

R-BAND MONITORING OF PATROCLUS AND MENOETIUS MUTUAL EVENTS

Misty C. Bentz
Department of Physics and Astronomy
Georgia State University
25 Park Place, Suite 605
Atlanta, GA 30303 USA
bentz@astro.gsu.edu

Ruel Brown, Sebastian Carrazco-Gaxiola, Akshat S. Chaturvedi,
Karina Kimani-Stewart, Ryan Lange, Luke Miles, Mahir Patel,
Tamima Saba, Yasmeen Shah, Ben Tipton, Christopher Whyte
Georgia State University
Atlanta, GA USA

(Received: 2024 October 25 Revised: 2024 November 22)

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 $\Delta R = 0.65$ -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.

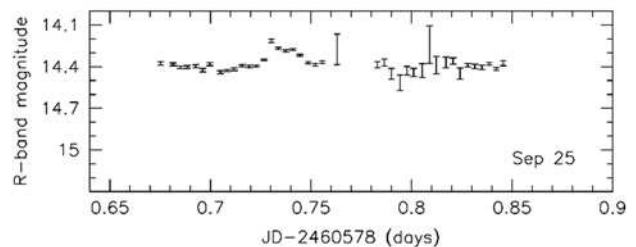
In response to the call for observations of the Patroclus-Menoetius binary pair, we conducted broad-band photometric monitoring over the course of several nights between UT dates 2024 September 25 and October 17. Observations were collected by undergraduate, postbaccalaureate, and graduate students at 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 Astrogaph 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 $\times$ 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 ($\delta \approx -15^\circ$) 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.

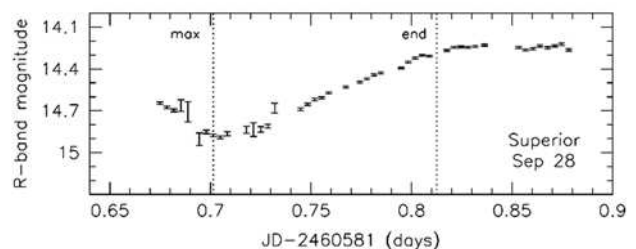
Images were reduced in IRAF following standard procedures, which included bias and overscan subtraction, dark subtraction, and flat fielding. Aperture photometry was also carried out in IRAF, with measurements of the asteroids and 5-6 field stars acquired from each reduced image. Calibrated R-band measurements 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, $\Delta R = 0.19 \pm 0.02$ 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.



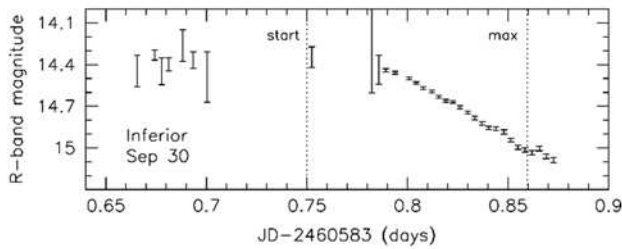
September 28. Observations covered the second half of a predicted superior mutual event with a typical photometric precision of 0.008 mag. The event maximum was predicted to occur at UT 04:50, which is within 5 min of our observed maximum. The event end was predicted to occur at UT 07:30, which is also 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-2460581 = 0.8210 d, or UT 07:42, which is 12 min after the predicted time. The event depth was observed to be $\Delta R = 0.64 \pm 0.02$ mag.



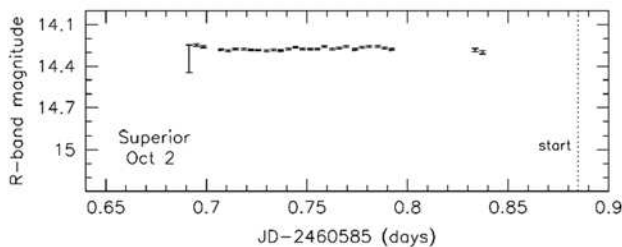
Number	Name	yyyy mm/dd	Phase	L _{PAB}	B _{PAB}	Period(h)	P.E.	Amp	A.E.	Grp
617	Patroclus	2024 09/25-10/17	*4.1,5.8	5	-17	4.282753	0.000023	0.65	0.03	9202

Table I. Observing circumstances and results. The phase angle is given for the first and last date. If preceded by an asterisk, the phase angle reached an extrema during the period. L_{PAB} and B_{PAB} are the approximate phase angle bisector longitude/latitude at mid-date range (see Harris et al., 1984). Grp is the asteroid family/group (Warner et al., 2009). The listed period is for the binary system (Brozović et al., 2024).

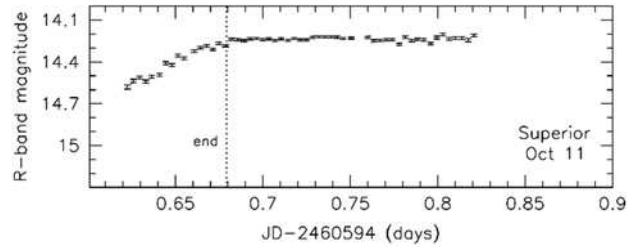
September 30. Partly cloudy conditions in the first half of the night prohibited us from observing the start of the predicted inferior mutual event at UT 06:00 and led to a slightly worse photometric precision overall, with a median value of 0.014 mag. Our observations concluded shortly after the predicted event maximum at UT 08:38, however it is difficult to determine from our lightcurve whether we actually observed the event maximum. This could be an artifact of the abrupt end to our time series, or it could indicate that the predicted timing was not accurate to within ~20 min. The asteroid binary varied in brightness by $\Delta R = 0.65 \pm 0.02$ mag over the course of our observations, which sets a lower limit for the event depth.



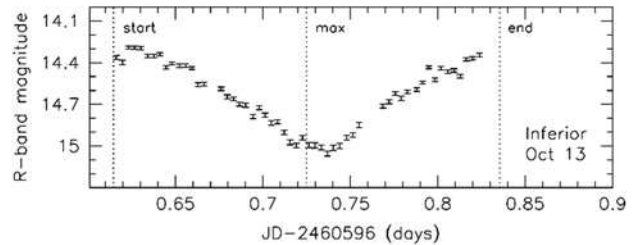
October 2. Mostly clear skies allowed us to observe the asteroid pair for a few hours before the superior event was predicted to begin at UT 09:14. Technical issues arose in the second half of the night, however, which effectively curtailed the observations as the asteroid pair began to set. We did not observe the onset of the superior event. Brightness variations were minimal over the time period covered by our observations, and our typical photometric precision was 0.006 mag.



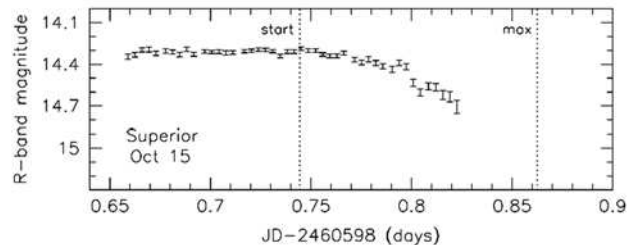
October 11. We observed the end of a superior event, which was predicted to conclude at UT 04:18. This predicted time agrees very well with our lightcurve. Clear skies throughout the night allowed us to achieve a typical precision of 0.008 mag. We detected a change in brightness of $\Delta R = 0.34 \pm 0.02$ mag, which is a lower limit to the event depth because our observations did not cover the event maximum.



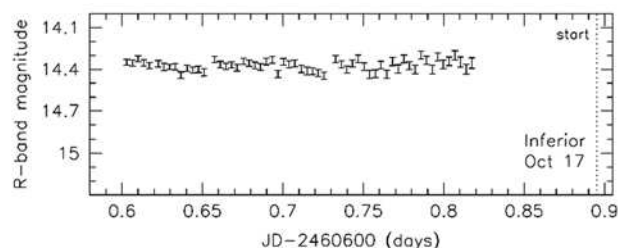
October 13. We observed most of an inferior event, just missing the end as the asteroids set below our window of visibility. Both the start of the mutual event and the maximum were observed to occur after their predicted times. While the predicted start of the event was at UT 02:45, our observations suggest it occurred about 15 min later around JD-2460581 = 0.625 d or UT 03:00. The mutual event maximum was predicted to occur at UT 05:24, and again our observations suggest that it was observed about 10-15 minutes later. The event depth was observed to be $\Delta R = 0.70 \pm 0.03$ mag, and we achieved a typical precision 0.014 mag with clear skies but somewhat poor seeing.



October 15. We observed the onset of a superior mutual event, which was predicted to start at UT 05:52. The precise onset of the mutual event is difficult to determine from simple examination of our lightcurve. Fitting the lightcurve with a smoothly broken power law, with the break amplitude fixed to the average magnitude before the predicted start of the event, suggests that the onset occurs at JD-2460598 = 0.7623 d, or UT 06:18, which is 26 min after the predicted onset. We detected variability of $\Delta R = 0.35 \pm 0.02$ mag, which is a lower limit to the event depth because our observations concluded before the event maximum occurred. Clear skies with a waxing gibbous Moon provided reasonable observing conditions but an increased background, leading to a typical precision of 0.015 mag.



October 17. We monitored the asteroid binary for several hours before the onset of an inferior event, which was predicted to start at UT 09:29. We did not observe any significant variability. Observations were acquired through clear skies with a nearly full moon, leading to a significantly elevated background and a typical precision of 0.025 mag.



In summary, we acquired observations of superior and inferior mutual events between 617 Patroclus and Menoetius over several nights in 2024 September and October. The low declination of the asteroid binary from our location in north Georgia limited the observing window each night, nevertheless we were able to monitor significant portions of several mutual events. The event timing predictions by Brozović et al. (2024) are in general agreement with our observations, though we find discrepancies in the predicted vs. observed timing of 5-25 min. From those lightcurves that covered more than half of an event, we measured event depths of $\Delta R = 0.65$ -0.70 mag, and we provide lower limits on the event depth from lightcurves that covered less than half of an event. Our typical photometric precision varied with the observing conditions and moon phase, ranging from 0.006 mag under excellent conditions to 0.025 mag under a nearly full moon. We expect these observations will assist in a more precise determination of the binary orbit as well as the asteroid sizes and shapes, in preparation for the planned flyby of the system by NASA's Lucy Mission in 2033.

Acknowledgements

NOIRLab IRAF is distributed by the Community Science and Data Center at NSF NOIRLab, which is managed by the Association of Universities for Research in Astronomy (AURA) under a cooperative agreement with the U.S. National Science Foundation. This research was made possible in part based on data from the AAVSO Photometric All-Sky Survey (APASS), funded by the Robert Martin Ayers Sciences Fund and NSF AST-1412587.

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 Bull.* **51**, 212.
- Brozović, M.; Jacobson, R.A.; Park, R.S.; Descamps, P.; Berthier, J.; Pinilla-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, 12pp.
- Harris, A.W.; Young, J.W.; Scaltriti, F.; Zappala, V. (1984). "Lightcurves and phase relations of the asteroids 82 Alkmene and 444 Gytis." *Icarus* **57**, 251-258.
- Henden, A.A.; Terrell, D.; Levine, S.E.; Templeton, M.; Smith, T.C.; Welch, D.L. (2009). "APASS: The AAVSO Photometric All-Sky Survey." <http://www.aavso.org/apass>
- Jordi, K.; Grebel, E.K.; Ammon, K. (2006). "Empirical color transformations between SDSS photometry and other photometric systems." *Astron. Astrophys.* **460**, 339-347.
- Levison, H.F.; Olkin, C.B.; Noll, K.S.; Marchi, S.; Bell, J.F.; Bierhaus, E.; Binzel, R.; Bottke, W.; Britt, D.; Brown, M.; Buie, M.; Christensen, P.; Emery, J.; Grundy, W.; and 16 colleagues (2021). "Lucy mission to the Trojan asteroids: Science goals." *Planetary Sci. J.* **2(5)**, 13pp.
- 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.
- Warner, B.D.; Harris, A.W.; Pravec, P. (2009). "The Asteroid Lightcurve Database." *Icarus* **202**, 134-146. Updated 2023 Oct 1. <http://www.MinorPlanet.info/php/lcdb.php>