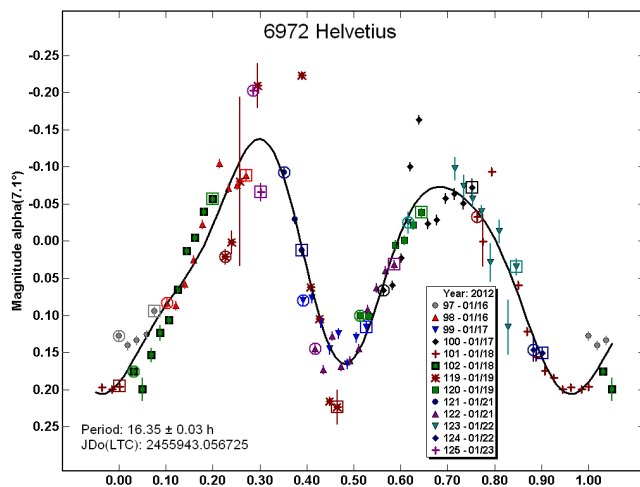
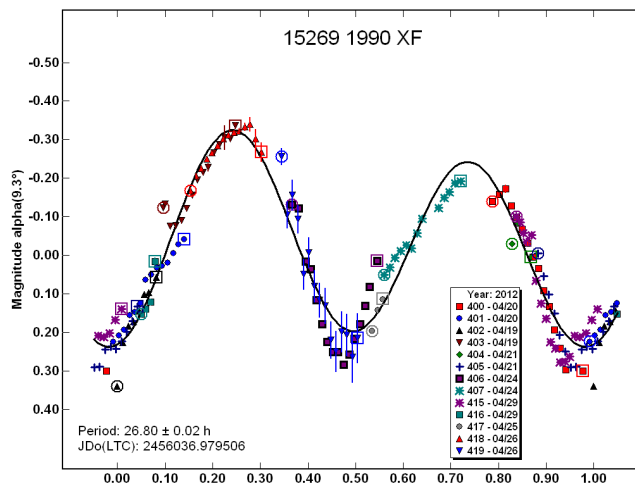
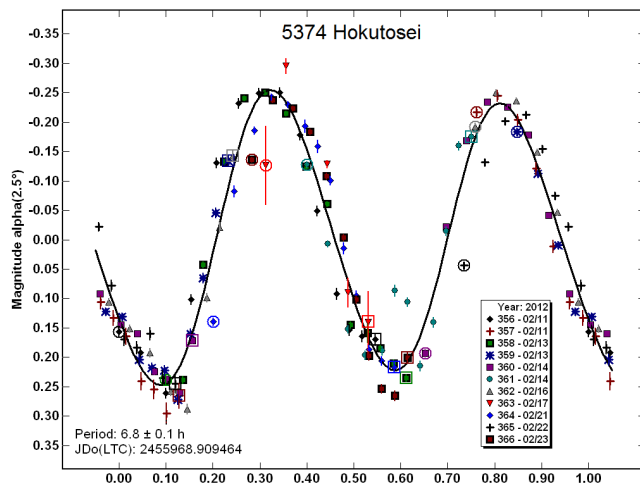
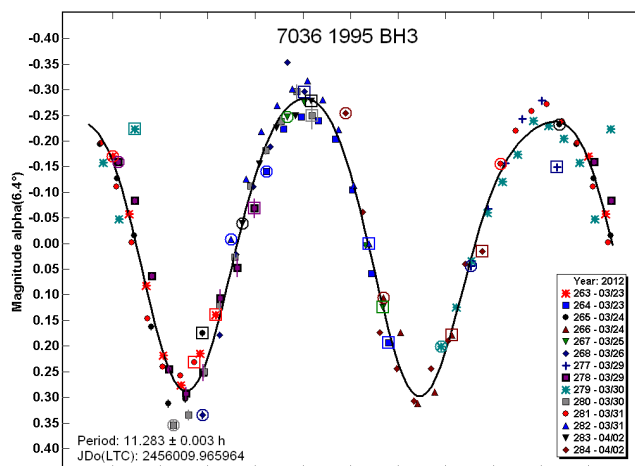
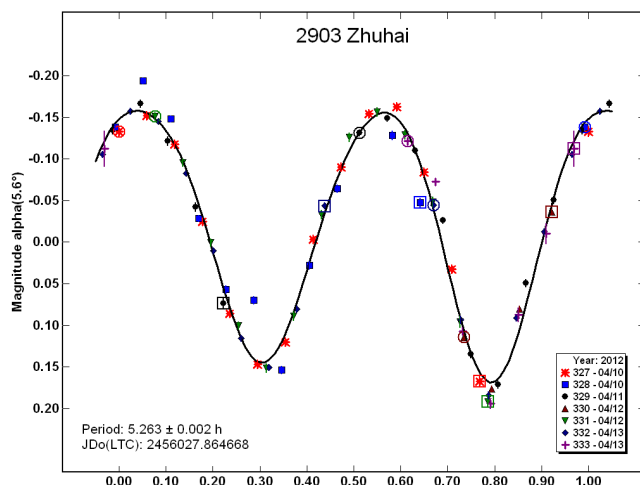




LIGHTCURVE INVERSION FOR 47035 (1998 WS)

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

Daniel A. Klinglesmith III
Etsorn Campus Observatory Socorro, NM 87801

Brian A. Skiff
Lowell Observatory, Flagstaff, AZ

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Observations of (47035) 1998 WS between 2012 January and April showed a large change in lightcurve shape. By combining sparse data from the Catalina Asteroid Survey with our dense data set, we have been able to determine a preliminary spin axis and shape model. The synodic period is on the order of 3.995 h. The amplitude ranged from 0.10 to 0.20 mag.

The Mars-crossing asteroid 47035 (1998 WS) has also been designated 1976 UA21 and 1982 GD. It has an orbital period of 4.33 years. Astrometric observations have been made during 11

oppositions (JPL Small-Body Database Browser, 2012). During the 2012 apparition, Klinglesmith and Skiff observed the asteroid between January and April. Observations in January were made at Etsorn Campus Observatory by Klinglesmith. Observations in March were made at Lowell Observatory by Skiff. Observations were made at both locations in April.

The Etsorn observations were made with a Celestron 0.35-m Schmidt-Cassigrain telescope with an SBIG STL-1001E CCD, unbinned, 1024x1024 24-micron pixels. All exposures were 180 seconds through a clear filter. The images were dark-subtracted, flat-field corrected, and aligned using *IDL* procedures (Visual Information Solutions, 2012). The reduced images were then processed by *MPO Canopus* (Warner, 2012). The Lowell Observations were all taken with the Lowell 0.78-m *f*/8 reflector with a e2v chip 2x2k in size binned 2x2. Exposures were 90 s with an Rc filter. Image scale was 0.9 arcsec/pixel. Measurements were made using *MPO Canopus* using a 13-pixel diameter aperture for differential photometry. The photometric zero-points were set using SDSS *r'* magnitudes incorporated in the MPOSC3 catalog in *MPO Canopus*.

The Lightcurve and Synodic Period

The solar phase angle did not change by a large amount during the apparition, being 31° on January 10, reaching a minimum of 27.5° on February 22, and increasing to 30.6° on April 6. However, the lightcurve shape changed significantly (Figures 1-5) due to changes in the viewing aspect as defined by the phase angle bisector (PAB) This is the vector connecting the center of the asteroid and the midpoint of the great circle arc between the sub-Earth and sub-solar points (see Magnusson *et al.*, 1989). The caption for Figures 1-5 gives the PAB (longitude, latitude) either as a single value or, as in Figure 1, the values for the end points of the date range.

Initial analysis lead to the conclusion that the period was $P \sim 7.995$ h, which was used to generate a spin axis and shape model. However, the period required a quadramodal lightcurve, four minima and maxima per cycle, for the data in 2012 April and the resulting shape model, viewed from the poles, was almost a square. This prompted a second look at the solution where it was determined that the half-period, $P \sim 3.995$ h, was more likely correct since it would mean that the lightcurve evolved from a monomodal curve (probably a near pole-on viewing aspect) to a more typical bimodal lightcurve later in the apparition (a more equatorial viewing aspect). Analysis of asteroid lightcurve amplitudes (Harris, 2012) favors the shorter solution with less complex curve.

Figure 1 shows the lightcurve from 2012 January 10-20 when the lightcurve has a monomodal shape and amplitude $A \sim 0.12$ mag. By late January (Figure 2), the lightcurve started to show indications of having two maxima with the maximum range still $A \sim 0.12$ mag. In Figure 3, in late February, the shape was similar to the one in Figure 2 but with some subtle changes. By early- to mid-March (Figure 4), the lightcurve took on a significantly different shape, showing even stronger signs of a second maximum while the amplitude was $A \sim 0.13$ mag. The final data set from April 6 (Figure 5) showed a distinctly bimodal lightcurve with an amplitude $A \sim 0.20$ mag.

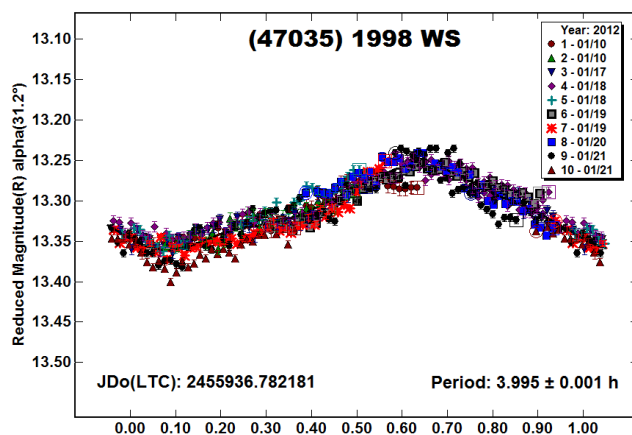


Figure 1. Lightcurve for 2012 Jan 10-21. PAB (120.1, +41.6) – (123.5, +40.5).

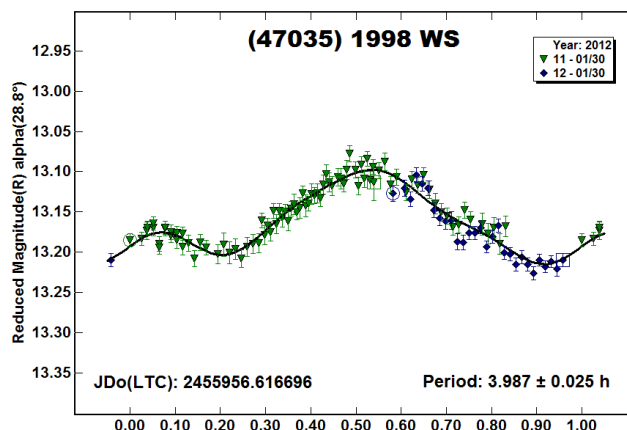


Figure 2. Lightcurve for 2012 Jan 30. PAB (125.9, +38.9).

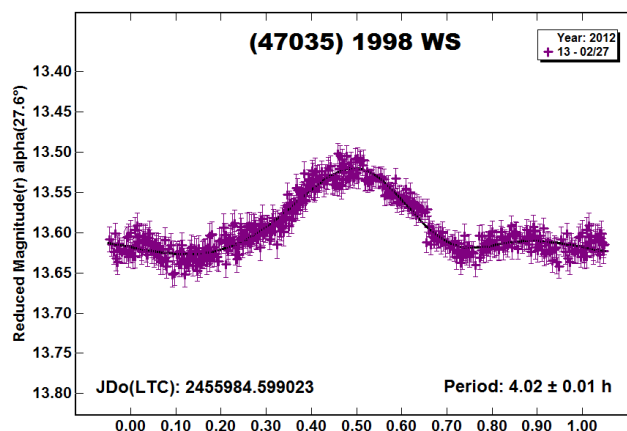


Figure 3. Lightcurve for 2012 Feb 27. PAB (133.3, +31.3).

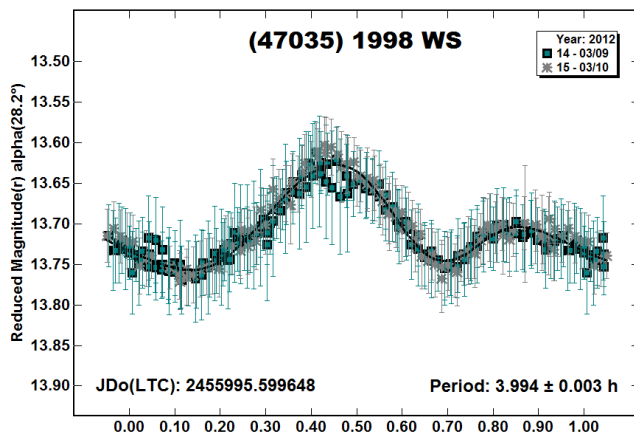


Figure 4. Lightcurve for 2012 March 9-10. PAB (136.5, +27.4).

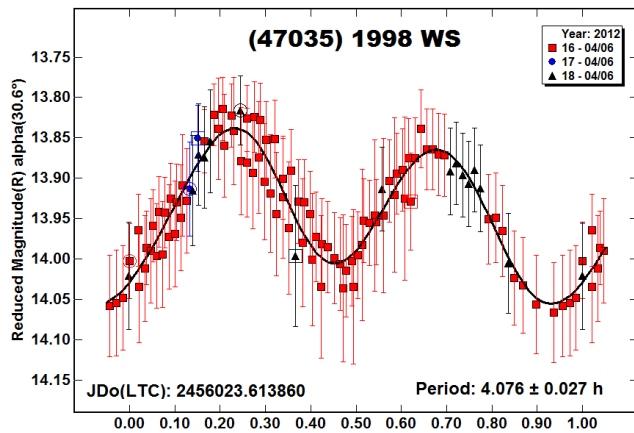


Figure 5. Lightcurve for 2012 Apr 6. PAB (145.8, +18.0).

Finding a Spin Axis and Shape Model

Usually, even when sparse data are used (see, e.g., Hanus *et al.*, 2011), having dense data from a single apparition is not enough to find a reliable spin axis and/or shape model. This is because the PAB values change very little over the apparition or, even if they do, the data set doesn't cover a sufficiently large range of PAB values. That was not the case here and so it was felt that it might be possible to derive a spin axis and shape model even though the dense data set was from a single apparition.

This approach has been tried successfully in the past. Kaasalainen *et al.* (2003) derived what is considered to be a good model of (5587) 1990 SB under similar circumstances, mostly because the dense data covered a large range of phase angles and the asteroid lightcurve showed significant changes in period and amplitude over the apparition, which, again, is what happened here. The data set reported in the paper by Koff *et al.* (2002) was the foundation for the model by Kaasalainen *et al.* That paper shows the significant changes that occurred over the apparition and gave hope for finding a model. As a test, using only the data from the Koff paper and no sparse data, Warner was able to recreate the Kaasalainen *et al.* model with the spin axis was within 10° of their solution and the shapes were very comparable.

In asteroid spin axis and shape modeling, it is critical that an unambiguous period first be established. Kaasalainen (2004) showed that the use of sparse data (a small handful of data points per night over a large time span) allows establishing a unique period, especially when combined with dense data (the typical

lightcurves presented in the *MPB*). However, this is true only if the sparse data are of sufficient photometric quality and cover a large range of PAB longitudes. We were lucky in this case in that a good set of sparse data from the Catalina Sky Survey was available via the AstDys web site (<http://hamilton.dm.unipi.it/astdys2/>). The set included data not only from longitudes well-removed from the dense data (Figure 6) but with a latitude range of $+40^\circ$ to -10° . The quality of the CSS data is not always the best – it is usually too noisy – but in this case it supplemented the available dense data to the point where we could find a reliably unique sidereal period.

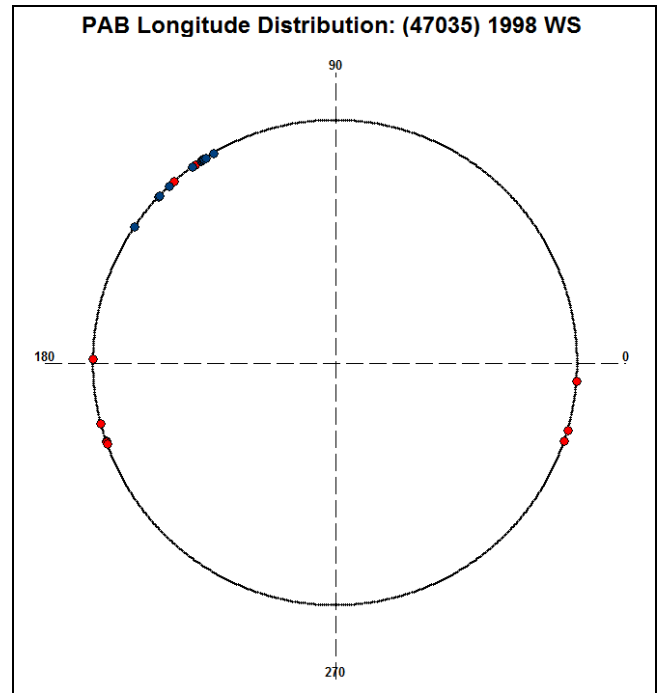


Figure 6. PAB longitude distribution for dense (blue) and sparse (red) data.

Using *MPO LCInvert* (Warner, 2012), which implements lightcurve inversion code developed by Kaasalainen and Durech (see Durech *et al.*, 2009, and references therein), we first did a period search that looked for the sidereal period with the minimum ChiSq value. This search can find many local minimums and so it's necessary to cover a sufficient range of values centered on the suspected period to assure that the correct period is found. This is a very CPU-intensive process. In this case, looking for a period in the range of 3.95 – 4.05 h took almost 18 hours of CPU time on a 1.8 GHz PC. Figure 7 is a plot of the period search spectrum, which shows a decided minimum. While we chose the discrete period at the bottom of the “dip”, it would have been better to use an algorithm that found a more accurate minimum, one that most likely was between the discrete data points. However, it should be noted that the period search algorithm steps sizes are managed in such a way to help avoid “stepping over” the best solution

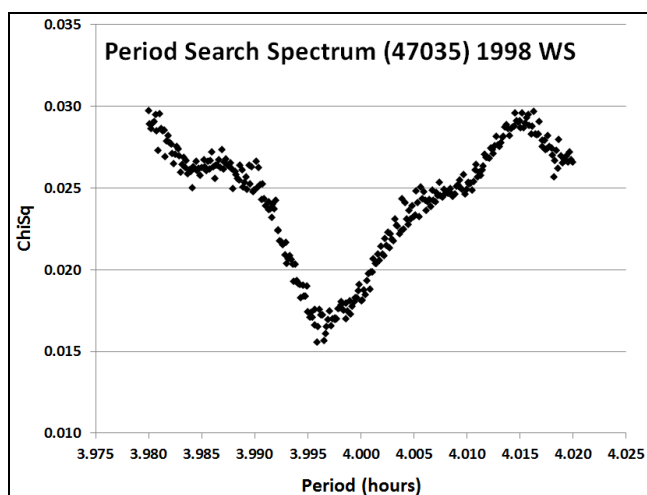


Figure 7. The period search spectrum from MPO LCInvert for (47035) 1998 WS. In this case, there is a decided minimum in the spectrum, which gave confidence in proceeding with a model search.

Once a period search has been done and a reliable period found, that result is used to examine the fit to each of more than 300 models with discrete longitude/latitude poles. In this search, the longitude and latitude are fixed but the period is allowed to “float.” This search results in a plot like the one shown in Figure 8. Low ChiSq values are represented by blue regions, the lowest ChiSq value indicated by a dark blue region. As the ChiSq value increases, the color evolves from blue to aqua to green, to yellow, to orange, and then to red. The highest ChiSq value is represented by a dark red (maroon) region.

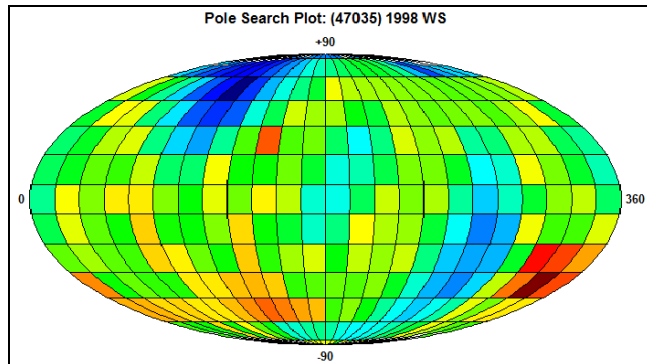


Figure 8. Pole search plot. ChiSq values increase from lowest (blue) to highest (red).

Ideally, one hopes for a plot with a single small area of dark blue and mostly greens to red for the rest. In some cases, there will be a second region of bluer colors. This is a result of the inversion process that often generates two pole solutions, usually differing by 180° in longitude but sometimes being “mirrored”, i.e., 180° off in longitude and a latitude about equally above (or below) the ecliptic plane. A positive latitude indicates prograde rotation while a negative latitude indicates retrograde rotation. In our solution, Figure 8 shows a very strong preference for a pole at about $(90^\circ, +70^\circ)$.

The pole search was refined using this initial solution as the starting point, this time allowing the longitude and latitude to float as well as the period. The final result was $(\lambda = 72.5, \beta = +70.9, P = 3.99590 \pm 0.00001 \text{ h})$. The pole uncertainty is about $\pm 10^\circ$ (a circle of that radius about the given position). The period uncertainty is

determined by the period and total time span of the data set and is equal to the time for a 10° rotation error over the total span of the data set.

Figure 9 shows the shape model for the asteroid, giving views from the north and south poles as well as in the asteroid’s equatorial plane with a Z-axis rotation of 0° and 90° . Besides putting trust in a “reasonable shape” and the pole search results, the results can be checked by plotting the model’s lightcurve against the actual data. Figures 10 (early January) and 11 (early April) show two such comparisons. These give the relative intensity (not magnitude) of the lightcurve, normalized to 1.0, with the model curve in black and the actual data in red. The fits are very good and so add confidence in the final solution.

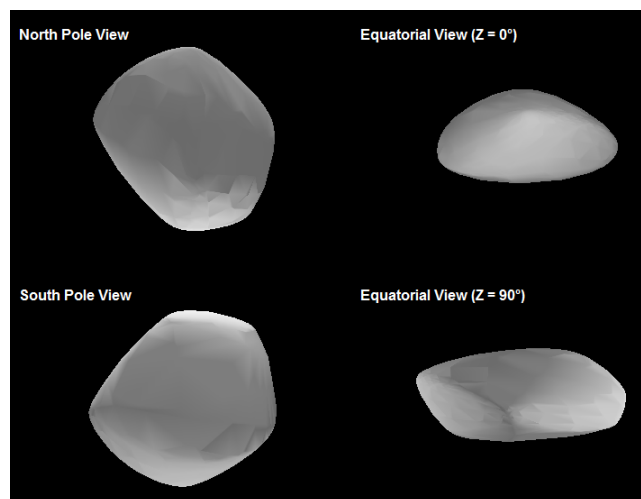


Figure 9. Shape model for (47035) 1998 WS. Clockwise from upper left: North Pole view; equatorial view, Z rotation = 0° ; equatorial view, Z rotation = 90° ; and South Pole view.

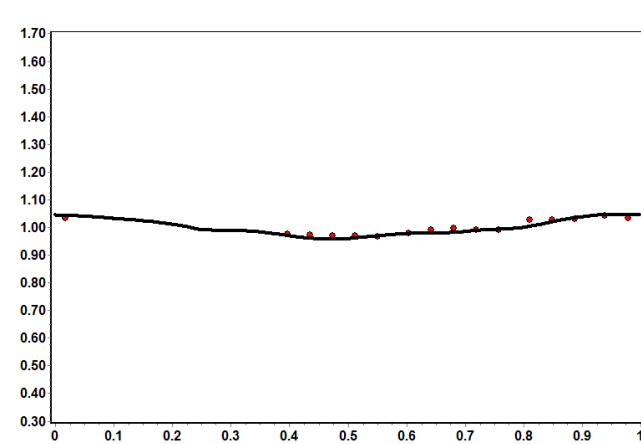


Figure 10. Comparison of model (black) and data (red) curves for 2012 Jan 10.

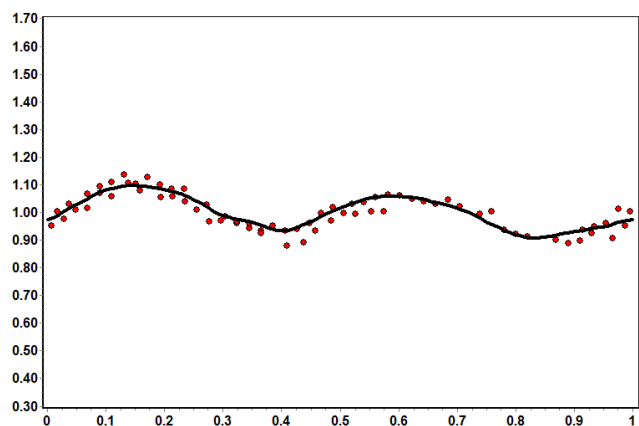


Figure 11. Comparison of model (black) and data (red) curves for 2012 Apr 6.

As mentioned earlier, we did two models, one based on periods of about 4 and 8 hours. While the fit of the model to the data for the 8-hour period was also good, the shape was less reasonable (“too square”) and the pole search results were less definitive. More to the point, however, is that the ChiSq values for both the period search and pole search were significantly lower, almost half, for the shorter period. This gives further reason to believe that the shorter period of about 4 hours is the correct one. It’s very likely that additional dense data, especially at an apparition with the PAB longitude about 90° from the one in 2012, will refine both the period and the pole.

We *strongly* caution that this was a rare set of fortunate circumstances that allowed finding what appears to be a good spin axis solution based on dense data from only one apparition. In the *large* majority of cases, even with good sparse data, obtaining a solution of reasonable and sufficient confidence requires having a much larger set of good-quality sparse data and, more important, dense lightcurve data sets from at least three apparitions.

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ROTATION PERIOD DETERMINATIONS FOR 47 AGLAJA, 252 CLEMENTINA, 611 VALERIA, 627 CHARIS, AND 756 LILLIANA

Frederick Pilcher
4438 Organ Mesa Loop
Las Cruces, NM 88011 USA
pilcher@ic.edu

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Synodic rotation periods and lightcurve amplitudes have been found for 47 Aglaja: 13.175 ± 0.002 h, 0.09 ± 0.01 mag; 252 Clementina: 10.864 ± 0.001 h, 0.37 ± 0.02 mag; 611 Valeria: 6.977 ± 0.001 h, 0.08 ± 0.01 mag; 627 Charis: 27.888 ± 0.002 h, 0.35 ± 0.02 mag; and 756 Lilliana: 7.834 ± 0.001 h, 0.17 ± 0.01 mag.

All observations reported here were made at the Organ Mesa Observatory using a Meade 35-cm LX-200 GPS Schmidt-Cassegrain (SCT), SBIG STL-1001E CCD, and clear filter. Exposures were unguided. Analysis used differential photometry only. Image measurement and lightcurve analysis were done by *MPO Canopus*. Because of the large number of data points, the data for the lightcurves presented here have been binned in sets of three points with a maximum time interval between points no greater than 5 minutes. In all cases, full or at least nearly-full phase coverage was obtained for the double period. When phased to the double period the two halves of the lightcurve looked the same within variations to be expected from observational error or changing phase angle. The probability of the double period being the correct one is extremely small and I reject all double-period solutions.

47 Aglaja. Several independent investigations listed in the Asteroid Lightcurve Data Base (Warner et al., 2012) are all consistent in showing a period near 13.178 hours. New observations were obtained on 6 nights from 2012 Apr 2 - May 7 to contribute to a