

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

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(Received: 2024 October 21)

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 $127 \times 117 \times 98$ km for Patroclus and $117 \times 108 \times 90$ km for Menoetius. These dimensions were refined by Grundy et al. (2018) to be $130.8 \times 126.2 \times 122.8$ km for Patroclus and $117.1 \times 110.8 \times 107.8$ 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).

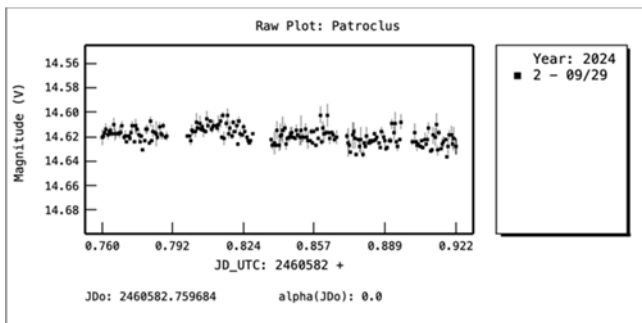


Fig. 1. Lightcurve of Patroclus-Menoetius on 29 September 2024. No mutual event was detected, as predicted.

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).

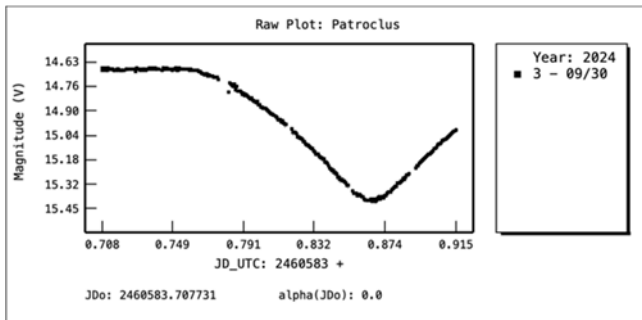


Fig. 2. Inferior mutual event lightcurve of the binary system Patroclus-Menoetius on 30 September 2024 UT.

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.

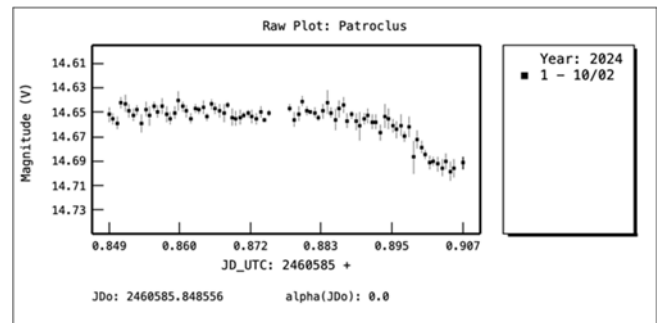


Fig. 3. Superior mutual event lightcurve of binary system Patroclus-Menoetius on 02 October 2024 UT. A drop occurred at the end of our observing window around 09:46:04.8 UT.

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).

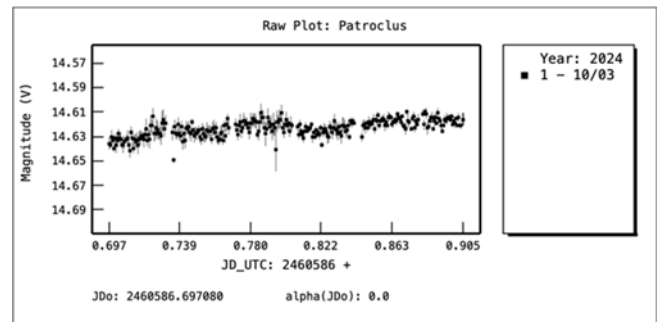


Fig. 4. Lightcurve of binary system Patroclus-Menoetius on 03 October 2024 UT. No signal of mutual even lightcurve is shown as predicted by Brozovic et al. (2024).

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).

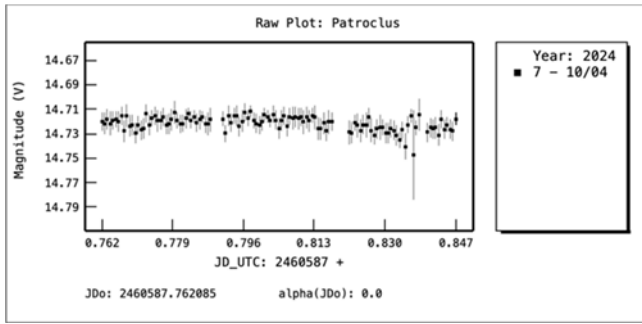


Fig. 5. Lightcurve of binary system Patroclus-Menoetius on the night of 04 October 2024. No mutual event was detected, as predicted.

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).

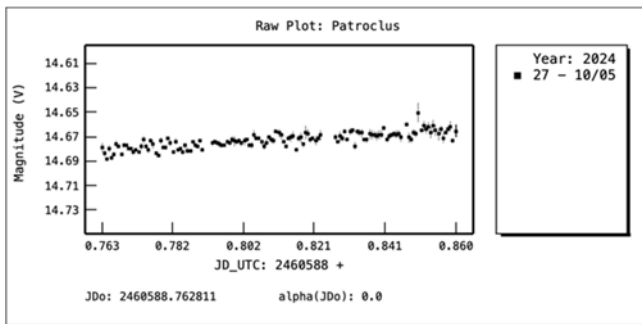


Fig. 6. Lightcurve of binary system Patroclus-Menoetius from the night of 05 October 2024 UT. No mutual event signal detected, as predicted.

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.

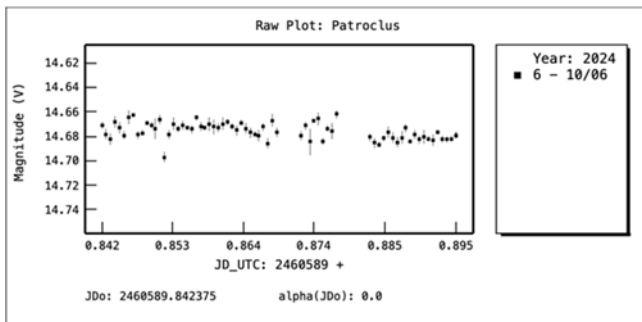


Fig. 7. Lightcurve of binary system Patroclus-Menoetius on the night of 06 October 2024 UT showed no signal of mutual event during this time interval, as predicted.

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).

Acknowledgements

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.

References

- Binzel, R.P. (2024). "Call for Observations of the Patroclus and Menoetius mutual events: Support for the Nasa Lucy Mission to the Trojan Asteroids." *Minor Planet Bulletin* **51**, 212.
- Brozovic, M.; Jacobson, R.A.; Park, R.S.; Descamps, P.; Berthier, J.; Pinila-Alonso, N.; Popescu, M.; Licandro, J. (2024). "Orbit of the Patroclus-Menoetius Binary System and Predictions for the 2024/2025 Mutual Events Season." *Astron. J.* **167**, 104, 12 pp.
- Buie, M.W.; Olkin, C.B.; Merline, W.J. and 26 colleagues (2015). "Size and Shape from Stellar Occultation Observations of the double Jupiter Trojan Patroclus and Menoetius." *Astron. J.* **149**, 113.
- Grundy, W.M.; Noll, K.S.; Buie, M.W.; Levison, H.F. (2018). "The Upcoming mutual event season for the Patroclus-Menoetius Trojan binary." *Icarus* **305**, 198.
- Kikwaya Eluo, J.B.; Hergenrother, C.W. (2023). "Lightcurves and Colors of Four Small Near-Earth Asteroids: 2020 BV14, 2023 HH3, 2023 HT3, 2023 KQ." *Minor Planet Bulletin* **50**, 300-303.
- Kikwaya Eluo, J.B.; Hergenrother, C.W. (2024). "Lightcurves and Colors of Seven Small Near-Earth Asteroids: 2023 LQ1, 2023 LT1, 2023 MC, 2023 VQ5, 2023 VE6, 2023 VF6, 2023 VV7." *Minor Planet Bulletin* **51**, 192-196.
- Levison, H.F.; Olkin, C.B.; Noll, K.S.; Marchi, S.; Bell, J.F., III; Bierhaus, E.; Binzel, R.; Bottke, W.; Britt, D.; Brown, M.; Buie, M.; Christensen, P.; Emery, J.; Grundy, W.; and 11 colleagues (2021). *Planetary Sci. J.* **2**, 171.
- Marchis, F.; Hestroffer, D.; Descamps, P.; Berthier, J.; Bouchez, A.H.; Campbell, R.D.; Chin, J.C.Y.; van Dam, M.A.; Hartman, S.K.; Johansson, E.M.; Lafon, R.E.; Le Mignant, D.; de Pater, I.; Stomski, P.J.; and 4 colleagues (2006). "A low density of 0.8 g cm⁻³ for the Trojan binary asteroid 617 Patroclus." *Nature* **439**, 565-567.
- Merline, W.J.; Close, L.M.; Siegler, N.; Potter, D.; Chapman, C.R.; Dumas, C.; Menard, F.; Slater, D.C.; Baker, A.C.; Edmunds, M.G.; Mathlin, G.; Guyon, O.; Roth, K. (2001). "S/2001 (617) 1" IAU Circular 7741 #2.
- Mueller, M.; Marchis, F.; Emery, J.P.; Harris, A.W.; Mottola, S.; Hestroffer, D.; Berthier, J.; di Martino, M. (2010). "Eclipsing binary Trojan asteroid Patroclus: Thermal inertia from Spitzer observations." *Icarus* **205**, 505.
- Stephens, R.D.; Warner, B.D. (2018). "The ALCDEF Database and the NASA SBN/PDS: The Perfect Merger." Astronomical Society, DPS Meeting #50, id 417.03.
- Warner, B.D.; Stephens, R.D.; Harris, A. H. (2011). "Save the Lightcurves." *Minor Planet Bulletin* **38**, 172-174.