2491 TVASHTRI: A NEW BINARY HUNGARIA ASTEROID

Brian D. Warner
Center for Solar System Studies – Palmer Divide Station
446 Sycamore Ave.
Eaton, CO 80615 USA
brian@MinorPlanetObserver.com

(Received: 2018 July 9)

CCD photometric observations were made of the Hungaria asteroid 2491 Tvashtri from 2018 Mar 29–April 27. Analysis of the data determined that the asteroid is binary with periods of P_1 = 4.0852 h and P_{ORB} = 26.712 h. The estimated ratio of effective diameters is $D_S/D_P \geq 0.24$.

The Hungaria asteroid 2491 Tvashtri has an estimated size of 4.5 km. While true Hungaria asteroids, those formed by the collision of two bodies, have a taxonomic class of E (Warner et al., 2009a), the orbital space ($1.78 < a < 2.0$ AU, $e < 0.18$, $16° < i < 34°$) contains a large number of interlopers of both high and moderate albedo (Warner et al., 2009a; Milani et al., 2010; McEachern et al., 2010; DeMeo and Carry, 2013; Lucas et al., 2017). Tvashtri is a type X under the Tholen taxonomic system; this is a catch-all class where the spectroscopic plot is nearly flat over a large range of colors. Members of type X can include types E ($p_V \sim 0.46$), M ($p_V \sim 0.16$, and P ($p_V \sim 0.06$) (Warner et al., 2009a). Thermal observations that find the object's albedo are usually the only certain method to resolve the ambiguity.

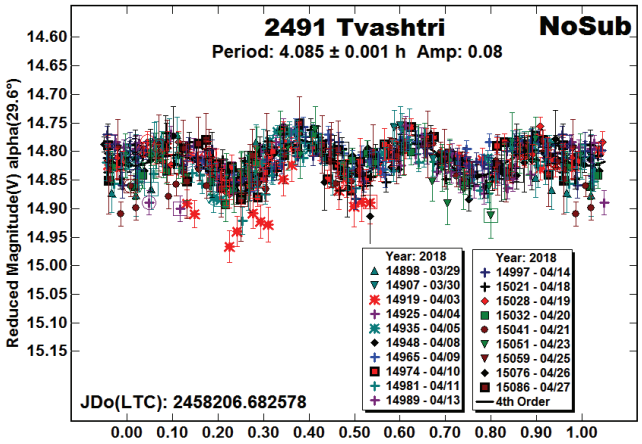
Previously published periods include Behrend (2008; 2.8 h), Stephens (2016; 4.274 h), and Waszczak et al. (2013; 5.662 h). The asteroid was also observed by the author on three previous occasions. Those will be discussed later. In all those earlier cases, there was no indication of a satellite.

The 2018 observations were made with a 0.35-m Schmidt-Cassegrain telescope and Finger Lakes ML-1001E, giving an image scale of about 1.5 arcsec/pixel. All exposures were guided, 240 sec, and unfiltered. Even a clear filter can cause a 0.1-0.3 mag loss. Measurements were made using *MPO Canopus*. The Comp Star Selector utility in *MPO Canopus* found up to five comparison stars of near solar-color for differential photometry. Catalog magnitudes were taken from the APASS catalog (Henden et al., 2009). The nightly zero points for the APASS catalogs are generally consistent to about ±0.05 mag or better, but occasionally reach > 0.1 mag. Period analysis was done with *MPO Canopus*, which implements the FALC algorithm by Harris (Harris *et al.,* 1989).

In the lightcurves below, the "Reduced Magnitude" is Johnson V as indicated in the Y-axis title. These are values that have been converted from sky magnitudes to unity distance by applying –5*log (rΔ) to the measured sky magnitudes with r and Δ being, respectively, the Sun-asteroid and Earth-asteroid distances in AU. The magnitudes were normalized to the phase angle in the parentheses using G = 0.15. The X-axis is the rotational phase ranging from –0.05 to 1.05. The plots of the satellite's mutual events are differential values with the zero point being the average magnitude of the primary lightcurve.

The 2018 Observations

Analysis was done using 567 data points obtained over a period of almost one month. Fortunately, the phase angle changed very little over that time; the same applied to the phase angle bisector (PAB) longitude and latitude. This meant that was very little change in the viewing aspect during that time and, as it turned out, in the lightcurve featuring the satellite's mutual events (occultations and/or eclipses).



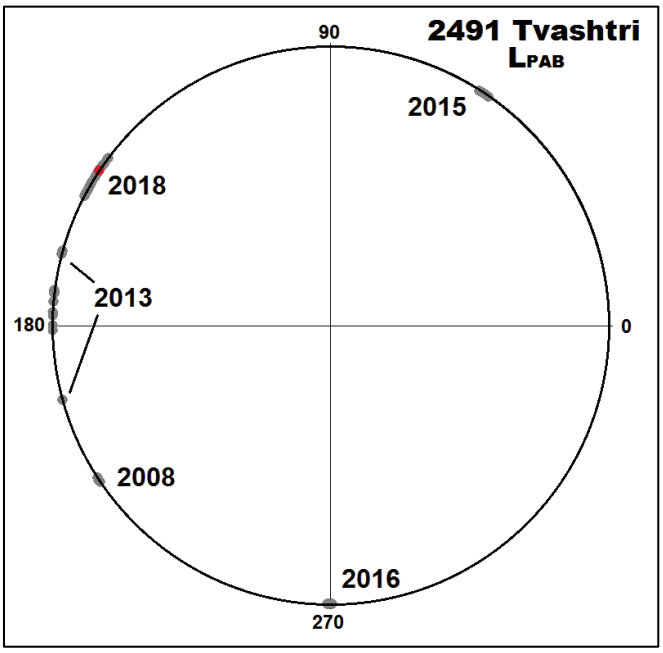
The single-period search preferred a solution of about 4.09 h. This produced a quadramodal lightcurve. This is not uncommon for low amplitude lightcurves (Harris et al. 2014). The half-period of 2.04 h produced a more typical bimodal shape with the amplitude of 0.08 ± 0.01 mag. Since the 4-hour period was similar to previous results, Warner (2008; 4.0839 h), (2013; 4.084 h), and (2015; 4.157 h), it was chosen as the more likely.

The single-period lightcurve appeared to show some deviations. The dual-period feature in *MPO Canopus*, which uses an iterative instead of simultaneous algorithm to find more than one period, was used to determine if the deviations were outlier data points or due to a second period. Given that all previous reports on the asteroid showed no signs of a satellite, the tendency was to favor spurious data.

However, it's worth noting at this point that in order to see the mutual events that confirm the existence of a satellite, the view of the asteroid must be (nearly) equatorial, assuming that the orbital plane of the satellite is close to the equatorial plane of the primary. If the pole of the primary has a very low obliquity, then the view is almost always equatorial. However, if the pole is significantly "tilted" (high obliquity) then getting an equatorial view is dependent on the viewing aspect. This is measured by the phase angle bisector longitude and, usually to a lesser degree, latitude.

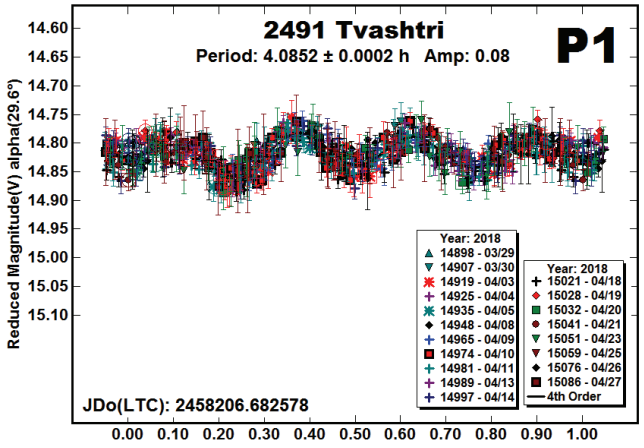
Number	Name	2018 mm/dd	Pts	Phase	L_{PAB}	B_{PAB}	Period(h)	P.E.	Amp	A.E.
2491	Tvashtri	03/29-04/27	567	29.6,33.6	148	19	4.0852	0.0002	0.08	0.01
	Orbital period						26.712	0.005	0.06-0.11	0.01

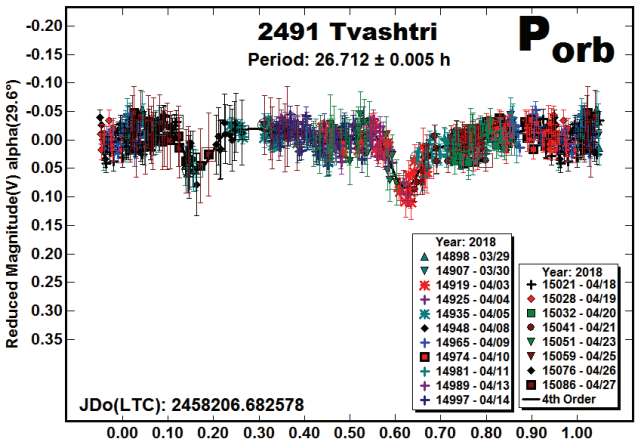
Table I. Observing circumstances and results. The phase angle (α) is given at the start and end of each date range. L_{PAB} and B_{PAB} are, respectively, the average phase angle bisector longitude and latitude (see Harris *et al.*, 1984). The first line gives the results for the primary in the binary system. The second line gives the orbital period of the satellite and the amplitude range of mutual events.



The plot of phase angle bisector longitudes shows the values for the previous apparitions as well as in 2018. The 2013 observations (Waszczak et al., 2015) were very sparse, only a few data points a night, and so, even if conditions were right, a satellite could not have been found. The 2008 and 2015 apparitions differed by almost 180°, meaning they were essentially the same save for which of the asteroid's poles was being seen. The 2016 observations were almost 45° from the opposing longitude for 2018, making the two viewing aspects about as much different as possible. From all this, it's possible to give an approximate spin axis longitude of 145° or 325° and, less certain, |latitude| > 30°.

Using the 4-hour period as a starting point, the dual period search soon showed that the deviations were likely due to a satellite. With each night of additional data, the second period become better defined, as did the mutual events. Since the orbital period was just longer than an Earth day, getting sufficient data of the mutual events from a single longitude required a protracted campaign.





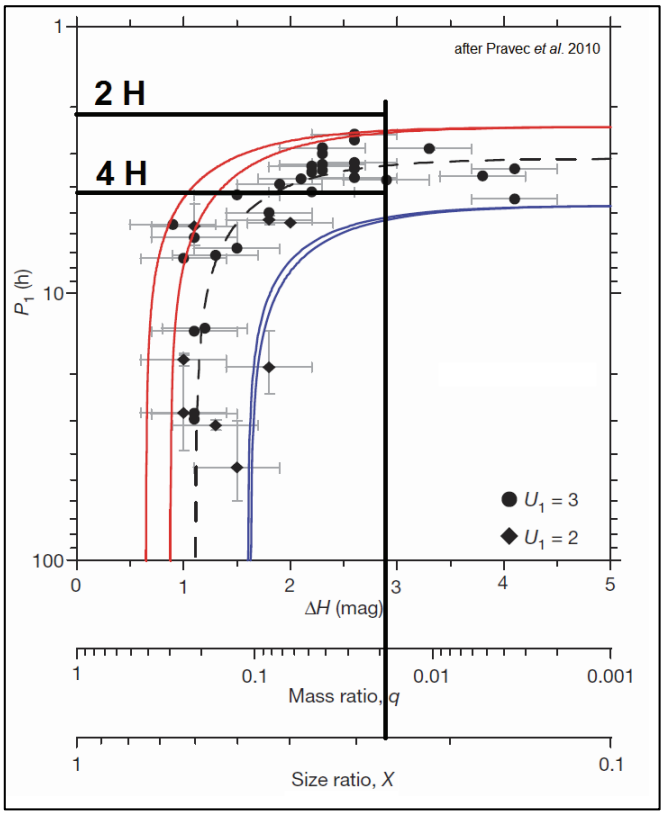
The "P_1" and "P_{ORB}" plots show the final results: P_1 = 4.0852 ± 0.0002 h, A_1 = 0.08 mag and P_{ORB} = 26.715 ± 0.005 h, A_{EVENTS} = 0.06-0.11 mag. The secondary lightcurve was flat outside of the events, indicating that the satellite is nearly spheroidal and probably tidally locked to the orbital period.

Using the lesser amplitude finds

$$\frac{Ds}{Dp} = \sqrt{(10^{0.4\Delta m} - 1.0)}$$

$$\geq 0.24 \pm 0.02$$

where D_S and D_P are, respectively, the effective diameters of the satellite and primary. The value is a minimum since no total eclipses were seen.



Positions using a 2-hour and 4-hour primary period are in shown the plot of primary period to size ratio (based on Pravec et al., 2010). The shorter period places the system outside the envelope

while the 4-hour period is well within. This supports, but does not confirm, that the longer period is the more likely. "Rules are made to be broken."

The asteroid lightcurve database (LCDB; Warner et al., 2009b) has 48 Hungaria binaries, 26 of those are confirmed binary or multiple systems. This compares to 68 confirmed near-Earth asteroids (Johnston, 2018), who lists 21 confirmed binary/multiple Hungarias. Even when using the more conservative numbers, this gives N_H/N_{NEA} of 31%.

It's not expected that the two numbers be the same. Instead, the ratio being well above zero helped determine that it was not tidal forces during planetary encounters that formed NEA binaries (e.g., Warner and Harris, 2006; Pravec et al., 2008) but that the thermal YORP (Yarkovsky–O'Keefe–Radzievskii–Paddack; Rubincam, 2000) effect had caused small asteroids to "spin up" (periods shortened) to where they shed mass and formed a satellite.

Acknowledgements

Work on the asteroid lightcurve database (LCDB) was funded by National Science Foundation grant AST-1507535. This research was made possible through the use of the AAVSO Photometric All-Sky Survey (APASS), funded by the Robert Martin Ayers Sciences Fund.

References

Behrend, R. (2008). Observatoire de Geneve web site. *http://obswww.unige.ch/~behrend/page_cou.html*

DeMeo, F.E., Carry, B. (2013). "The taxonomic distribution of asteroids from multi-filter all-sky photometric surveys." *Icarus* **226**, 723-741.

Harris, A.W., Young, J.W., Scaltriti, F., Zappala, V. (1984). "Lightcurves and phase relations of the asteroids 82 Alkmene and 444 Gyptis." *Icarus* **57**, 251-258.

Harris, A.W., Young, J.W., Bowell, E., Martin, L.J., Millis, R.L., Poutanen, M., Scaltriti, F., Zappala, V., Schober, H.J., Debehogne, H., Zeigler, K.W. (1989). "Photoelectric Observations of Asteroids 3, 24, 60, 261, and 863." *Icarus* **77**, 171-186.

Harris, A.W., Pravec, P., Galad, A., Skiff, B.A., Warner, B.D., Vilagi, J., Gajdos, S., Carbognani, A., Hornoch, K., Kusnirak, P., Cooney, W.R., Gross, J., Terrell, D., Higgins, D., Bowell, E., Koehn, B.W. (2014). "On the maximum amplitude of harmonics on an asteroid lightcurve." *Icarus* **235**, 55-59.

Henden, A.A., Terrell, D., Levine, S.E., Templeton, M., Smith, T.C., Welch, D.L. (2009). *http://www.aavso.org/apass*

Johnston, W.R. (2018). "Asteroids with Satellites" web site. *http://www.johnstonsarchive.net/astro/asteroidmoons.html*

Lucas, M.P., Emery, J.P., Pinilla-Alonso, N., Lindasav, S.S., Lorenzi, V. (2017). "Hungaria asteroid region telescopic spectral survey (HARTSS) I: Stony asteroids abundant in the Hungaria background population." *Icarus* **291**, 268-287.

McEachern, F.M., Cuk, M., Steward, S.T. (2010). "Dynamical evolution of the Hungaria asteroids." *Icarus* **210**, 644-654.

Milani, A., Knezevic, Z., Novakovic, B., Cellino, A. (2010). "Dynamics of the Hungaria asteroids." *Icarus* **207**, 769-794.

Munos, J.L. (2017). Carlsberg Meridian Catalog web site. *http://svo2.cab.inta-csic.es/vocats/cmc15/*

Pravec, P., Harris, A.W., Vokrouhlický, D., Warner, B.D., Kušnirák, P., Hornoch, K., Pray, D.P., Higgins, D., Oey, J., Galád, A., Gajdoš, Š., Kornoš, L., Világi, J., Husárik, M., Krugly, Yu.N., Shevchenko, V., Chiorny, V., Gaftonyuk, N., Cooney, W.R., Gross, J., Terrell, D., Stephens, R.D., Dyvig, R., Reddy, V., Ries, J.G., Colas, F., Lecacheux, J., Durkee, R., Masi, G., Koff, R.A., Goncalves, R. (2008). "Spin rate distribution of small asteroids." *Icarus* **197**, 497-504.

Rubincam, D.P. (2000). "Relative Spin-up and Spin-down of Small Asteroids." *Icarus* **148**, 2-11.

Stephens, R.D. (2016). "Asteroids Observed from CS3: 2016 April - June." *Minor Planet Bull.* **43**, 336-339.

Warner, B.D., Harris, A.W. (2006). "A Comparative Study of Hungaria versus NEA Binary Populations and Spin Axis Characteristics." *Bull. American Ast. Soc.* **38**, p. 596.

Warner, B.D., Harris, A.W., Vokrouhlicky, D., Nesvorny, D., Bottke, W.F. (2009a). "Analysis of the Hungaria asteroid population." *Icarus* **204**, 172-182.

Warner, B.D., Harris, A.W., Pravec, P. (2009b). "The Asteroid Lightcurve Database." *Icarus* **202**, 134-146. Updated 2018 June. *http://www.minorplanet.info/lightcurvedatabase.html*

Warner, B.D. (2008). "Asteroid Lightcurve Analysis at the Palmer Divide Observatory: February-May 2008." *Minor Planet Bull.* **35**, 163-167.

Warner, B.D. (2013). "Asteroid Lightcurve Analysis at the Palmer Divide Observatory: 2013 January – March." *Minor Planet Bull.* **40**, 137-145.

Warner, B.D. (2015). "Asteroid Lightcurve Analysis at CS3-Palmer Divide Station: 2014 December - 2015 March." *Minor Planet Bull.* **42**, 167-172.

Waszczak, A., Chang, C.-K., Ofek, E.O., Laher, R., Masci, F., Levitan, D., Surace, J., Cheng, Y.-C., Ip, W.-H., Kinoshita, D., Helou, G., Prince, T.A., Kulkarni, S. (2015). "Asteroid Light Curves from the Palomar Transient Factory Survey: Rotation Periods and Phase Functions from Sparse Photometry." *Astron. J.* **150**, A75.