Taylor, R.C., Gehrels, T., and Silvester, A.B. (1971). "Minor Planets and Related Objects. VI. Asteroid (110) Lydia." *Astron. J.* **76**, 141-146.

Warner, B.D., Stephens, R.D., Harris, A.W., and Shepard, M.K. (2009). "Coordinated Lightcurve and Radar Observations of 110 Lydia and 135 Hertha." *Minor Planet Bul.* **36**, 38-39.

SEEING DOUBLE OLD AND NEW: OBSERVATIONS AND LIGHTCURVE ANALYSIS AT THE PALMER DIVIDE OBSERVATORY OF SIX BINARY ASTEROIDS

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Results of the analysis of lightcurves of six binary asteroids obtained at the Palmer Divide Observatory are reported. Of the six, three were previously known to be binary: 9069 Hovland, (26471) 2000 AS152, and 1994 XD. The remaining three are new confirmed or probable binary discoveries made at PDO: 2047 Smetana, (5646) 1990 TR, and (52316) 1992 BD.

As a result of an ongoing CCD asteroid photometry program at the Palmer Divide Observatory near Colorado Springs, CO, more than 40 asteroids were observed from 2012 October to December. Of this number, three were known binary objects. 9069 Hovland, a Hungaria, was first reported as a binary by Warner *et al.* (2004). (26471) 2000 AS152, also a Hungaria, was reported to be binary in 2009 (Warner *et al.*, 2009). The third known binary was 1994 XD, first reported as such in 2005 based on radar observations (Benner *et al.*, 2005)

On the other hand, three other objects were found for the first time to show evidence of a satellite. 2047 Smetana, a Hungaria, had been observed before by the author, in 2006 and 2011, but no evidence of a satellite was seen. (5646) 1990 TR is a near-Earth asteroid (NEA) that was observed as the program at PDO shifts emphasis towards that group. (52316) 1992 BD, another Hungaria, was observed for the first time at PDO in 2012. Details of the observations and analysis for each asteroid are given below.

General Discussion

See the introduction in Warner (2010b) for a discussion of equipment, analysis software and methods, and overview of the lightcurve plot scaling. The "Reduced Magnitude" in the plots is Johnson V or Cousins R (indicated in the Y-axis title) corrected to unity distance by applying $-5*\log(r\Delta)$ 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 given in parentheses, e.g., alpha(6.5°), using $G = 0.15$, unless otherwise stated.

Lightcurve analysis was done using *MPO Canopus*, which implements the FALC algorithm by Harris (Harris *et al.*, 1989). There are several methods for extracting the two periods. The usual procedure at PDO is to find an approximate value for the short period first, presumably due to the primary's rotation, using *all* observations, including any possible events, i.e., occultations or eclipses due to the satellite. This produces a Fourier curve, usually one of 6^{th} order in the initial searches. A second search is then made for a longer period, subtracting the Fourier curve from the raw data before analysis. This usually produces a lightcurve that shows the events more clearly. The results (Fourier curve) from the second search are subtracted from the raw data when searching anew for the shorter period, resulting in a tighter fit of the data. This iterative process continues until the two period solutions stabilize.

Another approach, one that can help avoid misleading initial results, is to use only those data that do not include suspected events when doing the first search for the shorter period. From there, the iterative process can continue with more confidence. To be clear, with each new data set, only those data not suspected of being related to an event are used to refine the short period *before* the search for the orbital period is performed. This alternative method is sometimes used to confirm the solution found from the first method. In either case, as more data are added, the search starts again, although the initial period and range of possibilities can be constrained and found to a higher precision.

As a final check, the two curves are subtracted from the raw data and another period search conducted covering a range from about half the shorter period to 2-3x the longer period. Ideally, this would result in a flat lightcurve with scatter about equally distributed on either side. However, if the secondary (satellite) is not tidally-locked to the orbital period and is sufficiently elongated, a lightcurve with a third period might be found. In this case, the process becomes more involved but does not change substantially, other than keeping track of which two periods are being subtracted before analysis begins.

A thorough discussion of the analysis of lightcurves of binary systems can be found in Pravec *et al.*, 2006. That paper should be among the required reading for those doing asteroid lightcurve photometry.

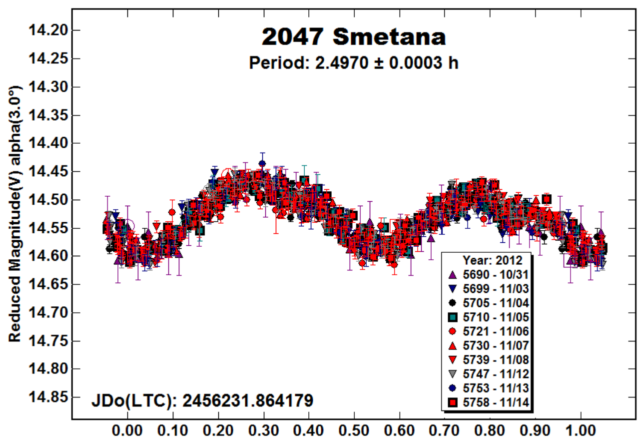
Individual Asteroids

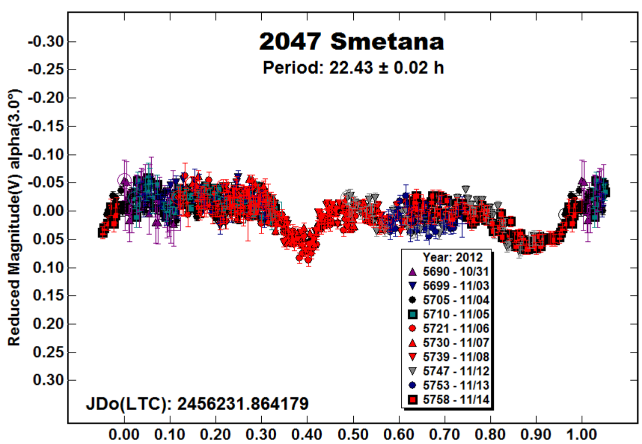
2047 Smetana (new binary). The author observed this Hungaria in 2006 and 2011 (Warner, 2006; 2011). In 2006, a period of P = 2.4969 h was reported and, in 2011, P = 2.4801 h. In the 2006 paper, it was noted that the period and amplitude were "binary friendly," that no evidence of a satellite was seen, and that follow-up observations were recommended. In the 2011 work, a period of about 2.497 h was found in addition to the one adopted. It was noted at that time that a period search routine used for finding the period in lightcurve inversion modeling favored that longer period. Still, the shorter period was adopted. It appears now that this was incorrect.

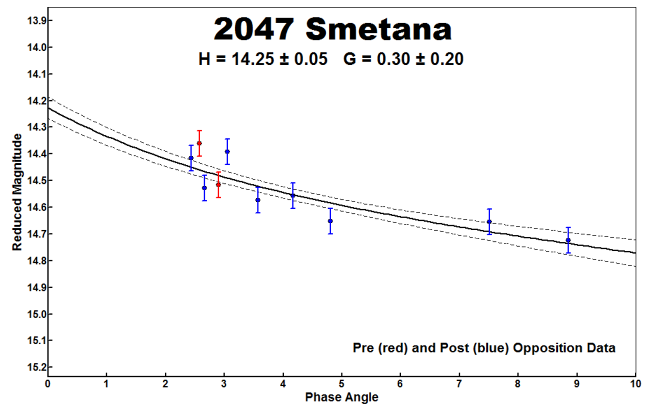
In 2012, observations were made at PDO starting on Oct 31 and continuing through Nov 14. Data from the first three nights seemed to show evidence of a satellite, thus prompting a more extended campaign. In all, 741 data points taken on 10 nights were used in the analysis. The result was a primary period, $P_1 = 2.4970 \pm 0.0003$ h with $A_1 = 0.12 \pm 0.01$ mag. The secondary period, that of the mutual events and, therefore, the orbital period, was $P_{Orb} = 22.43 \pm 0.02$ h with event amplitudes of 0.05 mag.

The event at about 0.9 rotation phase in the lightcurve for the orbital period appears close to, if not total. Assuming that the event is total, this establishes the secondary-to-primary effective diameter ratio as Ds/Dp = 0.21 ± 0.02. If one of the events were not total, then only a lower limit for Ds/Dp could be given.

Maisero *et al.* (2012) reported an albedo p_V = 0.544 ± 0.069 using *H* = 13.8 and *G* = 0.15. This is consistent with type E asteroids, the presumed type of the Hungaria parent body. The PDO data gave *H* = 14.25 ± 0.05 and *G* = 0.30 ± 0.20. If using a fixed value of *G* = 0.43 ± 0.08, the average for high albedo objects (see Warner *et al.*, 2009), the value for *H* changed by only 0.05 mag. The difference in *H* between the Maisero *et al.* and PDO values is significant and so the albedo and diameter were recalculated by applying the correction method of Harris and Harris (1997) that is required when dealing with original values derived from thermal observations. Masiero *et al.* gave *D* = 3.13 ± 0.15 km and p_V = 0.544 ± 0.069. The PDO values for *H* and *G* give *D* = 3.07 km and p_V = 0.37 ± 0.04.







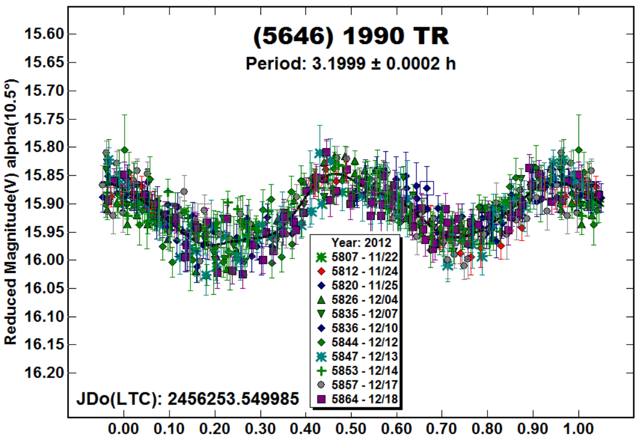
<u>(5646) 1990 TR (probable new binary)</u>. Wisniewski (1992) observed this near-Earth asteroid and reported a period of 6.25 h. While he reported the lightcurve to be "unusual", speculation in the paper about the reasons why did not include a satellite, very likely because, at that time, small satellites of asteroids had yet to be confirmed. Nowadays, those doing asteroid photometry are aware of the potential and so an "unusual" lightcurve is examined more carefully. It's worth some speculation about how many earlier efforts may have overlooked a satellite. Unfortunately, one aspect of those early data sets is that, because the specific need was not known, they were much sparser than would be the case today and so it would be more difficult to confirm a satellite.

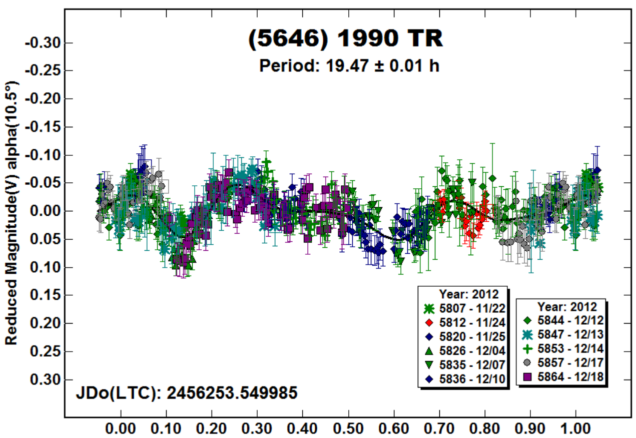
1990 TR is a near-Earth asteroid (NEA). When there are no Hungarias available, NEAs are given next priority. A total of 551 observations were made on 11 nights between 2012 Nov 22 and Dec 18. The initial period and amplitude, along with some suspicious data prompted the longer campaign. Analysis found P_1 = 3.1999 ± 0.0002 h and A_1 = 0.12 ± 0.01 mag. Suspected events of 0.03-0.05 mag were seen in the secondary lightcurve, which has a period of P_{Orb} = 19.47 ± 0.01 h.

It should be noted, however, that P_{Orb} is close to an exact 6:1 ratio of P_1 and so may be the result of the Fourier analysis latching onto harmonics in the data. A test against this was to see if the solution remained the same using orders that were not related to one another, e.g., not all even-numbered. The two periods remained the same within 1-sigma when trying fits of 2, 3, 4, 5, 6, and 7th order. Yet, this is still not conclusive evidence and so this object must be put into the "probable" category with follow-up observations requested at future apparitions.

Keeping the assumption that the asteroid is a binary, neither of the events seems total and so the derived size ratio is a lower limit, i.e., Ds/Dp ≥ 0.18 ± 0.02.

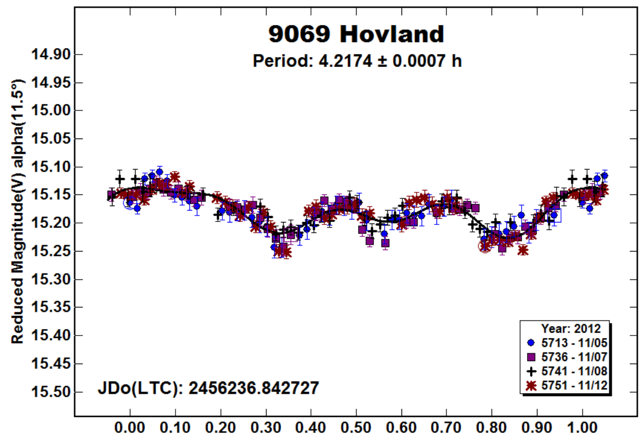
Alan Harris (MoreData!) digitized the Wisniewski plots from the original article to provide uncorrected UT/V sky magnitude data. These were imported into *MPO Canopus* for analysis. Since there were only two nights of data, separated by five nights, it was not possible to confirm even the short primary period, the closest solution being about 3.21 h.





9069 Hovland (known binary). This Hungaria was first reported to be binary in 2004 with P_1 = 4.2174 h and P_{Orb} = 30.35. The phase angle bisector longitude (L_{PAB}) was ~34°. No lightcurve was published at that time. Additional information about the asteroid was given by Harris and Pravec (2006) but still without a lightcurve. The 2004 lightcurve was eventually published by Warner *et al.* (2011) when additional data taken in 2004 were incorporated to refine the results to P_1 = 4.2173 h, A_1 = 0.09 mag, and P_{Orb} = 30.292 h. Marchis *et al.* (2012), using Spitzer IR data from 2008, did not detect the satellite but did find P_1 = 4.217 h, and A_1 = 0.10 mag at L_{PAB} ~ 131°.

The 2012 observations at PDO were made on 4 nights from Nov 5-12. No evidence of a satellite was seen in the lightcurve, which had parameters of P = 4.2174 ± 0.0007 h and A = 0.10 ± 0.01 mag. The approximate L_{PAB} was 51°. Since the 2004 events were somewhat shallow, not much above the ability to detect with photometry alone, the small difference in L_{PAB} could be the reason that no events were seen in 2012. The next apparition is in 2014 June (V ~ 16.5, Dec –15°). The L_{PAB} at that time will be 260° (L_{PAB}–180° = 80°), making it even less likely that mutual events might be seen.

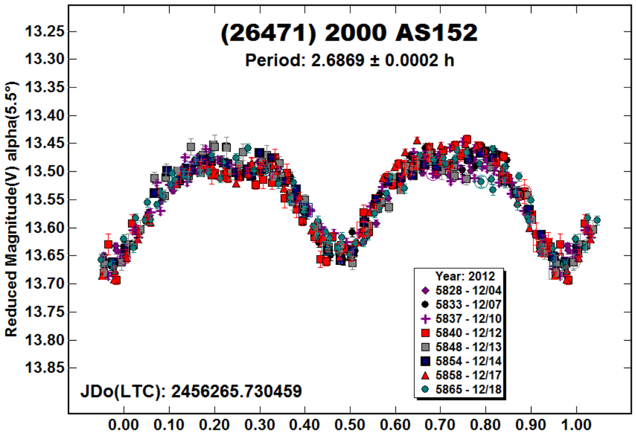


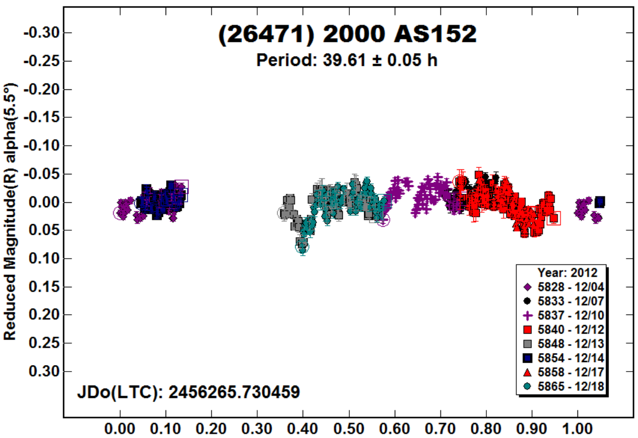
(26471) 2000 AS152 (known binary). This Hungaria was first observed in 2008 at PDO (Warner, 2008). Results were P = 2.687 h and A = 0.20 mag, which agreed with a period reported by Behrend (2001). The 2008 PDO data were somewhat noisy (error bars on the order of 0.02-0.03 mag) and so any low-level events would probably have been lost in the noise. The asteroid was first reported to be binary by Warner *et al.* (2009) in a Central Bureau Electronic Telegram (CBET). A lightcurve and more detailed analysis were later published by Warner *et al.* (2010) with parameters of P_1 = 2.68679 h, A_1 = 0.22 mag, and P_{Orb} = 39.28 h at L_{PAB} = 322°.

The 2012 observations were taken over 8 nights between Dec 4-18 and included 475 data points for analysis. The L_{PAB} was 75°, or about 70° from the line that joined the opposite sides of the orbit of the earlier observations. If the orbital plane of the asteroid is somewhat perpendicular to the orbit of the asteroid, then mutual events would not have been expected in 2012. If the plane is nearly in the plane of the asteroid's orbit, then events would be expected.

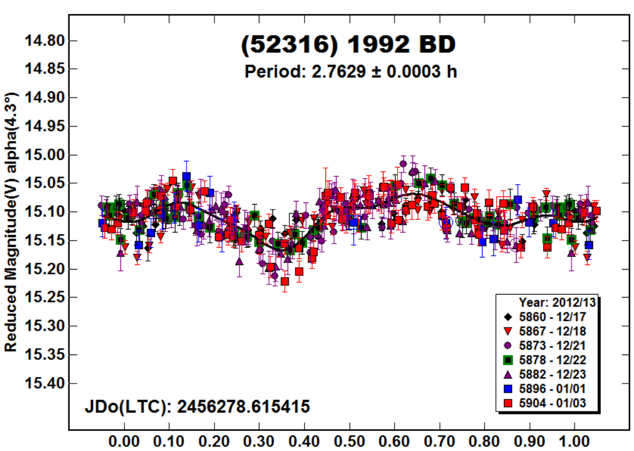
Events were seen, but only just above the observational limits for detecting satellites using only photometry. In fact, if the 2012 data set was the only one available, there would not be sufficient evidence to make an affirmative case for the asteroid being binary, only "probable" at best. The fact the events were seen and so shallow does help constrain the orientation of the satellite's orbit and the approximate longitude of the orbit's pole.

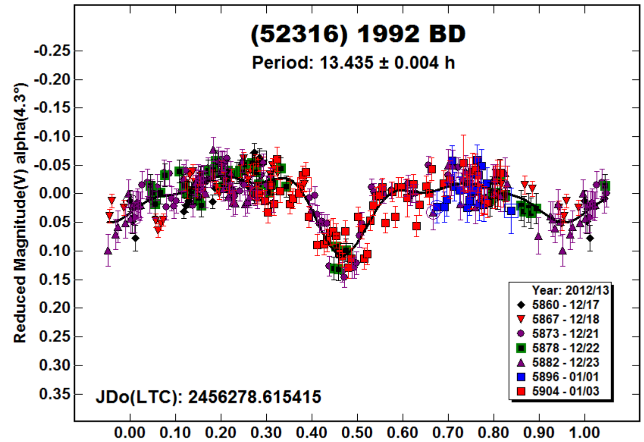
Despite the low amplitude, it was possible to look for the orbital period by restricting the primary period to a small range about the earlier results. This lead to finding P_{Orb} = 39.61 ± 0.05 h. In the lightcurve for the events, the apparent "bowing" due to a tidally-locked and slightly elongated satellite can been seen, almost more so than the mutual events. The value for P_{Orb} from 2012 is significantly different from the earlier result. If not the result of a lack of data, then the change may be due to different shadowing effects with different phase angles. In 2009, the phase angle was about 29° but only 5° in 2012. When more data become available, this information may prove useful for modeling.





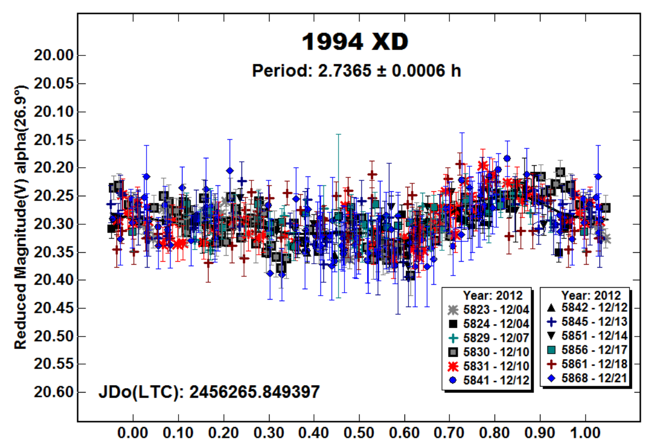
<u>(52316) 1992 BD (new binary)</u>. Observations of 1992 BD occurred on 7 nights between 2012 Dec 17 and 2013 Jan 3. A total of 341 data points were obtained. This is a little less than often required but the very deep primary event (~0.12 mag) made the case for a satellite much stronger and easier to prove. The results of analysis were P_1 = 2.7629 ± 0.0003 h, A_1 = 0.10 ± 0.01 mag, and P_{Orb} = 13.435 ± 0.004 h. The secondary event, used to estimate the size of the satellite, was only 0.03 mag. This gives Ds/Dp = 0.16 ± 0.02. Since neither event is total, this must be taken as a lower limit. The lightcurve showing the events gives strong indications of a tidally-locked, elongated satellite by virtue of the overall "bowing" in the shape.

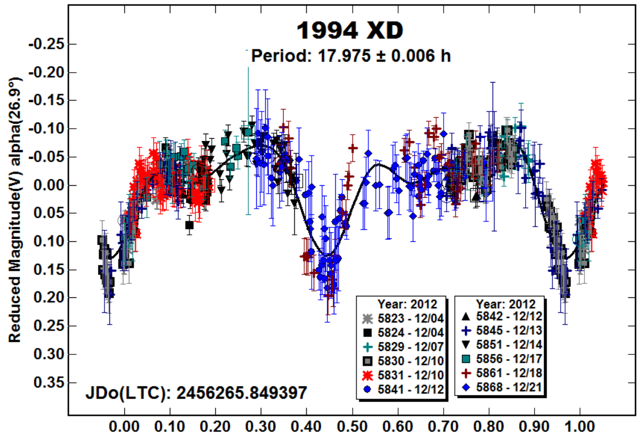




<u>1994 XD (known binary)</u>. This NEA was reported to be binary following radar observations in 2005 (Benner *et al.*, 2005). Observations were made at PDO from 2012 Dec 4-21 on 9 nights. On some nights, the measurements had to be split into two "sessions" as the sky motion of the asteroid required using different sets of comparison stars. The split sessions were matched to one another by measuring a set of five images twice, first as the last five observations in the first session and then as the first five observations in the second session. If required, the zero point of the combined set was then adjusted to fit the other sessions.

Using only PDO data, the results were P_1 = 2.7365 ± 0.0006 h, A_1 = 0.08 ± 0.01 mag, and P_{Orb} = 17.975 ± 0.006 h. Pravec *et al.* (private communications), using a subset of the PDO data along with data from other observers, found different results, the primary period being about 0.04 h and orbital period about 0.07 h less than then PDO results. Attempts to reconcile the differences by forcing the PDO-only data set to periods near those from Pravec *et al.* were unconvincing. The PDO data set extended a week longer than the last reported set from Pravec. It's possible that the lightcurve, especially for the mutual events, underwent significant changes over the additional time, which leads to the discrepancies. With luck, when combined with the radar data analysis, a more definitive solution will be found, including actual sizes of the two bodies.





Hungaria Binary Status

This count of *known* Hungaria binary found at PDO now stands at 13. Five others have been discovered at other locations. Another 7 Hungarias (all but one found at PDO) are considered *probable* binaries but need additional confirmation. There are still 4 others that are suspicious but not sufficiently so to make them even probable discoveries. There are currently 278 Hungarias in the LCDB with statistically valid rotation rates. The 18 known binaries accounts for about 6% of that total. Making some assumptions about distribution of orbit pole orientations, the true number may be more on the order of 12%. If the 7 probable discoveries are included, the percentage increases to about 18%, which is in line with the estimated population among near-Earth asteroids of about 15% (Pravec *et al.*, 2006).

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References

Behrend, R. (2001). Observatoire de Geneve web site, *http://obswww.unige.ch/~behrend/page_cou.html*

Benner, L.A.M., Nolan, M.C., Ostro, S.J., Giorgini, J.D., Margot, J.L, and Magri, C. (2005). "1994 XD." *IAUC* **8563**

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., and Zeigler, K.W. (1989). "Photoelectric Observations of Asteroids 3, 24, 60, 261, and 863." *Icarus* **77**, 171-186.

Harris, A.W. (DLR), Harris, A.W. (JPL) (1997). "On the Revision of Radiometric Albedos and Diameters of Asteroids." *Icarus* **126**, 450-454.

Harris, A.W. and Pravec, P. (2006). "Rotational properties of asteroids, comets and TNOs" in Asteroids, Comets, Meteors, Proceedings of the 229th Symposium of the International Astronomical Union held in Búzios, Rio de Janeiro, Brasil August 7-12. (Daniela, L., Sylvio Ferraz, M., Angel, F. Julio, eds.) pp 439-447. Cambridge University Press, Cambridge.

Masiero, J., Mainzer, A.K., Grav, T., Bauer, J.M., Cutri, R.M., Nugent, C., and Cabrera, M.S. (2012). "Preliminary Analysis of WISE/NEOWISE 3-Band Cryogenic and Post-cryogenic Observations of Main Belt Asteroids." *Astrophys. J. Letters* **759**, L8.

Pravec, P., Scheirich, P., Kušnirák, P., Šarounová, L., Mottola, S., Hahn, G., Brown, P., Esquerdo, G., Kaiser, N., Krzeminski, Z., Pray, D.P., Warner, B.D., Harris, A.W., Nolan, M.C., Howell, E.S., Benner, L.A.M., Margot, J.-L., Galád, A., Holliday, W., Hicks, M.D., Krugly, Yu.N., Tholen, D., Whiteley, R., Marchis, F., Degraff, D.R., Grauer, A., Larson, S., Velichko, F.P., Cooney, W.R., Stephens, R., Zhu, J., Kirsch, K., Dyvig, R., Snyder, L., Reddy, V., Moore, S., Gajdoš, Š., Világi, J., Masi, G., Higgins, D., Funkhouser, G., Knight, B., Slivan, S., Behrend, R., Grenon, M., Burki, G., Roy, R., Demeautis, C., Matter, D., Waelchli, N., Revaz, Y., Klotz, A., Rieugné, M., Thierry, P., Cotrez, V., Brunetto, L., and Kober, G. (2006). "Photometric survey of binary near-Earth asteroids." *Icarus* **181**, 63-93.

Marchis, F., Enriquez, J.E., Emery, J.P., Mueller, M., Baek, M., Pollock, J., Assafin, M., Vieira Martins, R., Berthier, J., Vachier, F., Cruikshank, D.P., Lim, L.F., Reichart, D.E., Ivarsen, K.M., Haislip, J.B., and LaCluyze, A.P. (2012). "Multiple asteroid systems: Dimensions and thermal properties from Spitzer Space Telescope and ground-based observations." *Icarus* **221**, 1130-1161.

Warner, B.D., Pravec, P., Harris, A.W., Pray, D., Kanupuru, V., and Dyvig R. (2004). MPML, msg #13545.

Warner, B.D. (2008). "Asteroid Lightcurve Analysis at the Palmer Divide Observatory: December 2007 - March 2008." *Minor Planet Bul.* **35**, 95-98.

Warner, B.D., Harris, A.W., and Pray, D. (2009). "(26471) 2000 AS152." *CBET* **1881**.

Warner, B.D., Pravec, P., Kusnirak, P., Hornoch, K., Harris, A., Stephens, R.D., Casulli, S., Cooney, W.R., Jr., Gross, J., Terrell, D., Durkee, R., Gajdos, S., Galad, A., Kornos, L., Toth, J.,Vilagi, J., Husarik, M., Marchis, F., Reiss, A.E., Polishook, D., Roy, R., Behrend, R., Pollock, J., Reichart, D., Ivarsen, K., Haislip, J., Lacluyze, A., Nysewander, M., Pray, D.P., and Vachier, F. (2010a). "A Trio of Binary Asteroids." *Minor Planet Bul.* **37**, 70-73.

Warner, B.D. (2010b). "Asteroid Lightcurve Analysis at the Palmer Divide Observatory: 2010 March – June." *Minor Planet Bul.* **37**, 161-165.

Warner, B.D., Pravec, P., Kusnirak, P., Harris, A.W., Cooney, W.R., Jr., Gross, J., Terrell, D., Nudds, S., Vilagi, J., Gajdos, S., Masi, G., Pray, D.P., Dyvig, R., and Reddy, V. (2011). "Lightcurves from the Initial Discovery of Four Hungaria Binary Asteroids." *Minor Planet Bul.* **38**, 107-109.

Wisniewski, W.Z. (1992). "The unusual lightcurve of 1990 TR" in *Asteroids, Comets, Meteors 1991.* pp. 653-656 (A.W. Harris, E. Bowell, eds.) Lunar and Planetary Institute, Houston.