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

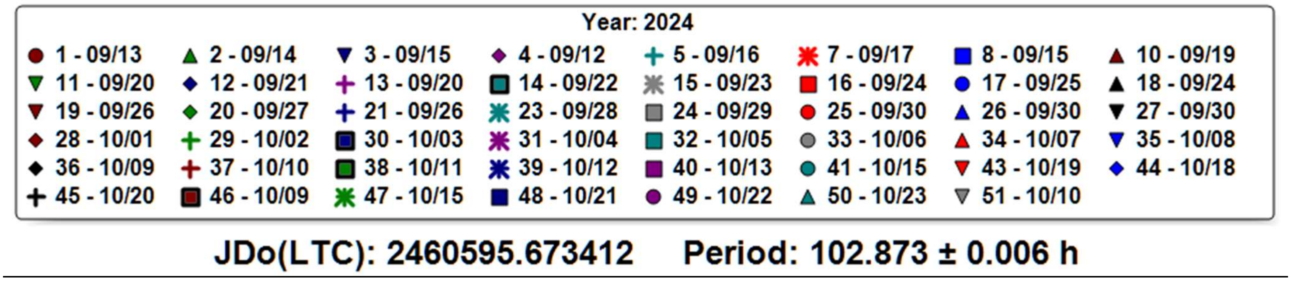
Inferior Events

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



The legend, JD zero-point, and derived period for the phased plot with events included. The plots with excluded events are based on a subset of the full data set and have their own legends, zero-point, and undefined period. Session numbers are mostly, but not always, in date order. A symbol size/color combination can appear more than once due to the limited number of solid colors and symbol shapes.

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.

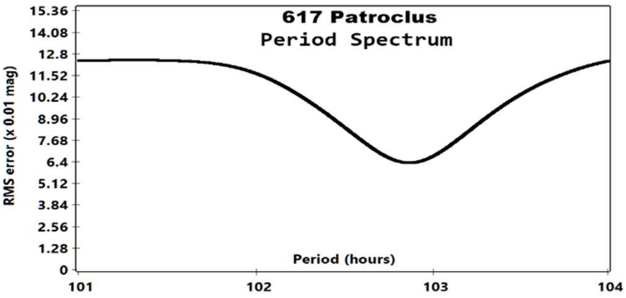
All observers made their original images available to Warner via a cloud account. This included light, flat, dark, and bias frames. Using *MPO Canopus* v12, Warner created a master dark, flat, and bias images when only submasters were available. These *master processing frames* were applied on-the-fly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

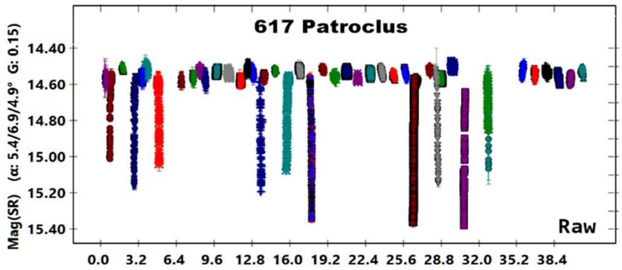
The images were all measured using *MPO Canopus* v12 which allows using the r′ (PR) magnitudes from the ATLAS refcat2 catalog for the up to 15 comp stars used for differential photometry. As noted above, the comp stars were restricted to those of near solar and asteroid color to minimize errors due to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

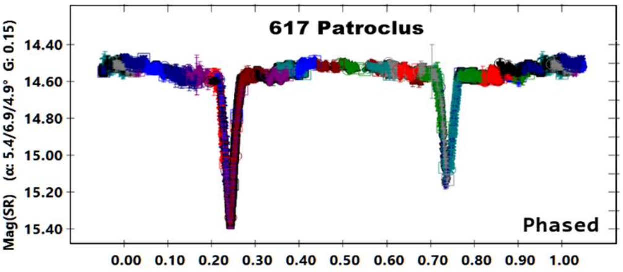
Period analysis was done with *MPO Canopus* v12 which incorporates the FALC Fourier analysis algorithm written by Alan Harris (Harris et al., 1989). Once events were included in the data set, the period search used 15th-order analysis because of the very deep and sharp minimums. The original period search 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.





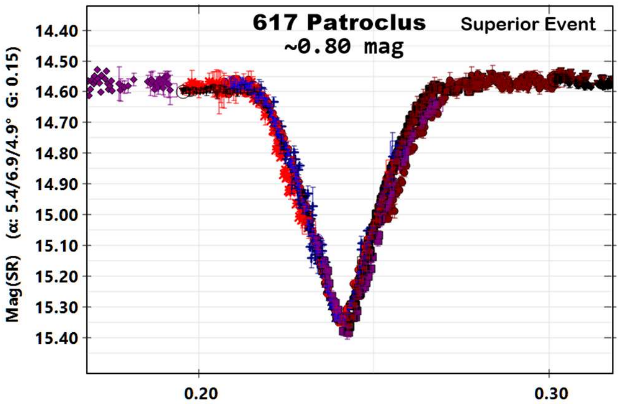


The raw plot shows the individual events and, when expanded, the slow periodic nature of the lightcurve outside events. The phased plot is fit to the adopted period of 102.873 ± 0.006 h. This is the formal error reported by the FALC algorithm. A better estimate is the error in the period that would shift 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.

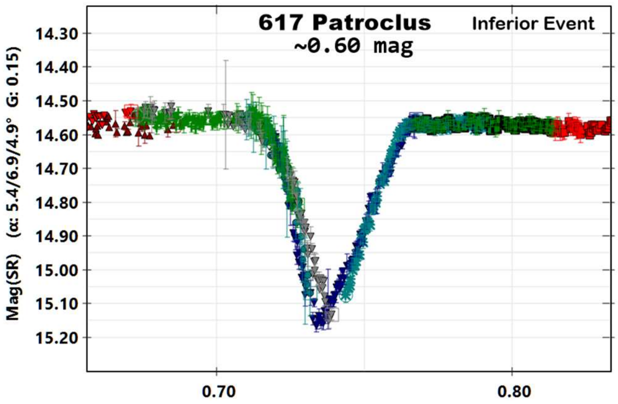
*To save space and repetition, the legend, zero-point JD, and period are included in the common plot above, which applies to **all** but the two plots where the period was found when excluding events.*

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.

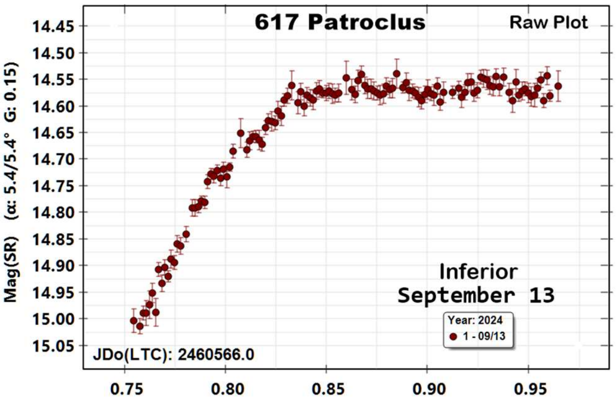
It is difficult to determine when the entire event begins and/or ends because there is no sharp shoulder point. In this case, a best guess data point was chosen for the end of the event. For events that were sharply defined on both sides of the minimum, the Time of Minimum/Maximum feature of *MPO Canopus*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

The algorithm is based on the method developed by Hertzsprung (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.

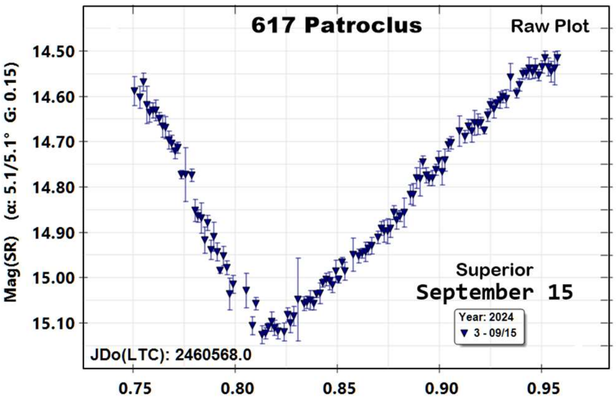
It's important to note that the values for raw data, not phased to a period nor from a Fourier curve, were used in the analysis. Noise in the data likely had a noticeable effect on our estimated times. Also important is that light-time corrected JD were used in the calculations for minimum. Individual 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.

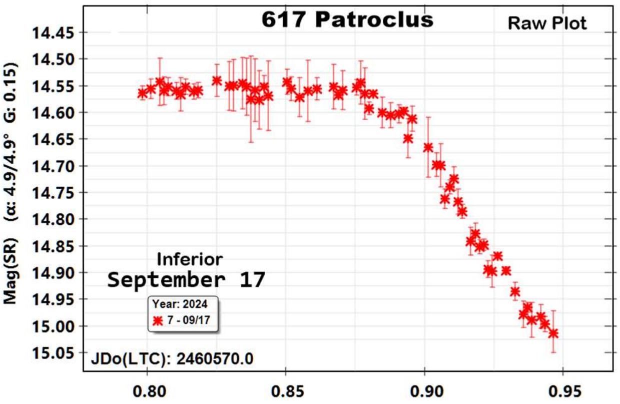
2024 September 13 (Inferior – **PO** PO+PE, PE). This was observed by Warner (U82). The estimated end of the event was 08:46 UT (0.835 d on the plot). Brozovic et al. (2024) predicted 08:31 UT (0.855 d).



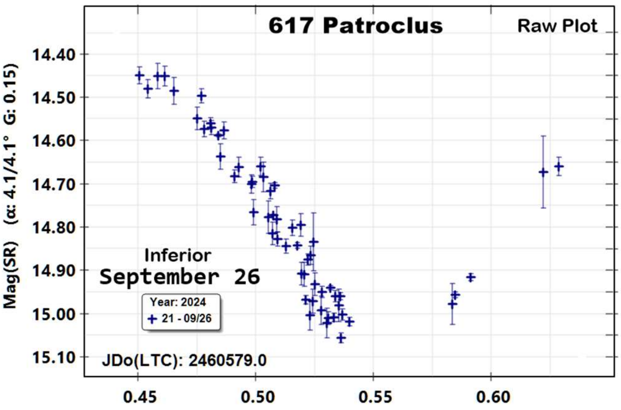
2024 September 15 (Superior – **PO** PO+PE, PE). Observed by Warner at (U82). The estimated time of minimum from our data is 08:09 UT (0.819 d on the plot). Brozovic et al. (2024) predicted 07:56 UT (0.810 d) for the deepest minimum.



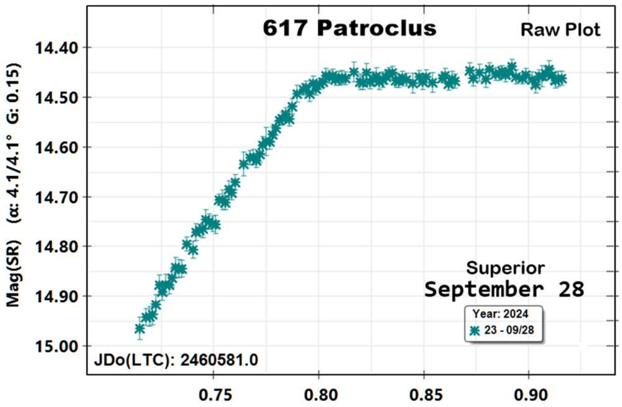
2024 September 17 (Inferior – **PO** PO+PE, PE). Observed by Warner (U82). Based on his data, the estimated time for the start of the event is 09:32 UT (0.877 d on the plot). Brozovic et al. (2024) gave 09:06 UT, or about 0.858 d on the plot.



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).



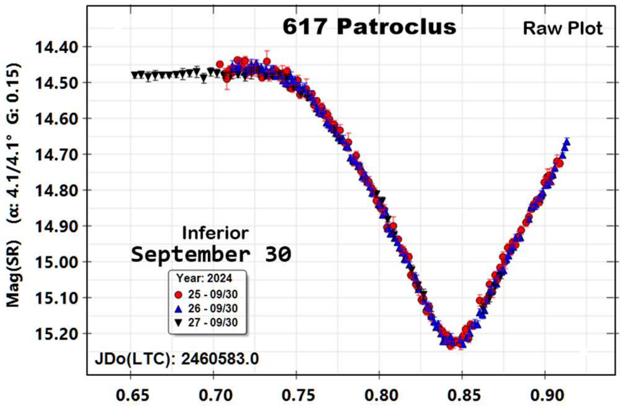
2024 September 28 (Superior – **PO** PO+PE, PE). Observed by Warner (U82). The estimated time for the end of the event is 07:48 UT (0.805 d on the plot). Brozovic et al. (2024) predicted 07:30 (0.793 d).



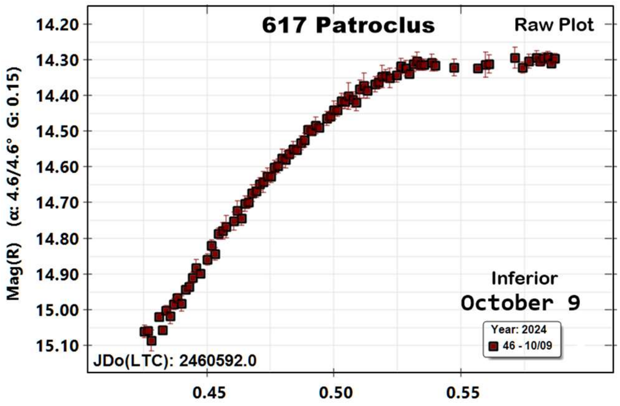
2024 September 30 (Inferior – **PO** PO+PE, AO+PE, PO+PE, PO). Observed by Warner (U82, red circles), Stephens (U81; blue up triangles), and Durkee (V61; black down triangles). The first plot shows how well the data overlapped and, if nothing else, confirmed no significant anomalies in any one data set.

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.



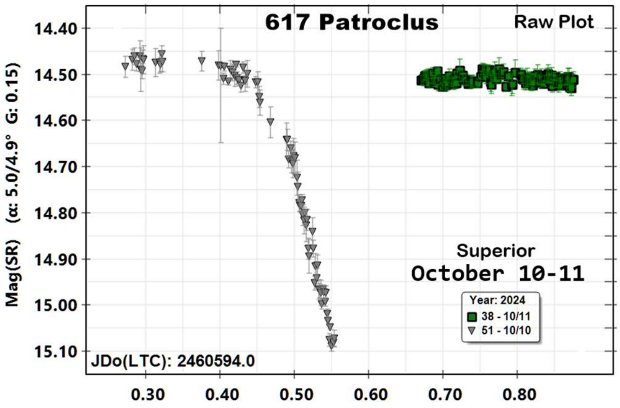
2024 October 9 (Inferior – **PO** PO+PE, AO+PE, PO+PE, PO). Observed by Fauerbach (950), our estimate of event end is 01:16 UT (0.533 d on the plot). Brozovic et al. (2024) predicted end-of-event for 01:05 (0.525 d). The minimum is not fully defined. The earliest data point is on Oct 8 at 22:44 UT (0.425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



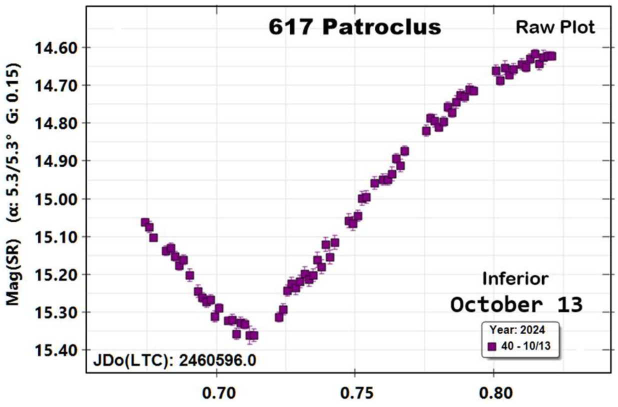
2024 October 10-11 (Superior – **PE** PO+PE, TO, PO+PE, PO). The start and apparent minimum of this event were observed by Nastasi (L34). Because of occasional periods of diminished transparency, the estimate for the start time is more uncertain than in other cases.

Our best estimate is on Oct 10 at 22:50 UT (0.431 d on the plot). Brozovic at 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).

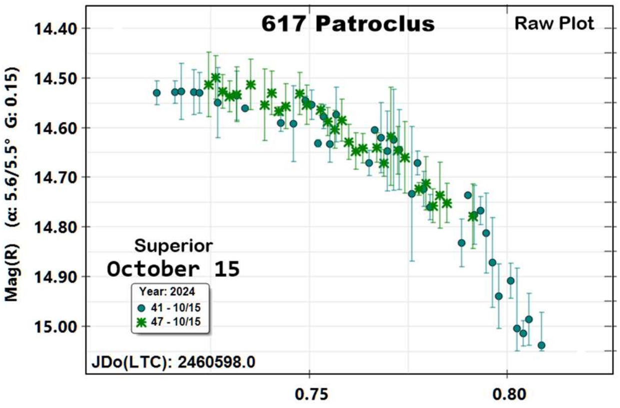
The end of the event is not defined, but the data from Warner (U82) around that time indicate approximate symmetry in the minimum point between start and end. The first data point in the Warner subset is at 04:35 UT (0.670 on the plot). Brozovic et al. (2024) predicted 04:08 UT (0.650 d) for event end.



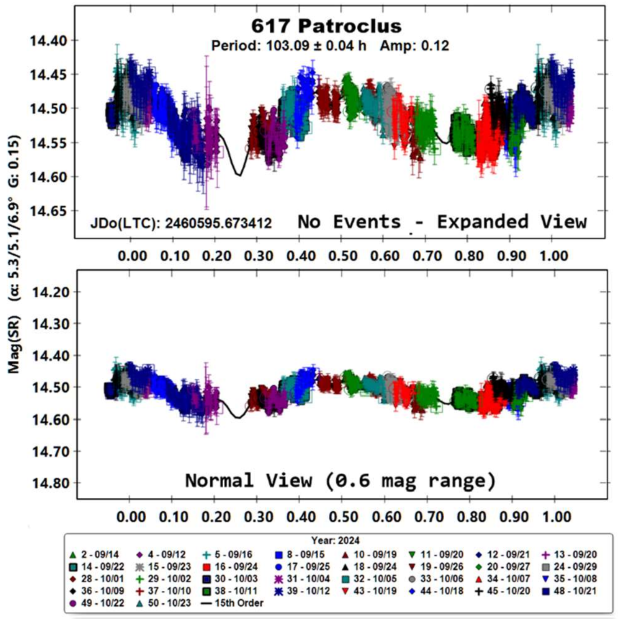
2024 October 13 (Inferior – **PE** PO+PE, PO). Observed by Warner (U82), the estimated time of minimum is 05:37 UT (0.713 d on the plot). Brozovic et al. (2024) listed 05:24 UT (0.704 d) for minimum and 08:03 UT (0.815 d) for end-of-event. Coverage at the end was not complete, but our best estimate is 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 ± 0.006	102.876 ± 0.005	0.003 h
Rotational Period without Events (h)	103.09 ± 0.04	103.08 ± 0.03	0.01 h
Minimum Depth (Superior, mag)	0.79 ± 0.03	0.76	0.03 mag
Maximum Depth (Inferior, mag)	0.60 ± 0.03	0.61	0.01 mag
Effective Diameter Ratio (Menoetius/Patroclus)	0.86 ± 0.03	0.92	0.06 ± 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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617 PATROCLUS-MENOETIUS MUTUAL EVENT LIGHTCURVES

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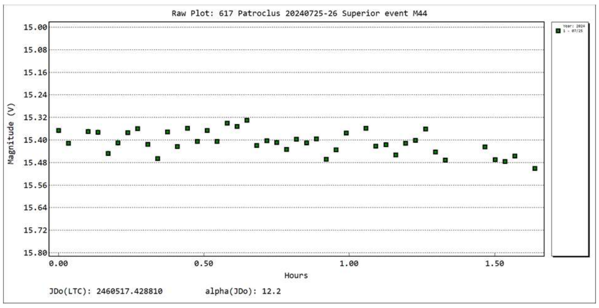
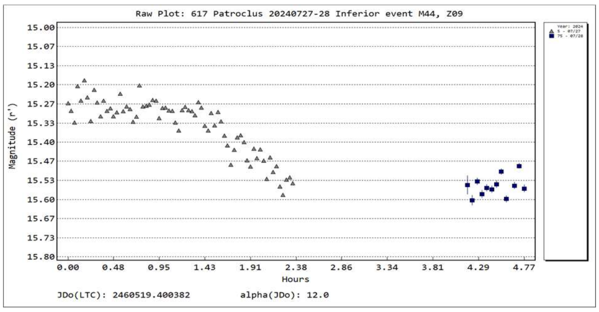
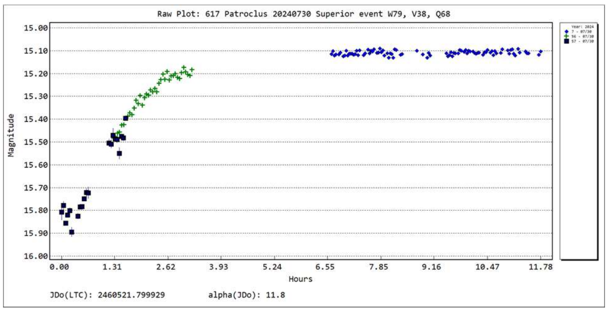
We report on photometric observations of the binary Trojan asteroid 617 Patroclus-Menoetius undertaken from July to October 2024.

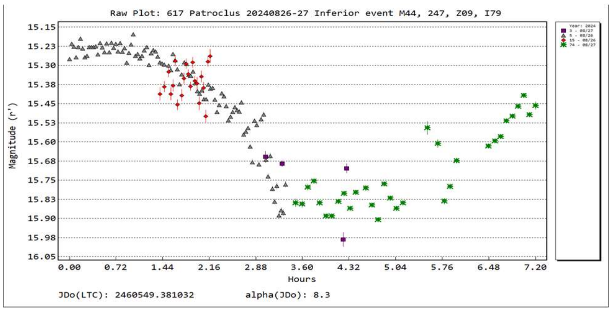
In response to the paper “Call for Observations of the Patroclus and Menoetius Mutual Events: Support for the NASA Lucy Mission to the Trojan Asteroids” (Binzel, 2024); photometric observations of the binary Trojan asteroid 617 Patroclus-Menoetius were undertaken from 25 July 2024 to 30 October 2024. 617 Patroclus, is a Trojan asteroid discovered 1906-10-17 by A. Kopff at Heidelberg. Its binary pair member, Menoetius was discovered in 2001, with the provisional designation: S/2001 (617) 1.

Here we present mutual event lightcurves derived from photometric images obtained from observatories around the globe. We used the predictions by Brozovic et al. (2024) as a basis for planning our observations. *All lightcurves presented have been light-time corrected accounting for the asteroid's changing distance to Earth.* Several of the co-authors used their own equipment and some used the Las Cumbres Observatory facilities. A full listing of observers and equipment is given in the accompanying table. Photometric reduction was carried out with *TychoTracker Pro* Version 11.7.5. (TT). We archive our data with the Asteroid Lightcurve Database (Warner et al., 2009).





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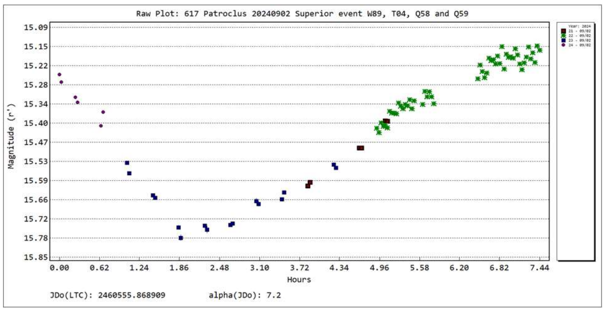
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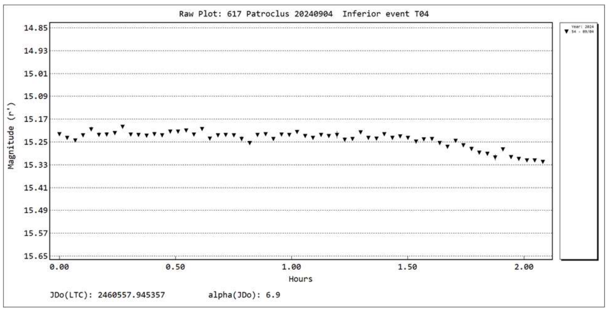
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Magnitude (r')
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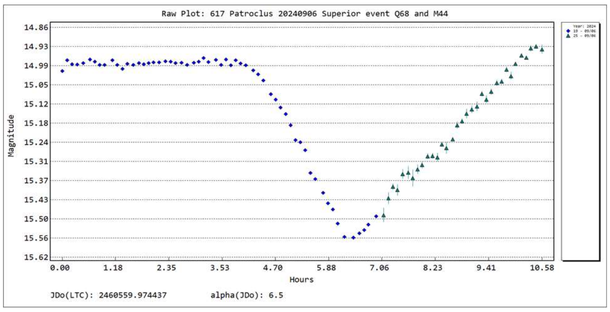
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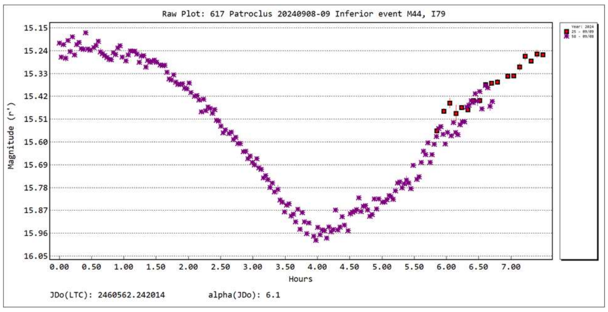
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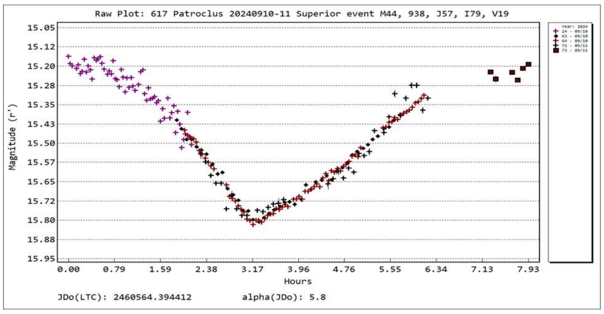
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Magnitude (r')
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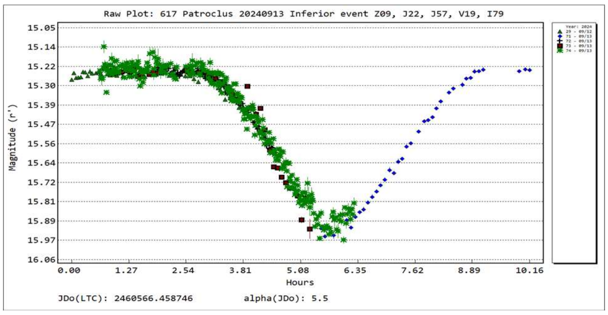
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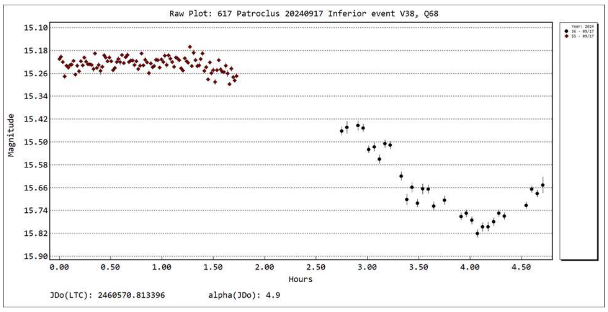
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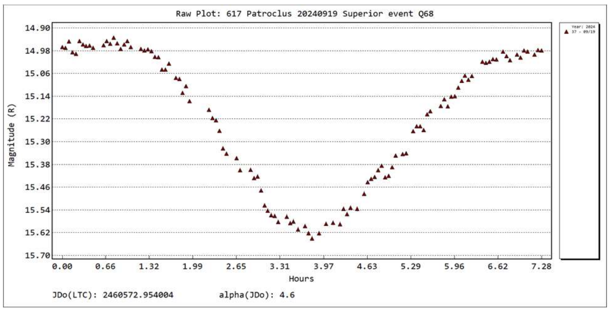
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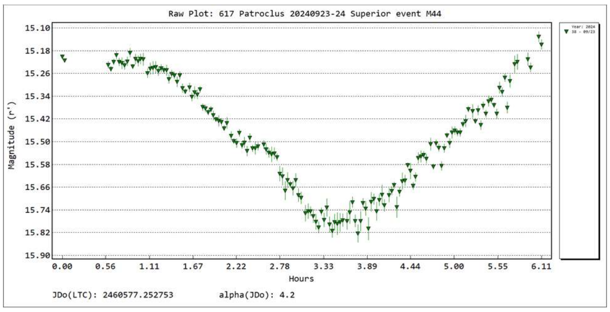
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Magnitude (r')
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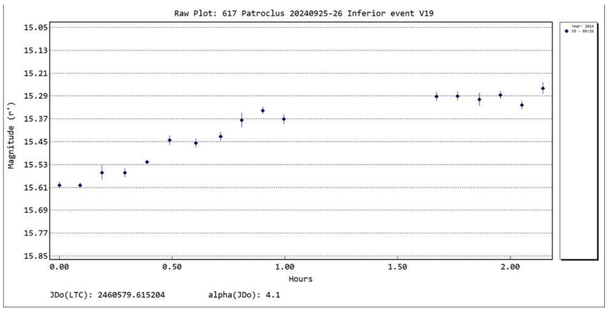
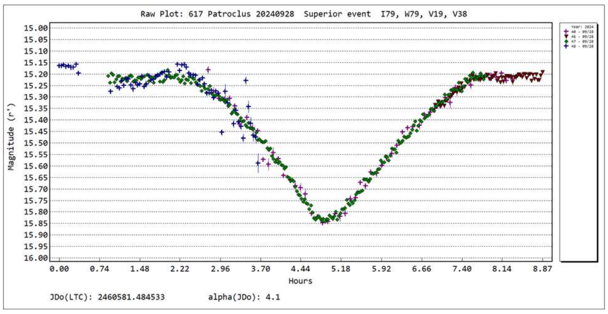
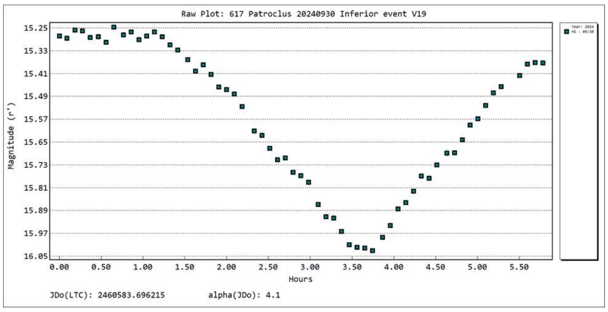
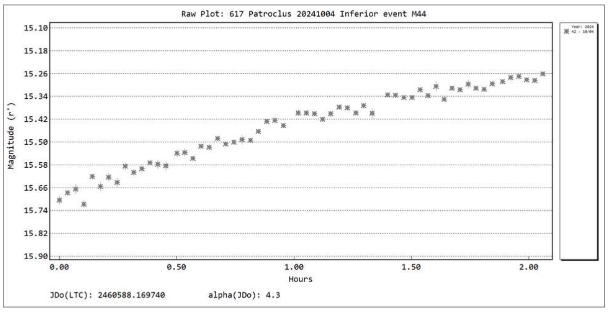
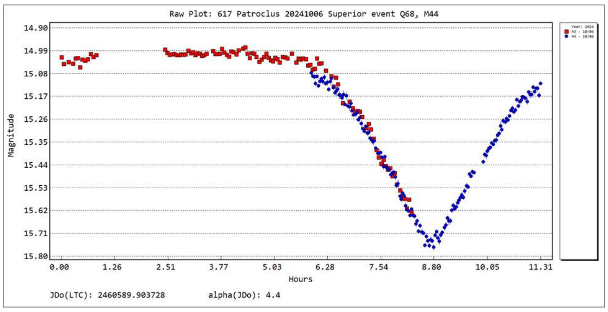


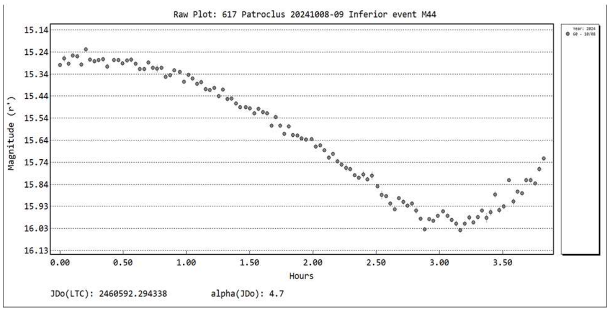


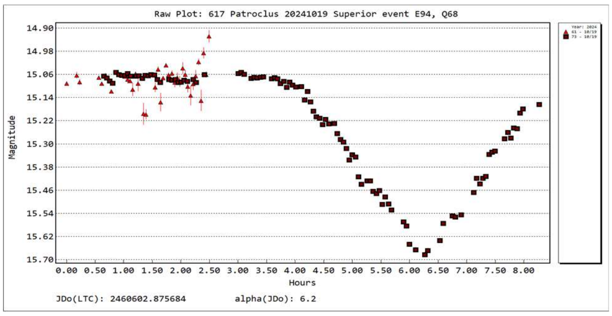


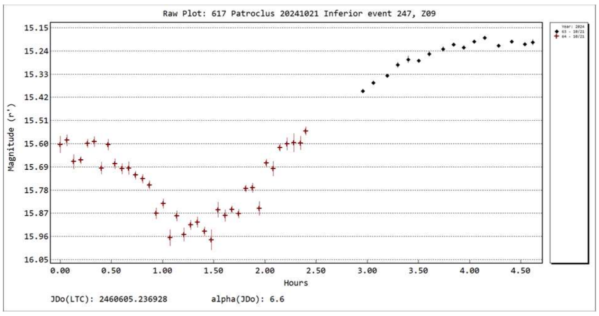




Observatory	Telescope	CCD/CMOS	Filter	Sessions
Old Orchard Observatory (Z09) Hawley	0.35-m SCT f/6.7	SX694 Trius Pro (2×2)	SR	6
Linhaceira Observatory (938) Gonçalves	0.35-m SCT f/5.6	ST-7XME (1×1)	C	2
Al Khatim Observatory (M44) Odeh	0.36-m SCT f/7.7	ASI2600MM Pro	C	10
Sutherland LCO-Aqawan A (L09) Armstrong, Marshall	0.4-m f/8	SBIG STL6303 (1×1)	SR	1
McDonald LCO-Aqawan A (V38) Armstrong, Marshall	0.4-m f/8	SBIG STL6303 (1×1)	SR	3
Tenerife-LCO Aqawan A #2 (Z17) Armstrong, Marshall	0.4-m f/8	SBIG STL6303 (1×1)	SR	2
Possum Observatory (E94) Drummond	0.35-m f/10	SBIG STL11000M (2×2)	C	2
AstroCamp, Nerpio (I79) Usatov	0.4-m f/6.8	Moravian C3-61000 Pro (2×2)	Lum	4
Siding Spring LCO-Clamshell #1 (Q58) Armstrong, Marshall	0.4-m f/8	SBIG STL6303 (1×1)	SR	1
Siding Spring LCO-Clamshell #2 (Q59) Armstrong, Marshall	0.4-m f/8	SBIG STL6303 (1×1)	SR	2
Blue Mountains Observatory (Q68) Oey	0.35-m f5/9	SBI STT-1603 3 (1×1)	C	6
Haleakala-LCO Clamshell #1 (T04) Armstrong, Marshall	0.4-m f/8	SBIG STL6303 (1×1)	SR	3
Cerro Tololo-LCO Aqawan B #1 (W79) Armstrong, Marshall	0.4-m f/8	SBIG STL6303 (1×1)	SR	4
Cerro Tololo-LCO Aqawan A #1 (W89) Armstrong, Marshall	0.4-m f/8	SBIG STL6303 (1×1)	SR	2
Centro Astronómico Alta Turia (J57) Álvaro Fornas Silva	0.43-m f/6.8	QHY600	Lum	2
Tacande Observatory (J22) Leyland	0.4-m Dilworth f/6.5	SX814 Trius Pro (2×2)	V	1
Whiskey Creek Observatory (V19) DeGroff	0.46-m Newt. f/4.2	QHY 268M	V	7
Pelagia-Eleni Observatory (247) Kardasis, Takoudi	0.28-m SCT f/10	ASI 183 Pro	V	2







Acknowledgements

Our thanks are extended to Daniel Parrott, author of *TychoTracker Pro*. This work has made use of data from the Asteroid Terrestrial-impact Last Alert System (ATLAS) project (Tonry et al., 2018). 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 catalogues 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 ATLAS Catalog makes use of the formulae to convert Pan-STARRS gri to BVRI. (Kostov and Bonev, 2017). This work makes use of observations from the Las Cumbres Observatory global telescope network. The research work at Blue Mountains Observatory is supported by the 2015 and 2018 Shoemaker NEO grant.

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OBSERVATIONS OF PATROCLUS AND MENOETIUS MUTUAL EVENTS WITH VATICAN ADVANCED TECHNOLOGY TELESCOPE (VATT)

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We report observations of mutual events for the Patroclus and Menoetius binary system. We observed on 7 nights from September 29 to October 6, 2024, UT with the Vatican Advanced Technology Telescope on Mount Graham, Arizona. Two clear mutual events lightcurves were obtained: September 30, 2024, from 06:07:12.0 UT to 09:57:36.0 UT with an amplitude of 0.82 magnitudes and October 02, 2024, from 09:28:48.0 UT to 09:46:04.8 UT with an amplitude of 0.05 magnitudes. On both dates, only part of the mutual event was observed. Three nights (29 Sept 2024 UT, 03 Oct 2024 UT, and 05 Oct 2024) did not show any mutual event as predicted by Brozovic et al. (2024). On two nights, 04 Oct 2024 UT, and 06 Oct 2024 UT, mutual events occurred outside the observing window at the VATT.

The Trojan binary asteroid system formed by (617) Patroclus and (617) I Menoetius is located in the Jupiter L5 Trojan cloud. Its binary nature was discovered in 2001 on Sept 22.6 UT using an adaptive optics system on the 8.1-m Geminid North Telescope on Mauna Kea in the J, H, and K' bands (Merline et al., 2001). The two components are similar in size, with Patroclus having an average diameter of 113 km and Menoetius slightly smaller at 104 km (Binzel, 2024). Buie et al. (2015) reported the two components to be ellipsoids with three-dimensional shape models of 127×117×98 km for Patroclus and 117×108×90 km for Menoetius. These dimensions were refined by Grundy et al. (2018) to be 130.8×126.2×122.8 km for Patroclus and 117.1×110.8×107.8 km for Menoetius. Not only are the two components nearly equal in size, but Mueller et al. (2010) has suggested that they have similar composition and surface properties. The orbital period of the two components while alternatively transiting and occulting each other is estimated to be 4.283 ± 0.004 days by Marchis et al. (2006) and 4.282760 ± 0.000005 days by Grundy et al. (2018).

The Patroclus-Menoetius binary asteroid is a target of the NASA Lucy mission. It is the only currently planned Lucy target in the Jupiter L5 Trojan cloud. After an encounter with the main-belt asteroid (52246) Donaldjohanson on 2025 April 20, Lucy will fly by several objects in Jupiter's L4 Trojan cloud, particularly (3548) Eurybates and its satellite Queta on 2027 August 12, (15094) Polymele on 2027 September 15, (11351) Leucus on 2028 April 2028 and (21900) Orus on 2028 November 11. Then on 2033 Mars 2, Lucy will make a flyby of (617) Patroclus and (617) I Menoetius (Levison et al., 2021).

The orbital plane of the Patroclus-Menoetius binary system crosses the Earth's line-of-sight twice during the course of its 11.89-year orbital period (Binzel, 2024). This favorable geometry occurred during the September 2024 opposition with the binary system having a brightness of 14.6 visual magnitude. It offered the opportunity to produce very precise "mutual event lightcurves" which would help to refine the binary orbit, the sizes and shapes of the two components (Binzel, 2024). These measurements would accurately support the instrument targeting during Lucy flyby to the binary Trojans.

Brozovic et al. (2024) presents precise predictions for mutual occultations and transits of the Patroclus-Menoetius system. Tables 3 and 4 of their work give the times for event start, stop, and mid-event. The work also includes the type of mutual event: 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 Eclipse), TE (Partial Eclipse), AO (Annular Occultation), and AE (Annular Eclipse).

Observation and reduction

The VATT observation campaign was conducted on 7 nights (between 2024 September 29 UT and 2024 October 06 UT). We used the Vatican Observatory's Vatican Advanced Technology Telescope, an f/1.0 telescope with a primary mirror of 1.8-m in diameter and a 0.38-m f/0.9 secondary mirror (Kikwaya and Hergenrother, 2023). The VATT is located at Mount Graham in southern Arizona with an MPC code of 290.

The VATT4k CCD camera with a 4064×4064 15×15 µm pixel detector was used. To reduce the readout time to 30 seconds, we binned 2×2, resulting in a plate scale of 0.375 arcsec/pixel. VATT4k covers the visible spectrum (300-1000 nm) and has a quantum efficiency that peaks at 450 nm (Kikwaya and Hergenrother, 2024).

For the entire observing run, we collected two hundred bias images and fifteen dome-flat images in the V filter to generate a master bias and a master flat. Several sequences of fifty images were acquired, with the focus being checked at the start and the end of each sequence to ensure the FWHM remained around 2.5 pixels or 1". Observations were limited to elevations higher than 30 degrees.

The *Tycho Tracker* software was used to reduce the data and generate a photometry file containing the time on Julian day, the magnitude of the binary system Patroclus-Menoetius, and the magnitude error. The overall value of the error was around 0.01 magnitude.

All timings reported in this work are for an Earth-based observer. No light-time corrections have been applied.

29 September 2024 UT. We collected 204 images from 06:13:41 UT to 10:06:49 UT. The observation window ended when Patroclus-Menoetius descended to an elevation of less than 30 degrees. There was no mutual event predicted for the night (Brozovic et al., 2024), and our data confirms the lack of a mutual event (Fig. 1).

Date (UT)	**Observation**		**# Images**	**Mutual Events**	
	Start	End		Predicted (Brozovic et al., 2024)	Observed
29 Sep 2024	06:13:41.655	10:06:49.662	204	None predicted	None seen (Fig.1)
30 Sep 2024	04:58:52.942	09:57:51.839	285	PO, PO+PE, AO+PE	PO or PO+PE (Fig.2)
02 Oct 2024	08:21:40.241	09:50:23.478	87	PO, PO+PE, TO	PO or PO+PE (Fig.3)
03 Oct 2024	04:43:32.683	09:42:24.439	285	None predicted	None seen (Fig.4)
04 Oct 2024	06:17:09.119	08:20:59.531	120	PO, PO+PE, AO+PE	None seen (Arizona daytime) (Fig. 5)
05 Oct 2024	06:18:11.866	08:38:03.675	137	None predicted	None seen (Fig.6)
06 Oct 2024	08:12:46.186	09:29:13.267	69	PO, PO+PE, TO	None seen (Arizona daytime) (Fig. 7)

Table I. Observations done during the campaign on mutual events Patroclus-Menoetius from 20 September 2024 UT to 06 October 2024 UT. Starting time, ending time, and number of images obtained during each night are reported. We put side by side the type predicted mutual event predicted by Brozovic et al. (2024) and the mutual event observed. The different types are PO (Partial Occultation), PE (Partial Eclipse), AO (Annular Occultation), TO (total occultation).

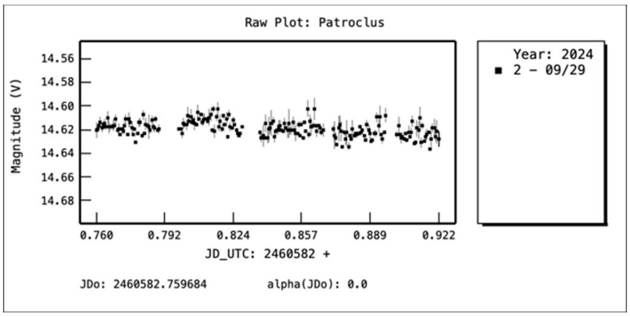

Fig.1. Lightcurve of Patroclus-Menoetius on 29 September 2024. No mutual event was detected, as predicted.

30 September 2024 UT. Two hundred and eighty-five (285) images were collected. The resulting photometry shows a clear mutual event that started at 06:07:12.0 UT and stopped at 09:57:36.0 UT. The mutual event lightcurve was not complete because the target reached the elevation limit of the telescope for our work. Nevertheless, we could estimate the amplitude of the mutual event lightcurve to be 0.82 magnitude. The type of mutual event was predicted to be a PO or PE (Fig. 2).

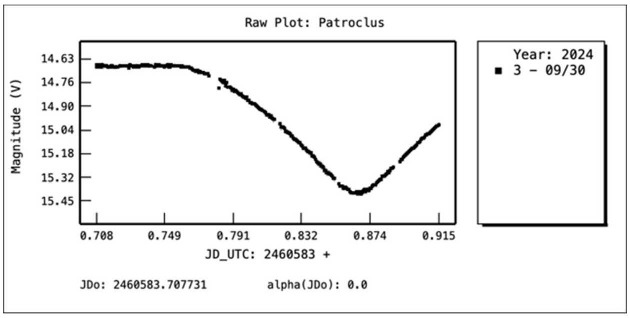

Fig. 2. Inferior mutual event lightcurve of the binary system Patroclus-Menoetius on 30 September 2024 UT.

02 October 2024 UT. We collected 87 images for the night of 03 October 2024. The observations only caught the first 18 minutes of a mutual event from 09:28:48 UT to 09:46:04 UT (Fig. 3). A small amplitude of 0.05 magnitude was estimated for the partially observed event. The elevation of the binary started at around 42 degrees, but dropped quickly below 30 degrees, the limit for our observations.

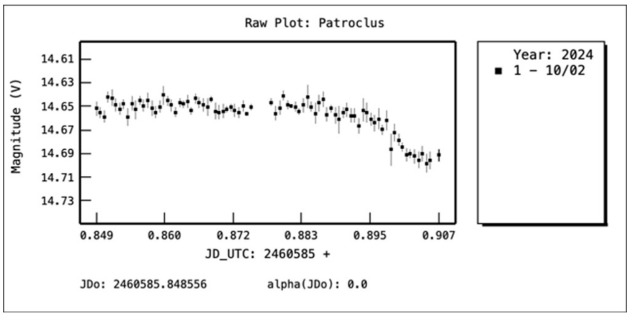

Fig. 3. Superior mutual event lightcurve of binary system Patroclus-Menoetius on 02 October 2024 UT. A drop occurred at the end of our observing window around 09:46:04.8 UT.

03 October 2024 UT. On 03 October 2024 from 04:43:32 to 09:42:24 UT, we collected 285 images. As predicted by Brozovic et al. (2024), no mutual event was observed (Fig. 4).

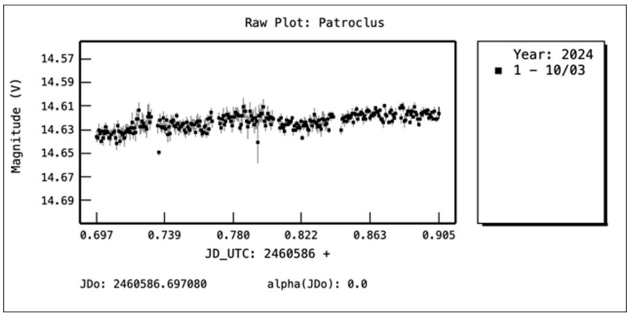

Fig. 4. Lightcurve of binary system Patroclus-Menoetius on 03 October 2024 UT. No signal of mutual even lightcurve is shown as predicted by Brozovic et al. (2024).

04 October 2024 UT. A total of 120 images of the Patroclus-Menoetius system were collected on the night of 04 October 2024 UT. No event was detected as the predicted event for that date occurred outside of the VATT's observing window (Fig. 5).

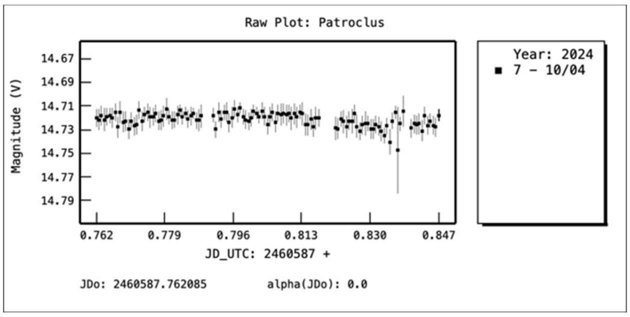

Fig. 5. Lightcurve of binary system Patroclus-Menoetius on the night of 04 October 2024. No mutual event was detected, as predicted.

05 October 2024 UT. On the night of 05 October 2024, 137 images were acquired. We computed the system lightcurve looking for any signal of mutual event (Fig. 6). No signal was detected as predicted by Brozovic et al. (2024).

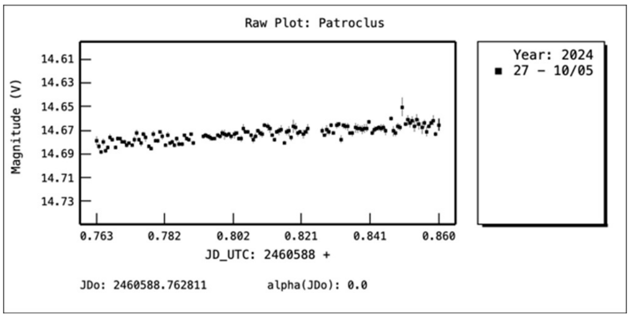

Fig. 6. Lightcurve of binary system Patroclus-Menoetius from the night of 05 October 2024 UT. No mutual event signal detected, as predicted.

06 October 2024 UT. Sixty-nine (69) images were collected on the night of 06 October 2024 UT (Fig. 7). Brozovic et al. (2024) predicted three types of signals: PO (Partial Occultation), PO+PE (Partial Occultation combined with Partial Eclipse), and TO (Total Occultation), but for a period outside of the VATT's observing window.

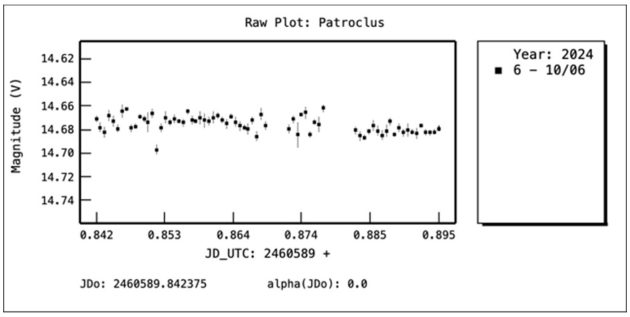

Fig. 7. Lightcurve of binary system Patroclus-Menoetius on the night of 06 October 2024 UT showed no signal of mutual event during this time interval, as predicted.

The Patroclus-Menoetius system photometry presented in this work has been archived with the Asteroid Lightcurve Photometry Database (ALCDEF) (Warner et al., 2011; Stephens and Warner, 2018).

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We want to thank the Vatican Observatory for allowing us to use VATT. We would also like to express our gratitude to the Vatican Observatory for providing us with funds necessary to complete this research.

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(617) PATROCLUS-MENOETIUS MUTUAL EVENTS OBSERVATIONS FROM OASI OBSERVATORY

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We present the mutual event lightcurves of the (617) Patoclus-Menoetius binary system acquired at the Observatório Astronômico do Sertão de Itaparica (OASI, MPC code Y28) from 2024 September 25 to 2024 October 12.

CCD photometric observations of (617) Patoclus-Menoetius binary system were carried out at the Observatório Astronômico do Sertão de Itaparica (OASI) (MPC code Y28, Nova Itacuruba) of the IMPACTON project, between 2024 September 25 and 2024 October 12. We used the 1.0-m f/8 telescope and a CCD Apo-U47-MB-0, with an array 1024×1024 pixels, set to 2×2 binning and R-Cousins filter. More details on available instrumentation at OASI are given in Rondón et al. (2020).

The data reduction was performed using the *IRAF* package (Tody, 1986) correcting the science image for bias, dark and flat frames. The lightcurves for the mutual events were built using the *MPO Canopus* software (Warner, 2018), computing the differential magnitude.

The asteroid (617) Patroclus-Menoetius, studied in this work, is a Jupiter Trojan binary system in synchronous rotation-orbit, with both components being of similar size (Merline et al., 2001). This object is a target for NASA's Lucy Mission. We observed mutual events for this object between 2024 September 25 AND 2024 October 12. In table I are given the observational dates and observational circumstances. During this period of time, we captured three inferior events, when Menoetius is on the near side to the observer, on the nights of September 25 (Fig. 1, upper panel), October 07 (Fig. 1, first middle panel), October 08 (Fig. 1, second middle panel) and October 12 (Fig. 1, bottom panel). The observed event durations were 3.146, 5.94 and 1.38 hours, respectively.

On the night of October 08 (Fig. 1, second middle panel) we were able to observe the mutual event from its maximum until its possible end, spanning 2.76 hours. The magnitude drop during this event was 0.786, from which we estimated a minimum diameter ratio of 0.717. Data coverage on the night was incomplete due to the object exceeding the telescope's altitude limit.

Figure 2 shows observations from the night of September 27, October 05, 06, and 09, when no mutual events were observed. The magnitude fluctuation seen in these plots are attributed to the rotational variation of each component of the system.

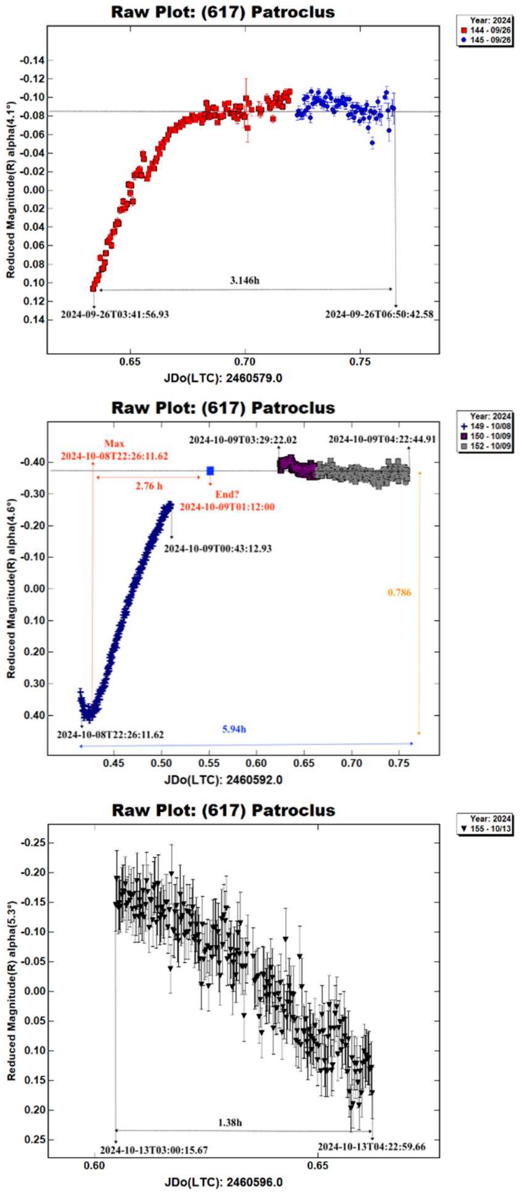
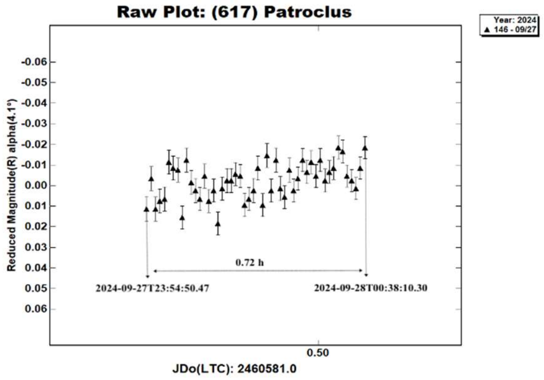


Fig. 1. Mutual events lightcurve observed on the night of September 25 (upper panel), October 07 (first middle panel), October 08 (second middle panel) and October 12 (bottom panel). All events detected were inferior events.



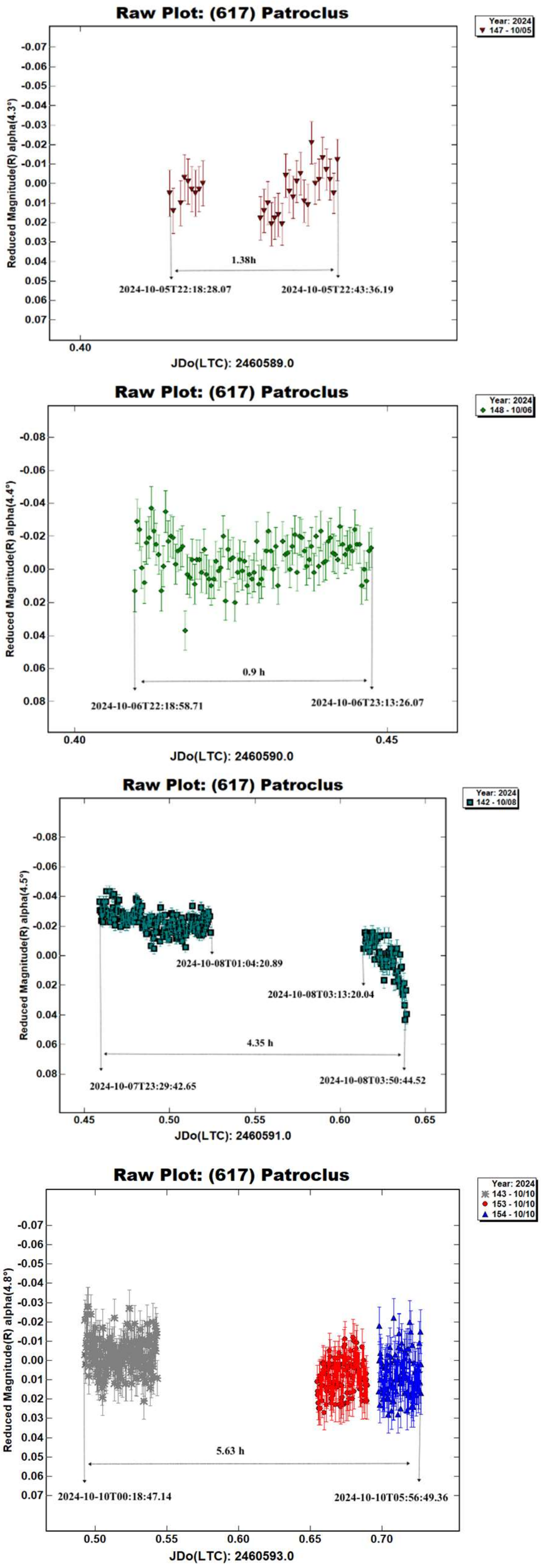


Fig.2. Lightcurve observed at the night of September 27 (upper panel), October 05 (first middle panel), 06 (second middle panel) and 09 (bottom panel). No mutual events were detected in these observation intervals, in agreement with Brozovic et al. (2024) predictions.

Night	Number of images used	Exposure time (s)	Delta (au)	r (au)	alpha(º)
2024-09-25	209	50	3,526	4,487	4.1
2024-09-27	49	50	3.526	4.488	4.1
2024-10-05	32	30	3.537	4.489	4.4
2024-10-06	99	30	3.539	4.489	4.5
2024-10-07	242	30	3.542	4.490	4.6
2024-10-08	600	30	3.546	4.490	4.7
2024-10-09	433	20	3.549	4.490	4.8
2024-10-12	213	20	3.555	4.490	5.0

Table I. Observational nights and observing circumstances, giving the dates, the number of images used, the exposure time, the distance to the Earth (Delta), the distance to the Sun (r), the solar phase angle (alpha).

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R-BAND MONITORING OF PATROCLUS AND MENOETIUS MUTUAL EVENTS

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R-band monitoring of 617 Patroclus and its companion Menoetius was conducted over the course of several nights in 2024 September and October. We report the observations of superior and inferior mutual events for this binary asteroid system. Overall, we find reasonable agreement between our observations and the predicted timing of the mutual events, though the observed timing was often discrepant by 5-25 min from the predictions. Event depths were observed to be ΔR = 0.65-0.70 mag. The observations reported here will assist in refining the binary orbit and the asteroid sizes and shapes in preparation for the planned flyby of Patroclus and Menoetius in 2033 by NASA's Lucy mission.

The NASA Lucy mission was launched in 2021 to study the Trojan asteroids of Jupiter. In particular, the binary asteroid pair 617 Patroclus and Menoetius is on the target list for a flyby in 2033 when Lucy reaches the L5 Trojan asteroid cloud (Levison et al., 2021). Patroclus and Menoetius are nearly equal in size, and the orbital period for the binary is 4.28 d (Marchis et al., 2006). However, the detailed shapes, sizes, and orbital parameters of the pair are still relatively uncertain, creating a high level of risk given the detailed planning that is needed for a successful flyby.

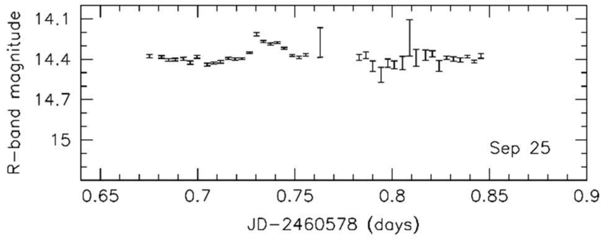
To improve the understanding of this binary system, a call for observations was issued for 2024 September-October (Binzel, 2024). Observations of the binary system were recommended during this time to take advantage of the bright visual magnitude of the asteroid pair at opposition as well as the orbital plane of the system crossing the Earth's line of sight, allowing for mutual events between the pair to be readily observed. The timing and duration of several mutual events were predicted by Brozović et al. (2024), and observations were requested to cover the events as well as one or more hours before and after each event, given the imprecise nature of the estimated timing.

In response to the call for observations of the Patroclus-Menoetius binary pair, we conducted broad-band photometric monitoring over the course of several nights between UT dates 2024 September 25 and October 17. Observations were collected by undergraduate, postbaccalaureate, and graduate students at Georgia State University's Hard Labor Creek Observatory in Rutledge, GA. For this program, we employed the Miller Telescope: a 24-inch Planewave f/6.5 Corrected Dall-Kirkham Astrograph equipped with an FLI ProLine CCD. All images were acquired through a Johnson-Cousins R filter, and each image covered a field of view of 26.3 arcmin × 26.3 arcmin with a pixel scale of 0.77 arcsec. Exposure times for individual frames were 300 s. The low declination of the asteroid binary ($\delta \approx -15°$) resulted in observations being acquired at airmasses of 1.5 - 2.5. Weather conditions were mixed across the nights, ranging from clear to partly cloudy.

Images were reduced in IRAF following standard procedures, which included bias and overscan subtraction, dark subtraction, and flat fielding. Aperture photometry was also carried out in IRAF, with measurements of the asteroids and 5-6 field stars acquired from each reduced image. Calibrated R-band measurements of field stars in the Vega system were estimated from Equation 7 of the transformation equations of Jordi et al. (2006) for Population I stars. Sloan g′-r′ colors and Johnson V magnitudes for the field stars were obtained from the AAVSO Photometric All-Sky Survey (Henden et al., 2009).

In the following, we summarize our observations and findings from each night of monitoring. Predictions of the timing of mutual events from Brozović et al. (2024) are indicated in the following lightcurve plots with vertical dotted lines. Julian dates are reported for the midpoint of each observation. All times reported in this discussion and shown in the figures are at Earth. No light-time correction has been applied.

September 25. Observations on this date did not cover any mutual events. Nevertheless, we observed interesting variability in the first half of the night, ΔR = 0.19 ± 0.02 mag between JD-2460578 = 0.73-0.75 d, that is potentially related to the rotation of either Patroclus or Menoetius. Our median precision for the evening was 0.01 mag. The second half of the night was affected by thin clouds, degrading our precision to 0.02 mag. We note that the following night on September 26, when a mutual event was predicted to occur, the first rain bands associated with Hurricane Helene reached northern Georgia, and Helene arrived one day after that.



September 28. Observations covered the second half of a predicted superior mutual event with a typical photometric precision of 0.008 mag. The event maximum was predicted to occur at UT 04:50, which is within 5 min of our observed maximum. The event end was predicted to occur at UT 07:30, which is also fairly consistent with our observations. Fitting a smoothly broken power law to the lightcurve, with the break amplitude fixed to the average magnitude after the predicted end of the event, suggests that the end occurs at JD-2406581 = 0.8210 d, or UT 07:42, which is 12 min after the predicted time. The event depth was observed to be ΔR = 0.64 ± 0.02 mag.