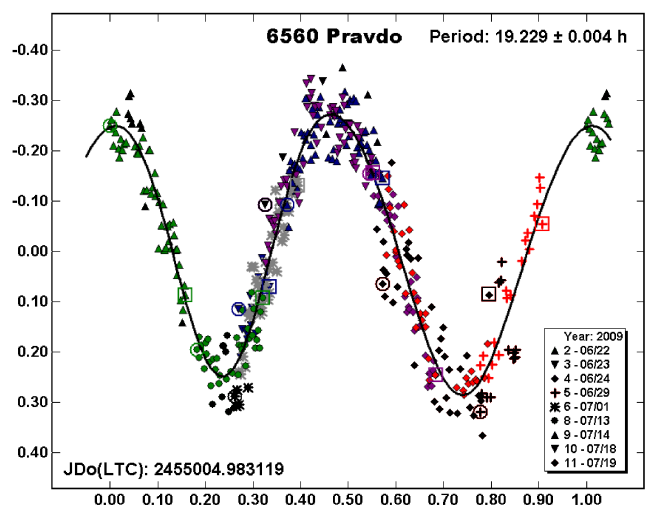
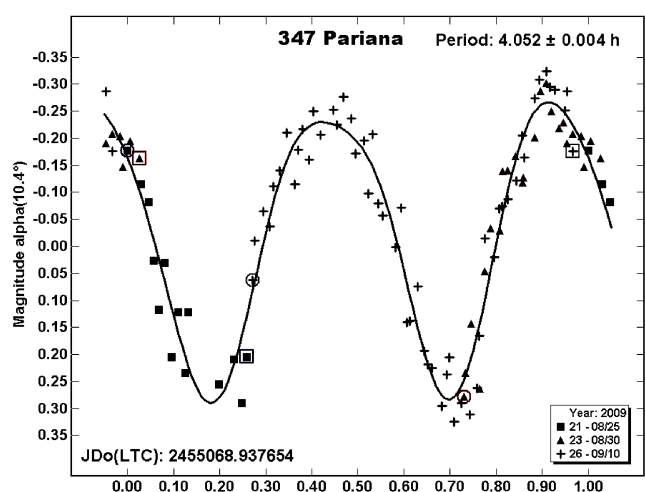
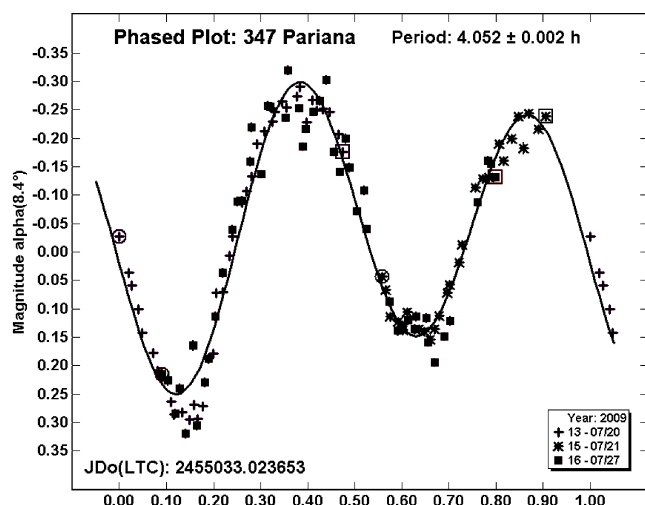




A TALE OF TWO ASTEROIDS: (35055) 1984 RB AND (218144) 2002 RL66

Brian D. Warner
Palmer Divide Observatory/Space Science Institute
17995 Bakers Farm Rd., Colorado Springs, CO 80908 USA
brian@MinorPlanetObserver.com

Petr Pravec, Peter Kušnirák
Astronomical Institute, Academy of Sciences
Ondřejov, CZECH REPUBLIC

Alan Harris
Space Science Institute
La Canada, CA USA

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We present the analysis of CCD observations of the Hungaria asteroid, (35055) 1984 RB, and Mars-crosser, (218144) 2002 RL66. For 1984 RB, because of a data set spanning several weeks, we were able to determine the synodic rotation period and lightcurve amplitude as well as H and G parameters. Furthermore, the amplitude-phase angle relationship and derived value for G are consistent with a S-type asteroid. 2002 RL66 may be an unusual binary with a very long period for the primary and an asynchronous satellite that is not tidally locked to its orbit. The analysis for both of these objects relied strongly on being able to link multiple data sets onto a common system with reliable zero point calibrations.

Observation Details

(35055) 1984 RB. This Hungaria asteroid was observed at the Palmer Divide Observatory from 2010 Feb 17 through Mar 18. A total of 583 observations were made using a 0.35-m Schmidt-Cassegrain and SBIG STL-1001E camera. Exposures were 300 s. See Warner (2010) for a general description of PDO equipment and analysis methods. See Warner (2007) and Stephens (2008) for details on data set calibration and methods using 2MASS (Skrutskie et al. 2006) to BVRI conversions. As described below, these methods were later abandoned for this asteroid after the initial data set led to erroneous conclusions.

(218144) 2002 RL66. This Mars-crosser was initially observed at the Palmer Divide Observatory from 2009 Nov 18 through Dec 11. The results were $P = 616$ h and $A = 0.34$ mag (Warner, 2010). At the time, it was noted that the combination of the period and estimated diameter would make the object a likely tumbler (in non-principal axis rotation) but no evidence was found (see Pravec et al. 2005, regarding tumbling damping times). Additional observations in 2010 March further refined the long period.

The Best and Worst of Times

The sequence of events for these two asteroids provides an interesting study of how one thing can lead to another in data analysis and the importance of having data that can be reliably placed on a consistent internal (or standard) system. The story begins with (218144) 2000 RL66.

After submitting the paper to the *Minor Planet Bulletin* on (218144) 2002 RL66, the data were sent to Pravec and Kušnirák,

who have the specialized tools to check for tumbling behavior. No evidence was found. However, Kušnirák did find a weak, second *additive* period of $P_{\text{short}} = 2.492$ h and $A = 0.04$ mag. This prompted the additional observations at PDO that spanned 2010 Jan 9 through Feb 13 and led to the refined lightcurve parameters for the long period of $P_{\text{long}} = 587 \pm 10$ h and $A = 0.25$ mag. The short period parameters remained essentially the same (Figs 1/2).

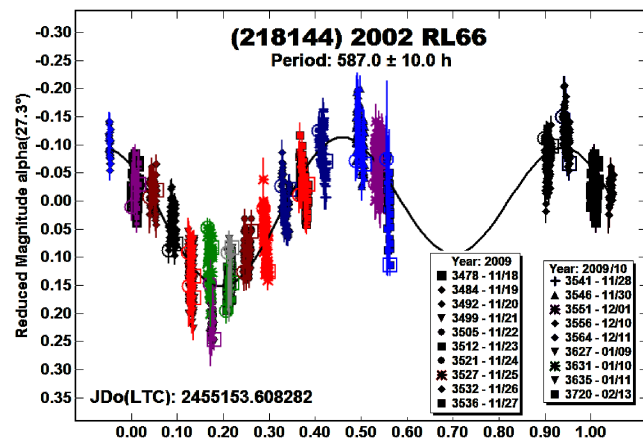


Figure 1. The long period lightcurve of (218144) 2002 RL66.

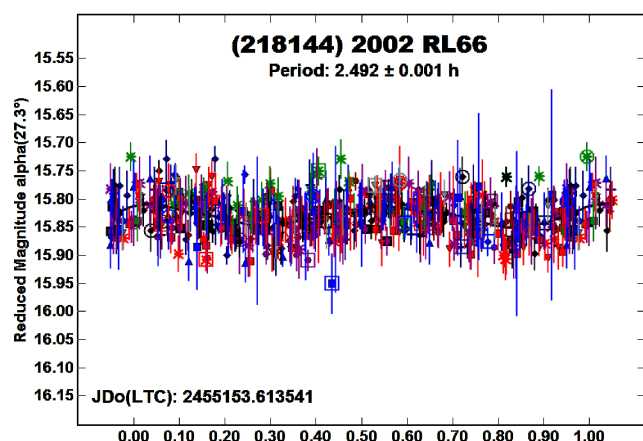


Figure 2. Short period lightcurve of (218144) 2002 RL66.

The presence of two *additive* periods is often an indicator for a binary system (for a detailed description of binary lightcurve analysis, see Pravec et al., 2006). However, the lack of mutual events (occultations and/or eclipses), prevented making such a claim for 218144 with certainty. If the system were binary, then it was an unusual one in that the primary period was very long while the secondary period was relatively short. Unusual, that is, until the initial data for (35055) 1984 RB were obtained and analyzed. On the presumption that the linkage of the data sets was correct, this led to the appearance that 35055 also had two additive periods, one of ~ 3.658 h and another on the order of 300 h. Influenced by the findings for 218144, we looked deeper into the possibilities for systems with these characteristics.

In any *known* model for a system with two additive periods, when the combined light is at a maximum, the amplitude of the shorter period lightcurve should be less than when the combined light is at a minimum. This stems from the fact that if the variation in *intensity units* of the shorter period is the same at all times, then when the longer period component is brighter, it dilutes the shorter period curve more in *magnitude units* than when it is fainter. For example, in our initial analysis for 35055, we found a mean

amplitude for the short period of 0.39 mag and 0.3 mag for the long period. Therefore, on the nights close to combined *minimum* magnitude, we would expect the short period amplitude to be about 15% *greater* than average, or about 0.45 mag, and about 15% *less* (0.34 mag) when the combined light was at *maximum*. While there was some night-to-night variation in amplitude of the short period (see below), it did not follow the pattern of larger amplitude at fainter level of the long period variation.

Using the principle of *Occam's Razor* (the simplest solution is mostly likely the correct one), the images were re-measured using SDSS (Stoughton et al., 2002) and CMC-14 (Evans et al., 2002) r' magnitudes for the comparison stars instead of the R magnitudes derived from 2MASS J-K magnitudes. The internal consistency of r' magnitudes is on the order of 0.02-0.03 mag (Dymock and Miles, 2009), thus removing some of the uncertainties in the data set linking. The result was the complete elimination of any secondary period, and the re-reduced data was well fit with a single synodic period of $P = 3.6586 \pm 0.0005$ h (Fig. 3).

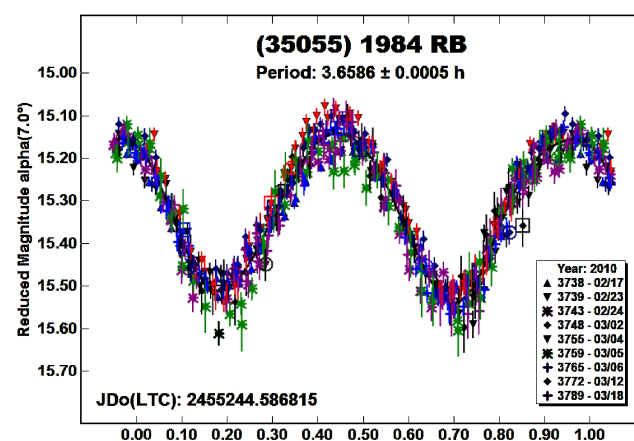


Figure 3. Lightcurve of (35055) 1984 RB. SDSS r' magnitudes.

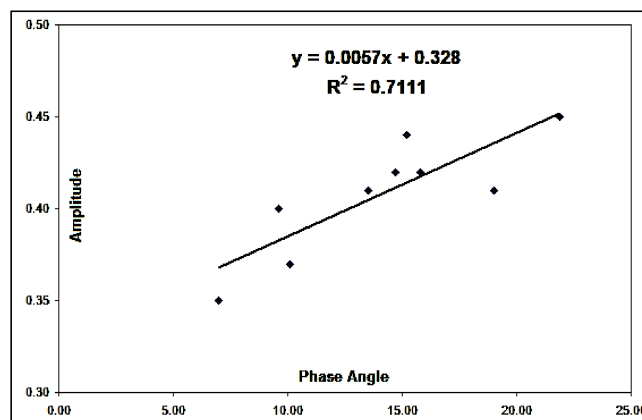


Figure 4. Amplitude versus phase for (35055) 1984 RB.

We plotted the amplitude versus phase angle (Fig. 4) and found a slope of ~ 0.006 , which is in the range found for S-class asteroids by Zappala et al. (1990). We then examined the *ugriz* magnitudes from the SDSS MOC (Ivezić et al., 2001) using Principal Component Analysis (PCA) as developed by Nesvorný et al. (2005). The results were consistent with an S-type asteroid.

Since the data spanned phase angles from 7° to 22° , we also were able to determine the absolute magnitude (H) and phase slope parameter (G) for the asteroid (Fig. 5). The magnitudes in that plot

are SDSS r' . The SDSS MOC gave a V-R for the asteroid of 0.44. Dymock and Miles (2009) convert r' to R using $R = r' - 0.22$, or $V-r' = 0.22$ for $V-R = 0.44$. Combining these values with our $H_V = 14.69$, we found $H_V = 14.91$. The value for G was 0.225 ± 0.025 , which is consistent with the default of $G = 0.24 \pm 0.11$ for S-class asteroids given by Warner et al. (2009). While none of these factors (amplitude vs. phase, colors, or phase relation) are certain determinations of S-class, together they constitute good evidence that this asteroid is of S-type. Assuming the default albedo for S-type asteroids, $p_V = 0.20$ (Warner et al., 2009), we estimate the size of the asteroid to be $D \sim 3.1$ km.

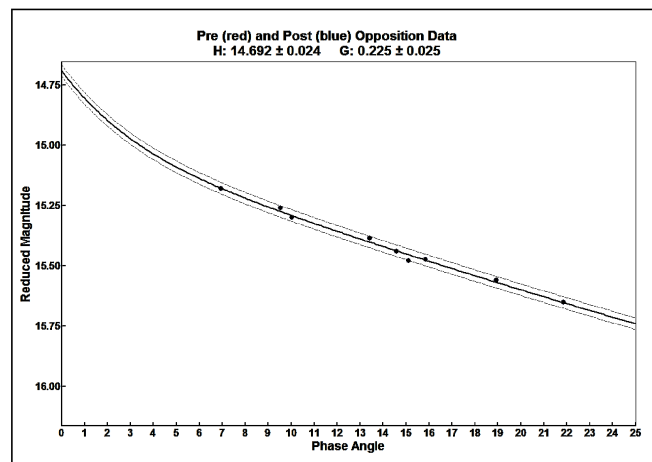


Figure 5. H-G plot for (35055) 1984 RB.

Conclusions

It is important to emphasize again that we do not have conclusive evidence that (218144) 2002 RL66 is a binary system. It is possible that future adaptive optics (AO) observations, when the asteroid is sufficiently bright, can be used to see if two bodies can be resolved, and it is also possible that photometric observations at a different aspect might show eclipse events. We strongly encourage AO and additional photometric observations of low noise (~ 0.01 mag) at future apparitions.

While the 2MASS to BVRI conversions have been used with great success in many cases, they failed in the case of (35055). The analysis for that asteroid showed that the better thing to do is use native catalog magnitudes that are internally consistent instead of relying on conversions from one magnitude system to another. This is not always possible since the SDSS/CMC-14 catalogs do not provide complete sky coverage. Since the methods used by Warner (2007) and Dymock and Miles (2009) both rely on J-K values from the 2MASS catalog to convert to the BVRI system, it would be prudent when using those methods to have some means of cross-checking the data to confirm the results, especially if those results seem to indicate something extraordinary.

Acknowledgements

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Analysis Center/California Institute of Technology, funded by NASA and NSF.

References

- Dymock, R. and Miles, R. (2009). "A Method for Determining the V magnitude of Asteroids from CCD Images." *J.B.A.A.* **119**, 149-156.
- Evans, D.W., Irwin, M.J., and Helmer, L. (2002). "The Carlsberg Meridian Telescope CCD drift scan survey". *Astron. Astrophys.* **395**, 347-356.
- Ivezić, Ž., 32 colleagues (2001). "Solar System objects observed in the Sloan Digital Sky Survey commissioning data." *Astron. J.* **122**, 2749-2784.
- Nesvorný, D., Jedick, R., Whitely, R.J., and Ivezić, Ž. (2005). "Evidence for asteroid space weathering from the Sloan Digital Sky Survey." *Icarus* **173**, 132-152.
- Pravec, P., Harris, A.W., Scheirich, P., Kušnirák, P., Šarounová, L., and 15 colleagues (2005). "Tumbling Asteroids." *Icarus* **173**, 108-131.
- Pravec, P., Scheirich, P., Kušnirák, P., Šarounová, L., and 53 colleagues (2006). "Photometric survey of binary near-Earth asteroids." *Icarus* **181**, 63-93.
- Pravec, P. and Harris, A.W. (2007). "Binary Asteroid Population. I. Angular Momentum Content." *Icarus* **190**, 250-259.
- Skrutskie, M.F., 29 colleagues (2006). "The Two Micron All Sky Survey." *Ap. J.* **131**, 1163-1183.
- Stephens, R.D. (2008). "Long Period Asteroids Observed from GMARS and Santana Observatories." *Minor Planet Bul.* **35**, 21-22.
- Stoughton, C., 191 colleagues (2002). "Sloan Digital Sky Survey: early data release." *Astron. J.* **123**, 485-548.
- Warner, B.D. (2007). "Initial Results of a Dedicated H-G Project." *Minor Planet Bul.* **34**, 113-119.
- Warner, B.D., Harris, A.W., and Pravec, P. (2009). "The Asteroid Lightcurve Database." *Icarus* **202**, 134-146.
- Warner, B.D. (2010). "Asteroid Lightcurve Analysis at the Palmer Divide Observatory: 2009 September-December." *Minor Planet Bul.* **37**, 57-64.
- Zappalà, V., Cellino, A., Barucci, A.M., Fulchignoni, M., and Lupishko, D.F. (1990). "An analysis of the amplitude-phase relationship among asteroids." *Astron. Astrophys.* **231**, 548-560.