# ON CONFIRMED AND SUSPECTED BINARY ASTEROIDS OBSERVED AT THE CENTER FOR SOLAR SYSTEM STUDIES: 2022 JUNE TO AUGUST

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Analysis of CCD photometric observations obtained in 2022 June to August of the inner main-belt asteroid 3533 Toyota and near-Earth asteroid (85804) 1998 WQ5 at the Center for Solar System Studies indicate that both asteroids are likely binary. For 3533, we found P1 = 2.9809 h and PORB = 16.070 h but, for the latter, solutions of 12.098 h and 24.2176 h cannot be formally excluded. (85804) 1998 WQ5 has P1 = 2.6761 h and PORB = 46.13 h. The estimated diameter ratio of the two bodies is >0.33.

CCD photometric observations of inner main-belt asteroid 3533 Toyota and near-Earth asteroid (85804) 1998 WQ5 were made at the Center for Solar System Studies in 2022 June to August. Data analysis makes it very likely that both objects are binary. This is based on there being a sufficiently distinct secondary period with its lightcurve showing what appear to be *mutual events* (occultations/eclipses) or a slightly elliptical body where the rotational and orbital periods are the same.

The observations were made with a 0.35-m Schmidt-Cassegrain and either an FLI Proline or Microline CCD camera as well as a 0.40-m Schmidt-Cassegrain with FLI Proline CCD camera. All cameras use a KAF-1001E chip, which has a pixel array of 1024×1024×24µ. The field-of-view and image scale were about 26×26 arcminutes and 1.5 arcsec/pixel, respectively, for the 0.35-m telescopes. The 0.4-m values were 20×20 arcminutes and 1.2 arcsec/pixel.

All lightcurve observations were unfiltered or with a clear filter, even though the clear filter can cause a 0.1-0.3 mag loss. The exposures varied depending on the asteroid's brightness and sky motion. Whether guiding on a field star or not, sometimes the asteroid was trailed on the image.

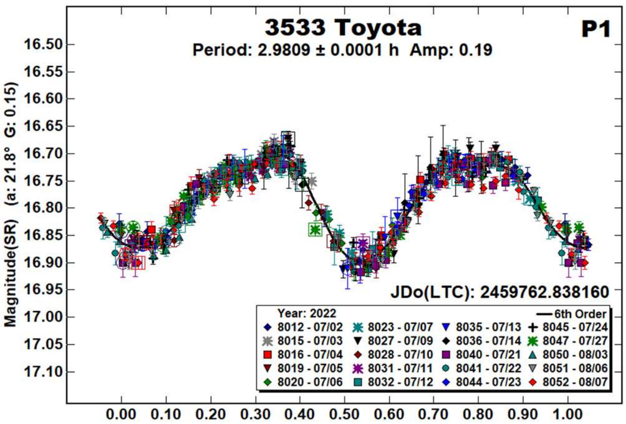
Measurements were made using *MPO Canopus*. The Comp Star Selector utility in *MPO Canopus* found up to five comparison stars of near solar-color for differential photometry. To reduce the number of adjusted nightly zero points and their amounts, the analysis of the data used the ATLAS catalog r´ (SR) magnitudes (Tonry et al., 2018). The rare zero-point adjustments of ≥ ±0.03 mag may be related to using unfiltered/clear observations, poor centroiding of the reference stars, not correcting for second-order extinction, or selecting a comp star that is an unresolved pair.

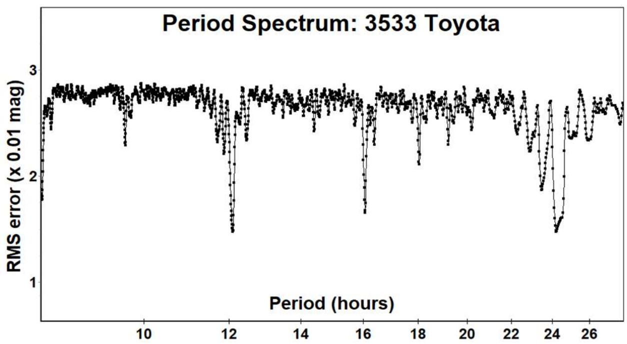
The Y-axis values are ATLAS SR "sky" (catalog) magnitudes. The two values in the parentheses are the phase angle (a) and the value of *G* used to normalize the data to the comparison stars used in the earliest session. This, in effect, corrected all the observations to appear that they were made at a single fixed date/time and phase angle, presumably leaving any variations due only to the asteroid's rotation and/or albedo changes. The X-axis shows rotational phase from -0.05 to 1.05. If the plot includes the amplitude, e.g., "Amp: 0.65", this is the amplitude of the Fourier model curve and *not necessarily the adopted amplitude for the lightcurve*.

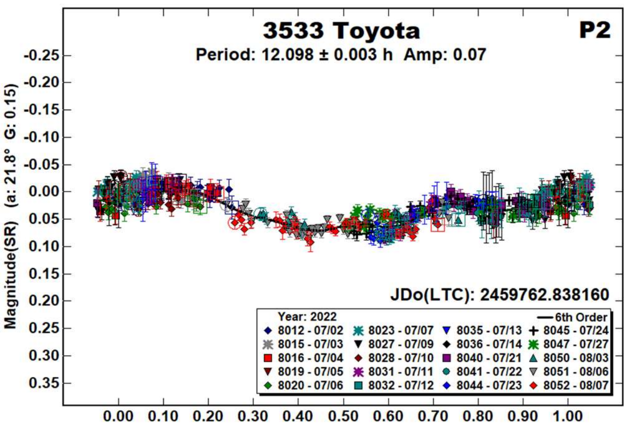
References to previous works were taken from the asteroid lightcurve database (Warner et al., 2009), known as "LCDB" from here on. Since most listed rotation periods for the primary were very similar, only a few of the LCDB references have been used.

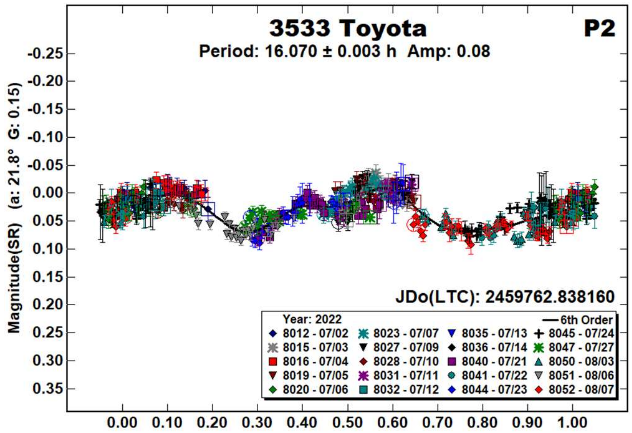
<u>3533 Toyota</u>. There are several previously reported periods for this asteroid, all with a single period close of 2.98 h, i.e., no indications of a satellite: Behrend (2006web); Pravec et al. (2009web; 2022web); Higgins (2011web); and Benishek (2020).

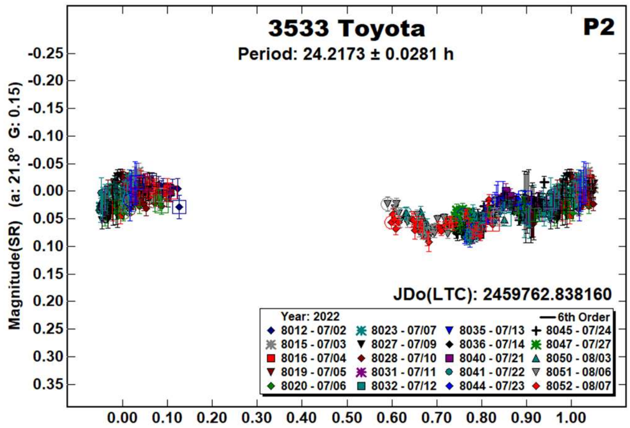
After several sessions, it was apparent that a second period was involved. Using the dual-period search in *MPO Canopus*, we found a primary period of $P_1$ = 2.9809 h and three possible secondary periods, each commensurate with an Earth Day (24 hours).






Finding a unique period for an Earth-day commensurate period from a single station is difficult at best. After nearly a month of observations, we adopted $P_{ORB}$ = 16.070 h, primarily because it produces a nearly sinusoidal bimodal lightcurve, which can be expected if the satellite is a slightly elongated body with its rotation and orbital periods being the same. There are no obvious signs of *mutual events*, i.e., occultations and/or eclipses, so we cannot give an estimate of the relative diameters between the primary and secondary bodies.

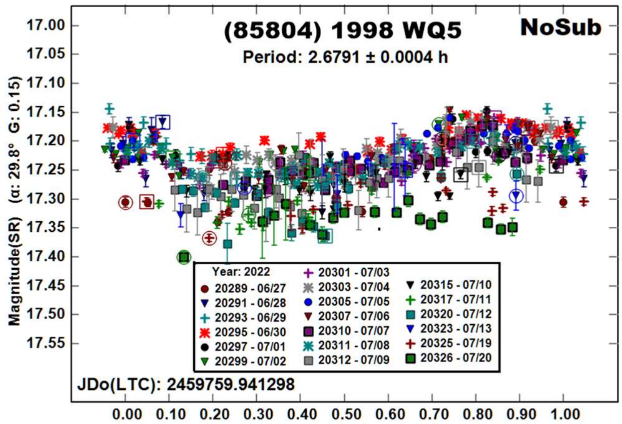
<u>(85804) 1998 WQ5</u>. Oey (2006) reported a period of 3.0089 h for this NEA while Higgins (2011web) found 3.71 h. Our previous work (Warner, 2015) gave a period of 6.028 h. Analysis of our 2022 data rejected all three results.

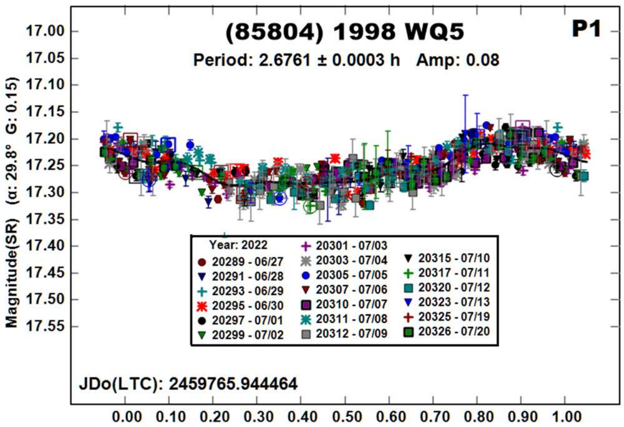
The "NoSub" plot shows the data phased to a single period. The numerous points below the "main" curve are often a good sign of a secondary period, most likely a satellite.

Once again, a month's worth of observations was needed to resolve the system characteristics to our satisfaction. The primary period seemed to resolve itself after a short time. However, being monomodal at 2.6761 h (after subtracting the proposed secondary period), there was a possibility the true value was the double period, or about 5.35 h (see Harris et al., 2014). Since a good majority of small binary asteroids have primary rotation period on the order of 2-4 hours, we have adopted $P_1$ = 2.6761 h for the primary.

Once this was settled, the search for the secondary period continued, sometimes changing significantly with the addition of another session's data. Eventually, we were led to $P_{ORB}$ = 46.13 h. Since there are nearly flat sections of the secondary period between the minima, we take those attenuations to be the result of mutual events and not just the rotation of an elliptical satellite.

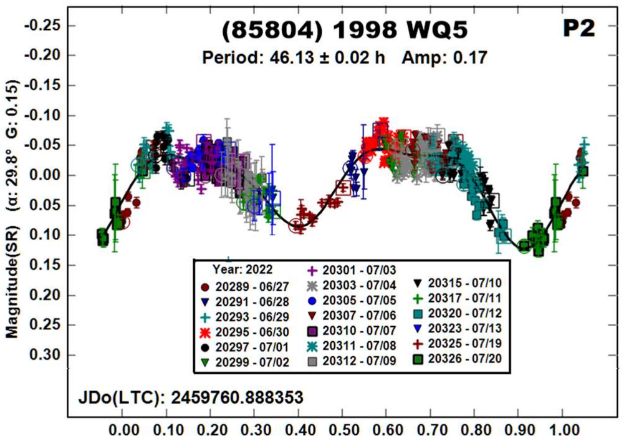
We estimate the attenuations to be 0.11 mag and 0.17 mag in depth. Using the smaller value allows finding the approximate effective relative diameters of the two bodies (*Ds/Dp*). In this case, the ratio is on the order of 0.33 ± 0.03. This is a minimum value since neither minimum is flat-bottomed, i.e., the mutual event would be total.




| Number | Name | 2022 mm/dd | Phase | $L_{PAB}$ | $B_{PAB}$ | Period(h) | P.E. | Amp | A.E. | Grp/Dr |
|---|---|---|---|---|---|---|---|---|---|---|
| 3533 | Toyota | 07/02-08/07 | 21.8,9.5 | 329 | 5 | 2.9809 | 0.0001 | 0.19 | 0.01 | MB-I |
| | | | | | | *16.070 | 0.003 | 0.08 | 0.01 | *UD* |
| 85804 | 1998 WQ5 | 06/27-07/20 | 29.8,18.4 | 314 | 13 | 2.6761 | 0.0003 | 0.06 | 0.01 | NEA |
| | | | | | | 46.13 | 0.02 | 0.17 | 0.01 | *>0.33* |

Table II. Observing circumstances. The first line for an asteroid gives the primary or dominant period. The second line gives the secondary period. * Indicates the preferred solution for the secondary period when more than one is found. The phase angle ($\alpha$) 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). For the Grp/Dr column, the first line gives the group/family: MB-I: inner main-belt, NEA: near-Earth asteroid. The code "UD" on the second line in the Grp/Dr column means "undetermined," primarily because there were no mutual events. Otherwise, the value is the ratio of the secondary-to-primary effective diameters.

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