FOLLOW-UP OBSERVATIONS OF 617 PATROCLUS-MENOETIUS MUTUAL EVENTS: 2024 NOVEMBER TO 2025 JANUARY

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We report on additional observations made and analysis following (Warner et al., 2025), continuing the effort to provide data prior to for NASA's Lucy fly-by mission in 2033 March. The additional data led to the same period, 102.873 h, but the formal precision was reduced by half to 0.003 h. Data for 2024 October 10-11 received after submission of our previous work filled in the missing part of the event, and we were able to refine the date and time for the start and minimum of the event. Other observations in late 2024 October through 2025 January 11 were either outside an event or covered only part of one. As before, we offer no interpretation regarding the parameters of the system beyond the rotation/orbital period. We also report H-G values of H_{PR} = 8.032 ± 0.042, G_{PR} = 0.075 ± 0.066. The value for H_{PR} was converted to H = 0.82 ± 0.06. The MPC reports H = 8.25 using G = 0.15.

In 2033 March, NASA's Lucy mission will fly by the Jupiter trojan 617 Patroclus and its moon, 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.

In response to this call, we observed the pair from 2024 September to mid-October. The details of our observations, data measurement, and analysis can be found in Warner et al. (2025; referenced from here on as WEA) and are not repeated here.

Our additional observations cover the period from 2024 November 8 through 2025 January 11. Table I gives the dates and observers for the new observations.

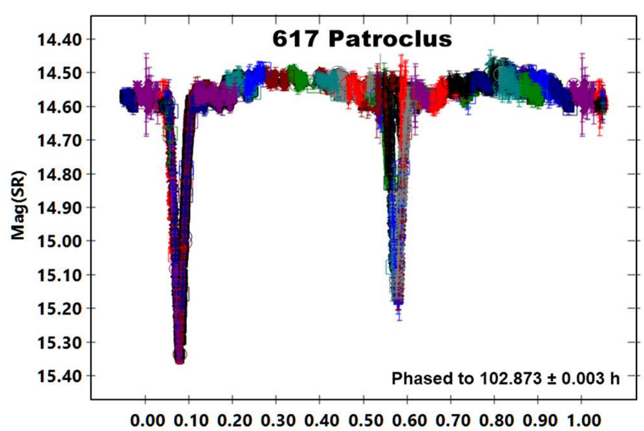
Lead	Observatory	Tel	MPC	Dates (mm/dd)
Gebauer	McCarthy	0.43	932	2024 10/10-11 2024 12/22 2025 01/09
Nastasi	Galhassin Robotic Telescope	0.40	L34	2024 10/10 2024 10/24
Sioulas	NOAK	0.25	L02	2024 10/23
Warner	CS3-U82	0.25	U82	2024 10/24-26 2024 11/08 2024 11/11-12 2025 11/08 2025 01/11

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

Orbital Period Analysis

The phased plot is fit to the adopted period of 102.873 ± 0.003 h. The period is the same as in WEA, but the formal precision is half that of the previous result. As noted in WEA, 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. Brozovic et al. (2024) reported 102.876 ± 0.005 h, so our result agrees with the margin of errors.

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.



Year: 2024-2025

1 - 09/13	2 - 09/14	3 - 09/15	4 - 09/12	5 - 09/16	7 - 09/17	8 - 09/15	10 - 09/19
11 - 09/20	13 - 09/20	14 - 09/22	15 - 09/23	16 - 09/24	17 - 09/25	18 - 09/24	19 - 09/26
20 - 09/27	21 - 09/26	22 - 09/24	23 - 09/28	24 - 09/29	25 - 09/30	26 - 09/30	27 - 09/30
28 - 10/01	29 - 10/02	30 - 10/03	31 - 10/04	32 - 10/05	33 - 10/06	34 - 10/07	35 - 10/08
36 - 10/09	37 - 10/10	38 - 10/11	39 - 10/12	40 - 10/13	41 - 10/15	43 - 10/19	44 - 10/18
45 - 10/20	46 - 10/09	47 - 10/15	48 - 10/21	49 - 10/22	50 - 10/23	51 - 10/10	52 - 10/24
53 - 10/23	54 - 10/23	55 - 10/23	56 - 10/25	57 - 10/26	58 - 11/08	59 - 11/11	60 - 11/12
61 - 11/23	62 - 12/22	63 - 10/11	64 - 01/09	65 - 01/09	66 - 01/11	67 - 01/11	

JDo(LTC): 2460578.461589 Period: 102.873 ± 0.003 h

Table II. The legend, JD zero-point, and derived period for the phased plot. The raw plots are based on a subset of the full data set and have their own legends, JD zero-point. 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.

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.*

Additional Observations: Updated/New/Out of Events

The superior event occurs when the secondary, Menoetius, *goes behind the primary*, Patroclus. The inferior event occurs when Menoetius *passes in front* of Patroclus. The depth of about 0.60 mag for the inferior event (the same as is in WEA) 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).

The X-axis of the plots use light-time corrected JD, which is required for proper period analysis. The program reports the UTC and LTC UTC when clicking on a point in the plot.

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.

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

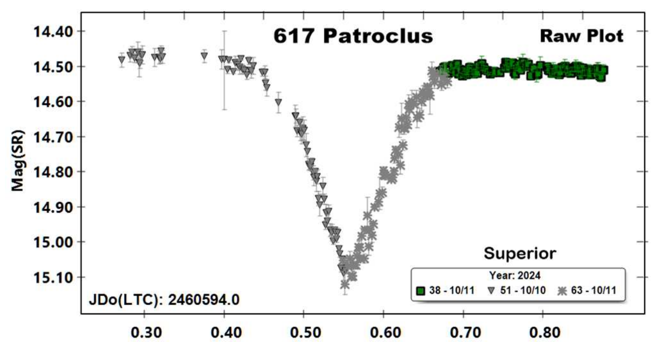
PO	Partial Occultation
PE	Partial Eclipse
PO+PE	Partial Occultation and Partial Eclipse with overlap
PO_PE	Partial Occultation and Partial Eclipse without overlap
AO	Annular Occultation
AO+PE	Annular Occultation and Partial Eclipse with overlap
AE	Annular Eclipse

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

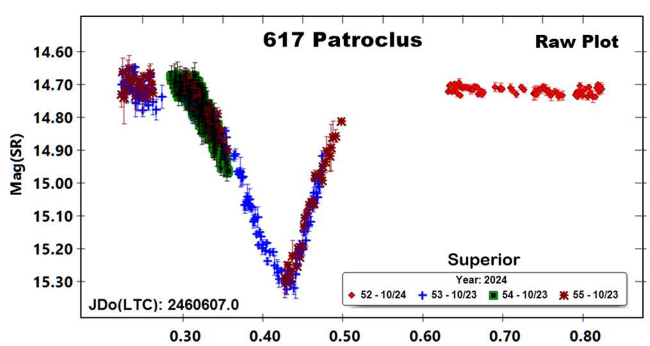
<u>2024 October 10-11 (Superior - **PE** PO+PE, TO, PO+PE, PO)</u>. The start and apparent minimum of this event were observed by Nastasi (L34). Because of occasional periods of diminished transparency, the estimate for the start time is more uncertain than in other cases.

Gebauer and Cloutier provided additional data after WEA publication that completed the ascending branch of the lightcurve, allowing us to find a better estimate for the minimum and event end.

For the start of the event, 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 is Oct 11 at 01:56 UT (0.554 d on the plot). Brozovic et al. (2024) predicted 01:45 UT (0.552 d). The predicted time of event end was Oct 11 at 04:18 UT. We estimate the time to be 04:35 UT.

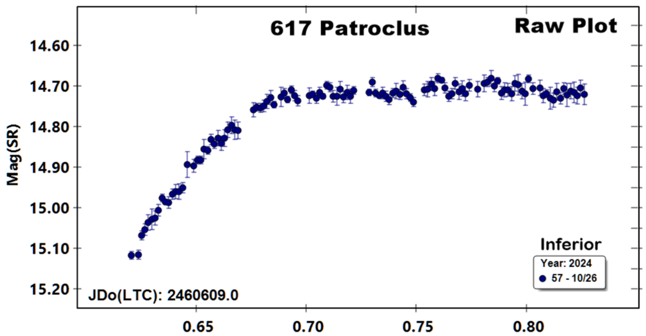


<u>2024 October 23-24 (Superior - **PE,** PO+PE, PO)</u>. Overlapping observations were made Nastasi and Sioulas. Observations by Warner were post-event, as shown on the right side of the plot.



Since the minimum was well-covered, it was possible to find a reasonably accurate time of minimum: 2024 Oct 10 at 22:39 UT. The prediction by Brozovic et al. (2024) was 22:37 UT on the same date. As noted in WEA, estimating the exact time of the start or end time for an event was not possible but, instead, only a best guess "fuzzy" estimate. Our estimate is 2024 Oct 23 at 19:21 UT.

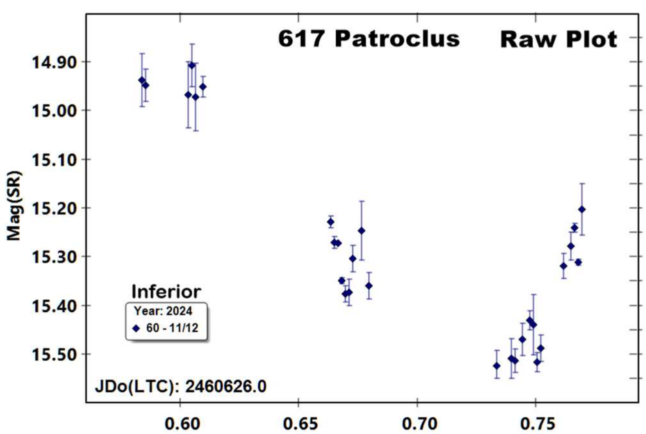
2024 October 25-26 (Inferior - **PE,** PO+PE, PO). Observations were made by Warner. The data covered the end of the event, but missed the start. The question of whether or not the minimum was caught left room for doubt.



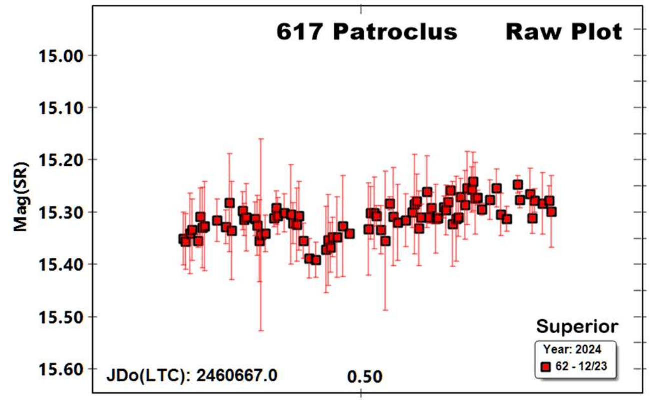
We took the liberty of using the magnitude drop of 0.4 mag to be 0.67 times the estimated full drop of 0.6 mag based on our analysis (see Table III). From the plot and Brozovic et al. (2024) times, the event was estimated to be about 300 minutes long and so the time from minimum to event end, assuming a symmetrical event, would be 150 minutes. Assuming that the rise from minimum to our first data point would take about 50 minutes, then we estimate the time of minimum to be 2024 Oct 26 at 02:34 UT. Brozovic et al. (2024) predicted a time of 02:18 UT.

2024 November 12 (Inferior - **PE,** PO_PE, PO). Observations were made by Warner. The data appear to begin near event start and only partially cover the minimum. Using the method by Hertzsprung (1928) as described by Henden and Kaitchuck (1990) and explained in WEA, we tried to extrapolate a time of minimum, which depended on which data point at the left-side of the plot we chose to be the start of the event; we used the first.

This eventually led to 2024 November 12 at 06:00 UT, ± 15 minutes. The mid-time is only one minute away from Brozovic et al. (2024).

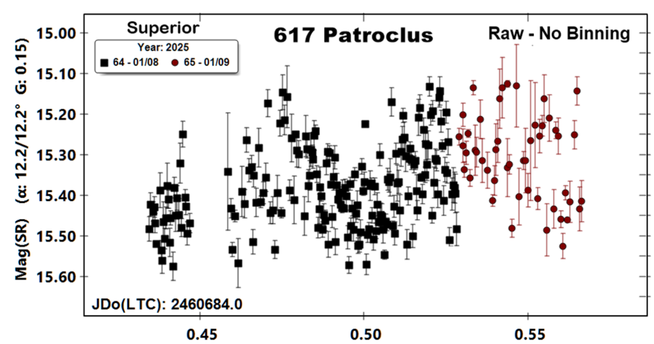


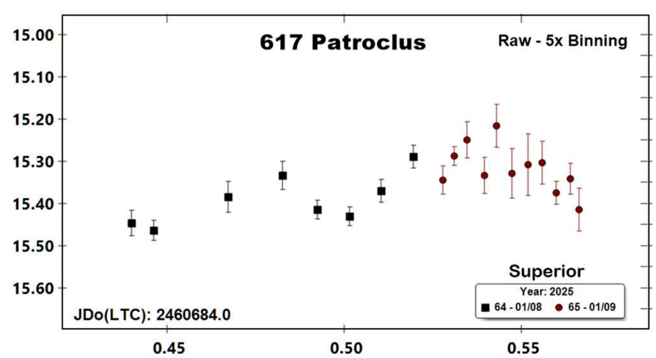
2024 December 22-23 (Superior - **PO**). Observations were made by Gebauer and Cloutier. It may not seem that any part of the event was captured. However, a close inspection of the phased plot shows that the lightcurve falls very briefly at the end of an event before slowing rising to a maximum half-way between the superior and inferior events.



The data seem to do something like that, and so we took the data point just before the small dip in the lightcurve to be the approximate end of the event (End 1), which was 2024 December 23 at 00:15 UT. On the other hand, the estimated time of minimum in that small dip (End 2) is 00:23 UT, or 2 minutes ahead of Brozovic et al.

2025 January 8-9 (Superior - **PO**). Observations were by Gebauer and Cloutier. Unfortunately, their observing run was hampered by the altitude approaching the preferred minimum of 30° and deteriorating conditions. Session 64 is based on the first two of three splits, the majority of the exposures being 30 seconds, with SNR ~ 40. By the time of the last of the three splits, SNR ~ 25.





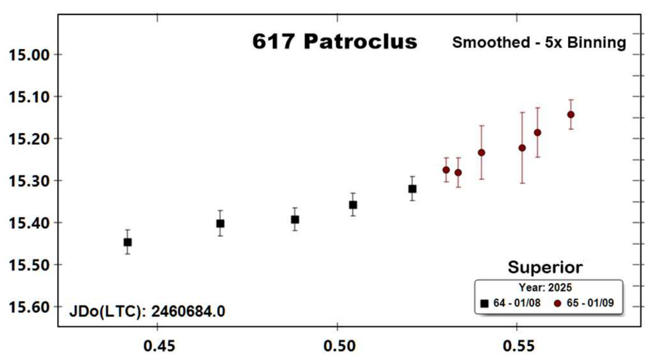
Parameters	This Paper	Brozovic et al.	Difference
Rotational Period with Events (h)	102.873 ± 0.006	102.876 ± 0.005	0.003 h
Minimum Depth (Superior, mag)	0.79 ± 0.03	0.76	0.03 mag
Maximum Depth (Inferior, mag)	0.60 ± 0.03	0.61	0.01 mag
Effective Diameter Ratio (Menoetius/Patroclus)	0.86 ± 0.03	0.92	0.06 ± 0.06

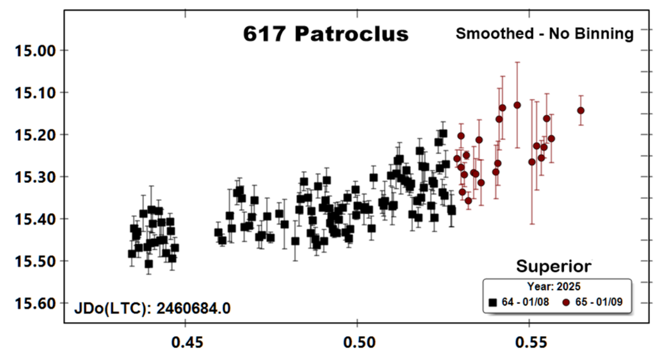
Observed Events	This Paper UT	Brozovic et al. UT	UT-Brozovic minutes
Oct 10 – Superior (start)	22:50	23:08	-18
(minimum – Oct 11)	01:56	01:45	+11
(end – Oct 11)	04:35	04:18	+17
Oct 23-24 – Superior (start)	19:21	19:22	-1
(minimum)	22:39	22:37	+2
Oct 25-26 – Inferior (minimum – see text)	02:34	02:18	+16
(end)	04:57	04:55	+2
Nov 12 – Inferior (minimum – see text)	05:45-06:15	05:59	+1
Dec 22-23 – Superior (end 1 – see text)	00:15	00:21	-6
(end 2 – see text)	00:23	00:21	+1
Jan 8-9 – Superior (minimum)	00:34	00:59	-25

Table IV. 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). The results for 2024 October 10-11 are based additional observations from Gebauer and Cloutier.

The "Raw - No Binning" plot shows the raw data as measured. From this, it's hard to say if the data were steadily increasing or covered a minimum with the initial data being "bad." The data were smoothed by binning them 5×10, meaning five successive data points, each no more than 10 minutes after the previous one, were averaged and used as a single data point. If two successive data points were more than 10 minutes apart, a new bin was started.

The result is shown in the "Raw - 5× Binning" plot, which, started to show a trend that steadily grew brighter. Going back to the unbinned raw plot, data points were excluded that, subjectively, strayed too far from the trend. The result is shown in the "Smoothed - 5× Binning" plot. When satisfied, the plot was reset to with no binning, as shown in "Smoothed - No Binning."

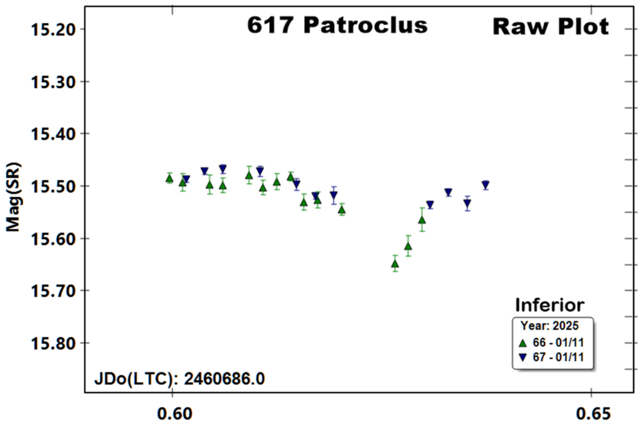




On the broad assumption that we were working with valid filtered data set, we hoped to use the Hertzsprung method to find a minimum. However, that method requires a minimum of three data points on either side of the proposed minimum. This condition could not be met. Therefore, we estimated the time of the minimum based on the earliest data point that seemed close to the trend line. This gave 2025 January 8 at 23:06 UT. Brozovic et al. (2024) predicted the minimum to occur on 2025 January 9 at 00:59 UT. The difference is almost two hours, or about 0.083 day.

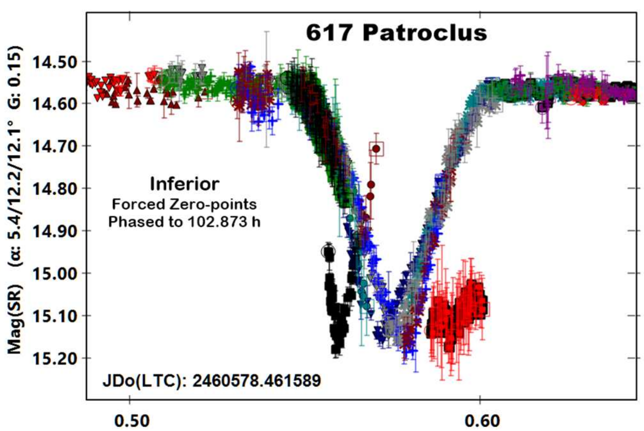
However, that time is almost the same as the predicted start of the event (2025 January 8 at 23:30). The data should be decreasing in brightness, but they are going in the opposition direction! There's yet one more, very intriguing problem. That is detailed in the "Square Pegs into a Round Hole" section below.

<u>2025 January 11 (Inferior - **PO**)</u>. By the time Warner made these observations, Patroclus was above the 30° minimum altitude for only about two hours. These would be the last observations of the campaign.



The time of the apparent minimum (2025 January 11 at 03:41 UT) is almost an hour before the 04:34 predicted by Brozovic et al. The data likely represent some sort of local minimum. On the other hand, if presuming that the data show the start of the event, an estimate of the start time is about 2025 January 11 at 03:18 UT. Brozovic et al. (2024) predicted 03:11 UT.

Square Pegs into a Round Hole



A magnified section of the phased plot, forced to a period of 102.873 h, shows the data from 2024 December 23 and 2025 January 9, both obtained by Gebauer and Cloutier. Several things stand out. We'll save the most interesting one for last.

Assuming that the location in the phased plot for these two data sets is correct, both required a nearly +0.5 mag zero-point adjustment to get an approximate match to the other inferior event minimums. Setting the zero-point offsets to 0.0 raised the January 9 data such that it was 0.1 mag brighter than any other part of the curve. Gebauer and Cloutier used an SR filter, which might have explained the issue, but the measurements were made using the ATLAS refcat2 (Tonry et al., 2018) r′ magnitudes, as were all others - Clear and SR filters alike. Such an offset should not be required since all the other sessions required no more than ±0.05 mag zero-point adjustment.

No amount of orbital period refinement and/or zero-point offsets could get either of those two sessions to match the rest of the data at the inferior event. Even if the two sessions are not included, there was no single-period solution that allowed all the inferior events to overlap perfectly. The data for all the observed superior events, fit tightly about the same minimum.

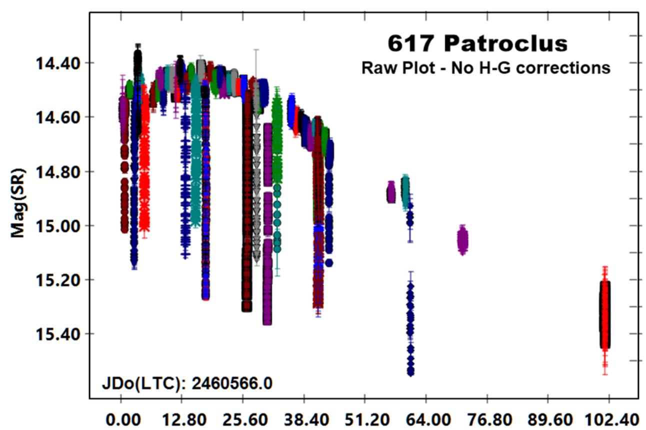
Now comes the most confusing result. The January 8-9 data are for a *superior* event. This means that they should be on the phased plot at about 0.08. Instead, they are near the inferior event phase near 0.60. Again, no combination of reasonable period changes or zero-point adjustments could resolve the issue. What's just as confounding is that the UT times of the data points are close to what they should be for the superior event, *not* inferior.

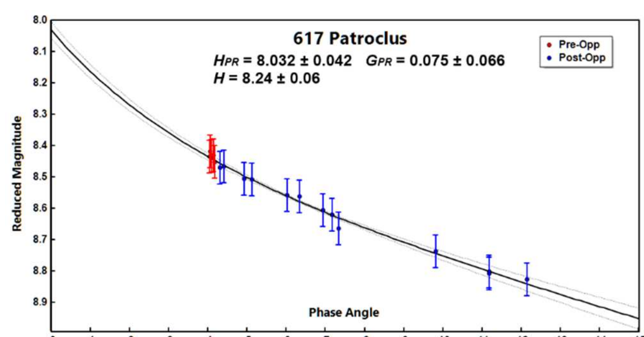
Any explanation of these issues, assuming valid data, is beyond the scope of this paper.

H-G Parameters

The complete data set covered phase angles from 4°, the minimum over the range of dates, to 12°. This allowed trying to find the absolute magnitude (*H*) and phase slope parameter (G) for the asteroid.

The "No H-G Corrections" plot shows the raw data set without correcting for changing Earth-Sun distances and phase angle. In other words, these are the raw "sky" (catalog) magnitudes plotted against Julian Date. The curve shows the expected behavior as the asteroid went from peak brightness near or at minimum phase angle (presumably also the closest Earth and Sun distances) and descended down and to right as the distances and phase angle increased.





The standard method to find H is to use the mean value of the amplitude of the lightcurve *at the time of the observation*. In cases where the period exceeds the maximum length of any observing run, there are several methods to interpolate that value based on the partial and full, phased lightcurve. In this case, Warner just "eyeballed" values after zooming tight on the curve and following the curve along the way. This is crude, but it was successful - *this time*.

The H-G plot shows the derived reduced magnitudes, i.e., the raw sky magnitudes assuming Earth and Sun distances of 1 au, and the phase angle. It shows a tight fit to the line that extrapolates to $H_{PR} = 8.032 \pm 0.042$ using $G_{PR} = 0.075 \pm 0.066$. The low albedo is consistent with darker asteroids, e.g., taxonomic type C, which - along with P - is the dominant type among the Jupiter Trojans.

By definition, *H* is a V magnitude. To get this required using some conversion formulae that started with V-R = 0.42 (Chatelain et al., 2016) and B-V = 1.12 (Chatelain, 2017) and used these in formulae from Kostov and Bonev (2018), who converted *griz* magnitudes to BVRI based on formulae from Stetson (2000). The net result was a correction of +0.21 mag, which gives $H = 8.24 \pm 0.06$. The MPC uses $H = 8.25$, $G = 0.15$. Note that the difference between H_{PR} and *H* is dependent on the color index of an object and so is not a constant.

Remarks

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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