asteroid lightcurve database (LCDB; Warner et al., 2009). With each new data set, the period search range was narrowed to focus on the merging period solution.

Period Analysis with Events

The period spectrum shows the expected minimum near 103 hours. Given the shape of the lightcurve and depth of minimums along with the known nature of the asteroid, no attempt was made to search for shorter or longer alias periods.

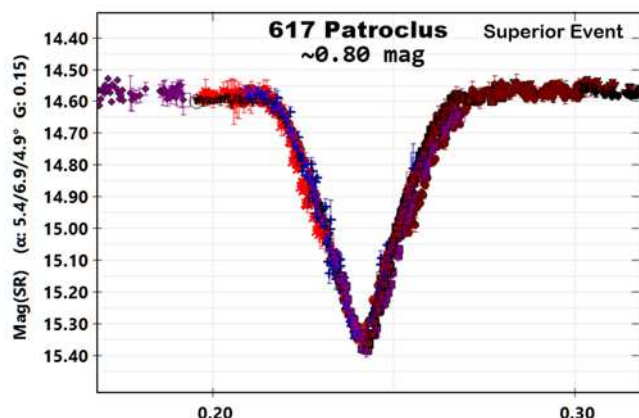


The raw plot shows the individual events and, when expanded, the slow periodic nature of the lightcurve outside events. The phased plot is fit to the adopted period of 102.873 ± 0.006 h. This is the formal error reported by the FALC algorithm. A better estimate is the error in the period that would shift the data from the initial match by 0.01 to 0.10 phase (the latter being the so-called 2% rule). Using 0.02 phase for the gauge, a more reasonable error is 0.04 h.

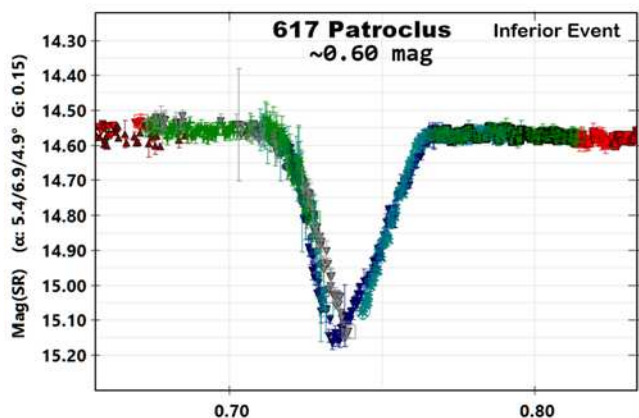
To save space and repetition, the legend, zero-point JD, and period are included in the common plot above, which applies to *all* but the two plots where the period was found when excluding events.

The Combined Events

Superior Event. The superior event occurs when the secondary, Menoetius, goes behind the primary, Patroclus. As an aside, Menoetius was Patroclus' father, so "dad" is taking a back seat in this case. The "Superior" plot shows a close-up the superior event. Zooming in even more shows that the multiple sessions covering the event do not have quite the same shape. This could be due to systematic errors among the data or, possibly, evolution of the mutual events with changing viewing aspect.



Inferior Event. When Menoetius passes in front of Patroclus, this is an inferior event. The depth of about 0.60 mag in the "Inferior" plot leads to an estimated effective diameter ratio between Menoetius and Patroclus of at least 0.86 ± 0.03 . This is close to the 0.92 based on the published effective diameters of the two bodies (LCDB; Warner et al, 2009).



There are much greater differences among the sessions covering the inferior event. Here again, it could be systematic errors or and evolving lightcurve. Detailed modeling will help determine how much of each is a contributor.

The Individual Events

For each event, the date and type are given. Use Table II to interpret the event types. An event in bold text is the one that causes the greatest magnitude drop. Since the full individual events were not observed in their entirety, only some of the mutual circumstances of an event were covered.

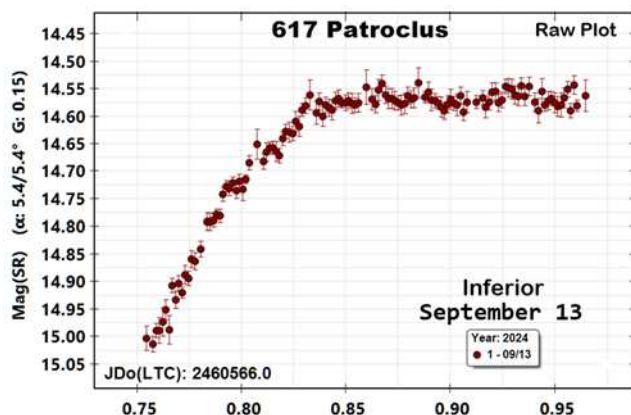
It is difficult to determine when the entire event begins and/or ends because there is no sharp shoulder point. In this case, a best guess data point was chosen for the end of the event. For events that were sharply defined on both sides of the minimum, the Time of Minimum/Maximum feature of *MPO Canopus* was used to estimate the time of minimum.

The algorithm is based on the method developed by Hertzprung (1928) as described by Henden and Kaitchuck (1990). This relies on several data points on either side of the minimum. Each point on one side of the minimum is "connected" to another at about the same amplitude on the other side. An iteration process eventually finds the best estimate for the time of minimum. In our case, about ten pairs were initially used to start the calculations. Since the interval between exposures was usually only a few minutes, this allowed for a fairly precise estimate of the time of minimum.

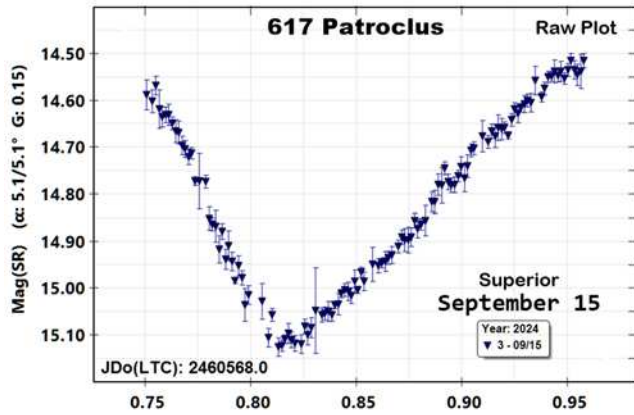
It's important to note that the values for raw data, not phased to a period nor from a Fourier curve, were used in the analysis. Noise in the data likely had a noticeable effect on our estimated times. Also important is that light-time corrected JD were used in the calculations for minimum. Individual raw data points were in UT. To compare to Brozovic et al. (2024), the times of minimum were adjusted to geocentric UT using a constant of 0.005785 d/au and computing the distance to units of 0.0001 au. This also means that the date/time of points on the plots are light-time corrected and that the correction must be reversed to get the UT value.

The description for computing the error of the estimate was not included in Henden and Kaitchuck. However, the latter provided the necessary details in a private communication.

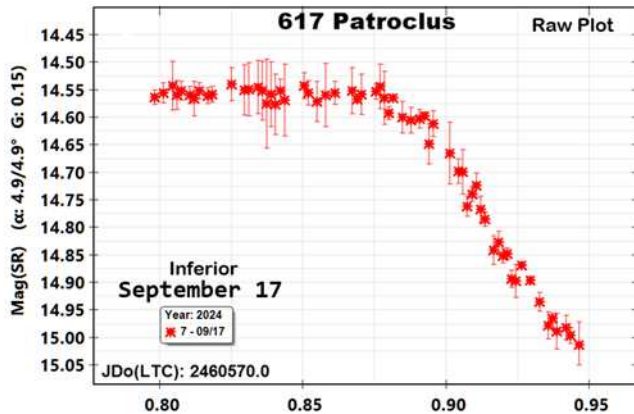
2024 September 13 (Inferior – PO PO+PE, PE). This was observed by Warner (U82). The estimated end of the event was 08:46 UT (0.835 d on the plot). Brozovic et al. (2024) predicted 08:31 UT (0.855 d).



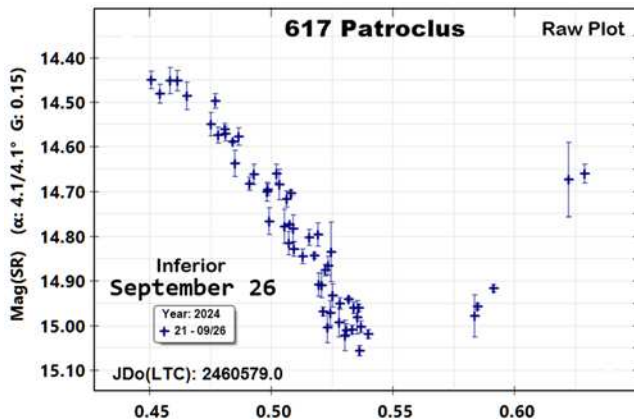
2024 September 15 (Superior – PO PO+PE, PE). Observed by Warner at (U82). The estimated time of minimum from our data is 08:09 UT (0.819 d on the plot). Brozovic et al. (2024) predicted 07:56 UT (0.810 d) for the deepest minimum.



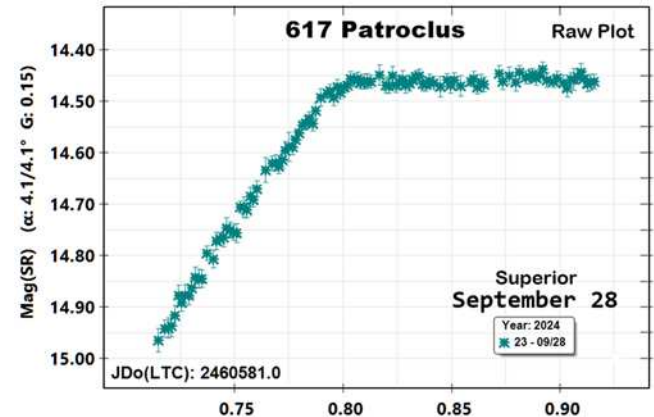
2024 September 17 (Inferior – PO PO+PE, PE). Observed by Warner (U82). Based on his data, the estimated time for the start of the event is 09:32 UT (0.877 d on the plot). Brozovic et al. (2024) gave 09:06 UT, or about 0.858 d on the plot.



2024 September 26 (Inferior – PO PO+PE, PE). Observed by Tedesco (Y16). A very rough estimate for the start of the event is Sep 25 at 23:34 UT (0.461 d on the plot). Brozovic et al. (2024) predicted Sep 25 at 23:02 UT (0.440 d). The left-most data point in the plot is on Sep 25 23:18 UT (0.451 d).



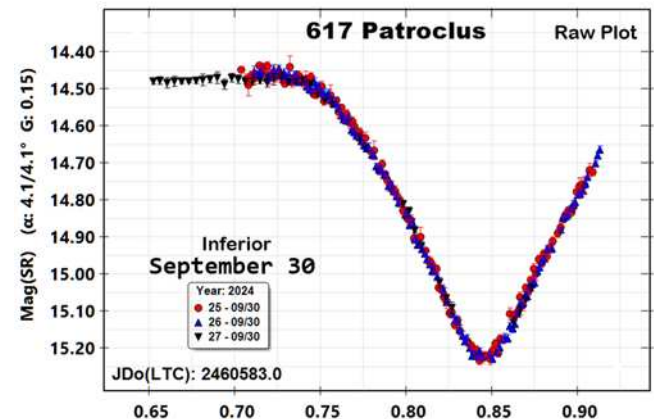
2024 September 28 (Superior – PO PO+PE, PE). Observed by Warner (U82). The estimated time for the end of the event is 07:48 UT (0.805 d on the plot). Brozovic et al. (2024) predicted 07:30 (0.793 d).



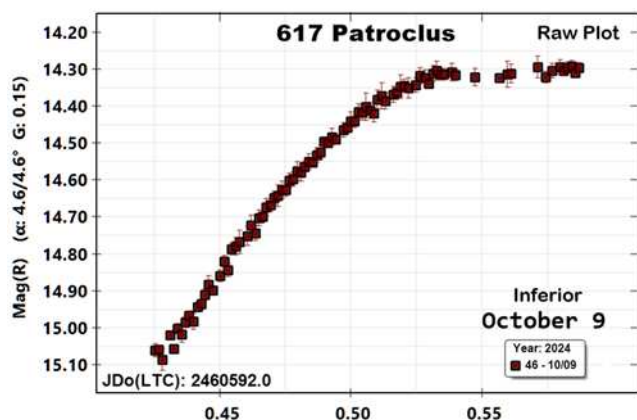
2024 September 30 (Inferior – PO PO+PE, AO+PE, PO+PE, PO). Observed by Warner (U82, red circles), Stephens (U81; blue up triangles), and Durkee (V61; black down triangles). The first plot shows how well the data overlapped and, if nothing else, confirmed no significant anomalies in any one data set.

Using Warner's data alone, the estimated time of minimum was 08:47 UT. Stephens' data gave 08:48 UT while Durkee's gave 08:45 UT. Of the three, the Stephens' data gave the strongest signs of a total event (flat bottom), which seems to confirm the annular occultation and partial eclipse with overlap predicted by Brozovic et al. (2024). Their prediction for deepest minimum was at 08:38 UT (0.86 d on the plot).

Start time based on Warner's data was 06:03 UT (0.732 d on the plot), 05:52 UT (0.724 d) from Stephens' data, and 06:14 UT (0.740 d) from Durkee's. Brozovic et al. (2024) predicted 06:00 UT (0.729 d on the plot). The differences are probably mostly due to the uncertainty in estimating the start time.



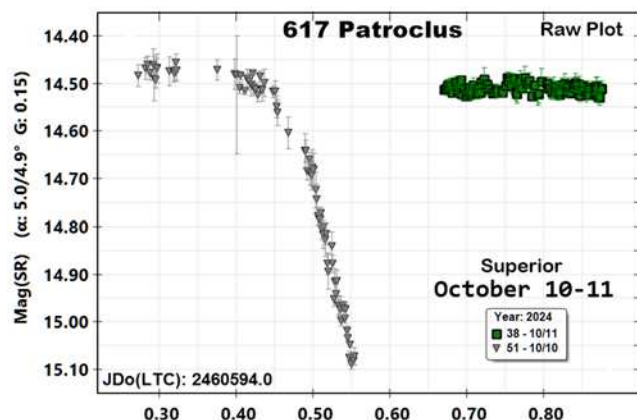
2024 October 9 (Inferior – PO PO+PE, AO+PE, PO+PE, PO). Observed by Fauerbach (950), our estimate of event end is 01:16 UT (0.533 d on the plot). Brozovic et al. (2024) predicted end-of-event for 01:05 (0.525 d). The minimum is not fully defined. The earliest data point is on Oct 8 at 22:44 UT (0.425 d on the plot). Brozovic et al. (2024) predicted 22:26 UT (about 0.415 d).



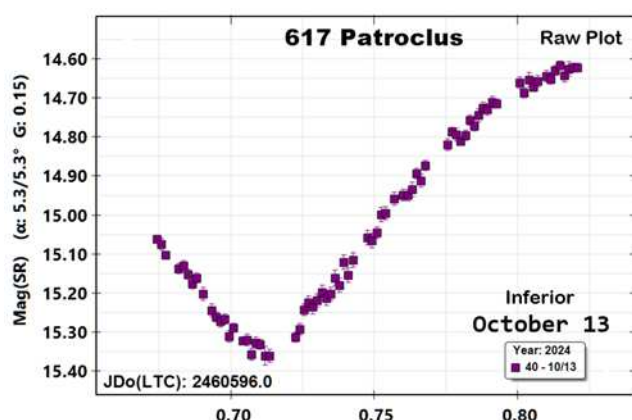
2024 October 10-11 (Superior – **PE** PO+PE, TO, PO+PE, PO). The start and apparent minimum of this event were observed by Nastasi (L34). Because of occasional periods of diminished transparency, the estimate for the start time is more uncertain than in other cases.

Our best estimate is on Oct 10 at 22:50 UT (0.431 d on the plot). Brozovic et al. predicted 23:08 UT (0.442 d). Our estimate for the time of minimum, based on the last data point at the low point, is Oct 11 at 01:47 UT (0.554 d on the plot). Brozovic et al. (2024) predicted 01:45 UT (0.552 d).

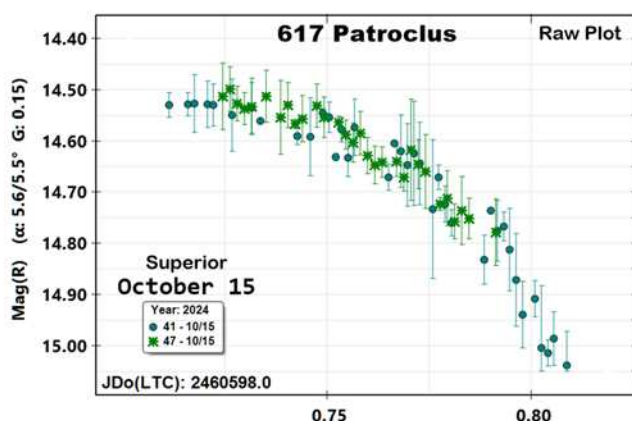
The end of the event is not defined, but the data from Warner (U82) around that time indicate approximate symmetry in the minimum point between start and end. The first data point in the Warner subset is at 04:35 UT (0.670 on the plot). Brozovic et al. (2024) predicted 04:08 UT (0.650 d) for event end.



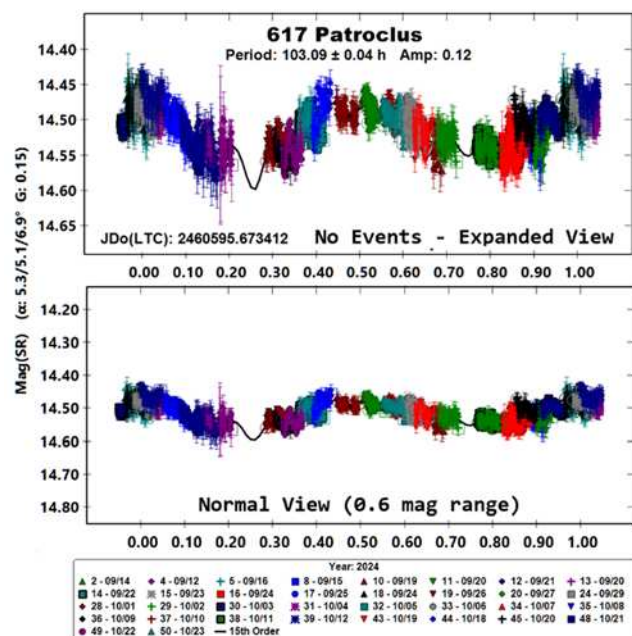
2024 October 13 (Inferior – **PE** PO+PE, PO). Observed by Warner (U82), the estimated time of minimum is 05:37 UT (0.713 d on the plot). Brozovic et al. (2024) listed 05:24 UT (0.704 d) for minimum and 08:03 UT (0.815 d) for end-of-event. Coverage at the end was not complete, but our best estimate is 08:07 UT (0.818 d).



2024 October 15 (Superior – **PE** PO+PE, PO). Observed by Fauerbach (807), whose data started close to the start of the event at 05:52 UT (0.724 d on the plot), which is the same time given by Brozovic et al. (2024). Warner (U82) also observed the same event, with his data starting about 20 minutes earlier. Those data give an estimated event start of 05:47 UT (0.721 d).



Periods Analysis Sans Events



Parameters	This Paper	Brozovic et al.	Difference
Rotational Period with Events (h)	102.873 $\pm$ 0.006	102.876 $\pm$ 0.005	0.003 h
Rotational Period without Events (h)	103.09 $\pm$ 0.04	103.08 $\pm$ 0.03	0.01 h
Minimum Depth (Superior, mag)	0.79 $\pm$ 0.03	0.76	0.03 mag
Maximum Depth (Inferior, mag)	0.60 $\pm$ 0.03	0.61	0.01 mag
Effective Diameter Ratio (Menoetius/Patroclus)	0.86 $\pm$ 0.03	0.92	0.06 $\pm$ 0.06
Observed Events	This Paper UT	Brozovic et al. UT	UT-Brozovic minutes
Sep 13 - Inferior (end)	08:46	08:31	+15
Sep 15 - Superior (minimum)	08:09	07:56	+14
Sep 17 - Inferior (start)	09:32	09:06	+26
Sep 26 - Inferior (start)	23:34	23:02	+32
Sep 28 - Superior (end)	07:48	07:30	+18
Sep 30 - Inferior (start)	06:14	06:00	+14
(minimum)	08:47	08:38	+9
Oct 09 - Inferior (minimum - Oct 8)	22:44	22:26	+18
(end)	01:16	01:05	+11
Oct 10 - Superior (start)	22:50	23:08	-18
(minimum - Oct 11)	01:47	01:45	+2
(end - Oct 11, earliest time)	04:35	04:08	+27
Oct 13 - Inferior (minimum)	05:37	05:24	+13
(end - ill-defined)	08:07	08:03	+4
Oct 15 - Superior (start - earliest time)	05:47	05:52	-5

Table III. A listing of the observed events, giving the estimated UT from this paper, the UT predicted by Brozovic et al. (2024), and the difference between our estimate and Brozovic et al. (2024). All times in this table are Earth-centric.

It might, maybe even should, be expected that the period derived when using the data with and without the events would be the same or within a couple sigmas. When excluding the events, the period found by *MPO Canopus* was 103.09 ± 0.04 h, making the lower 2-sigma result about 103.01 h. The result using the events was 102.873 ± 0.006 h. If using the more realistic 2-sigma value of 0.08 h, the maximum becomes about 102.879 h. We leave to others to reconcile the differences, which may be to do to with insufficient data outside the events, i.e., not enough overlapping sections of the lightcurve, shadowing effects, lightcurve evolution, or a permutation of the three.

Remarks

We plan additional observations as the mutual event season continues into 2025 mid-January. Most observers will limit their observations to dates and times that can cover some portion of an event. Warner will work the asteroid every possible night until the observing runs are cut too short as the asteroid moves westward across the sky. All the data used in the analysis will be uploaded to the Asteroid Lightcurve Data Exchange Format (ALCDEF) web site at <https://alcdef.org> after publication of the follow-up paper.

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