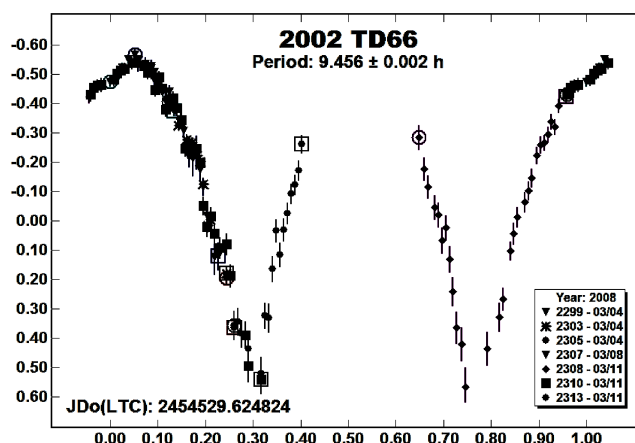
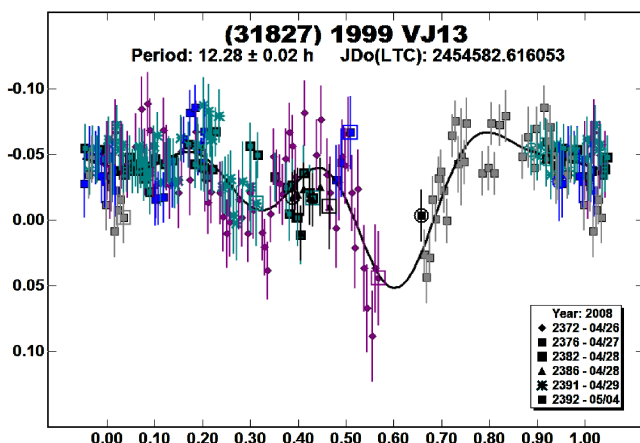




SHAPE AND SPIN AXIS MODELS FOR FOUR ASTEROIDS

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The authors present shape and spin axis models for four asteroids: 54 Alexandra, 167 Urda, 409 Aspasia, and 1022 Olympiada. The models were constructed using a combination of dense lightcurves and sparse data sets from USNO observations for lightcurve inversion. The use of combined dense and sparse data sets in order to find asteroid models will become more common as next-generation large surveys come on line.

The inversion of asteroid lightcurves into shape and spin axis models has been an on-going problem for many years. In the past decade or so, significant advancements have been made (see Warner 2008a and references therein). Even more recently, the use of “sparse” data sets in combination with typical “dense” lightcurves from two or more apparitions has allowed finding more models in shorter order (see Durech 2008a and references therein).

A “dense” data set is what one usually associates with an asteroid lightcurve, i.e., a large number of data points that cover one or more rotations in a given apparition. Several curves from a single apparition, especially if obtained over a wide range of phase angles, improve the quality of the final modeling solution. A “sparse” data set is a collection of data from many years where there might be only a few data points for a given apparition. If the data are calibrated to a common (internal or external) system, then

the entire set can be treated as a single relative data set, thus providing sufficient data for the inversion technique. It has been shown (Kasalainen 2004) that even sparse data sets alone can find reasonably accurate models.

It will take from 5-10 years after the surveys come on line before the sparse data sets are sufficient to allow independent modeling. Even then, dense curves will be needed to resolve “problem cases”, e.g., binary asteroids and otherwise ambiguous solutions. So there should be no fear that the “backyard astronomer” will be forced out of the asteroid lightcurve business anytime in the foreseeable future.

Data and Analysis

Dense lightcurves for 54 Alexandra, 167 Urda, 409 Aspasia, and 1022 Olympiada were obtained at PDO in late 2007 and early 2008 for the express purpose of modeling. Fauerbach and Fauvud also observed 54 Alexandra during this same period. Dense curves for the combined data sets were formed from the authors’ data and those from the Uppsala Asteroid Photometry Catalog (UAPC, Lagerkvist 2001). For the sparse data, observations by the US Naval Observatory were taken from the AstDys web site (<http://hamilton.dm.unipi.it/cgi-bin/astdys/astibo>). Durech has found these to be the most reliable magnitude data sets among the current surveys. Even so, the data must be inspected for obvious outliers and other problems. The sparse data magnitudes must also be reduced to unity Earth-asteroid and Sun-asteroid distances by applying $-5 * \log(Rr)$. This removes effects due to changing geometry but does not remove those due to phase angle. For this reason, instead of being fixed – as would be done when using only relative, dense lightcurves – the phase coefficients are allowed to float during modeling.

Once the combined sparse and dense data sets were constructed for each asteroid, they were combined into a single data set in *MPO LCInvert*, a program written by Warner that provides a Windows™ user-interface to the original FORTRAN and C code by Kasalainen and Durech. The core library code, in Delphi Pascal or the original C, is available as free downloads from

http://www.MinorPlanetObserver.com/MPOSoftware/Inversion_SourceCode.htm

The initial, and very critical step, is to find a sidereal period that fits all the data. The synodic period from a single apparition can serve to narrow the search range but that range must be

sufficiently wide to assure that the true sidereal period is found. Even on today's fast desktop computers, this can take a day or more if the data set is very large. Once the period is found, a search for pole solutions is done by looking at 30 initial poles ($\lambda = 0^\circ, 60^\circ, 120^\circ, 180^\circ, 240^\circ, 300^\circ$; $\beta = -60^\circ, -30^\circ, 0^\circ, +30^\circ, +60^\circ$). The pole solution and period are both allowed to float, i.e., they are not forced to maintain the initial values. The result is a set of period/axis solutions and chi-square values, with the most likely solution being the one with the lowest chi-square value, presuming that it is at least 10% lower than any other solution. See Warner (2008a) and Higley (2008) and references therein for a more detailed discussion about the modeling process.

PDO images were reduced and measured in MPO Canopus as was period analysis using an implementation of the Fourier analysis algorithm by Harris (1989). For each combined data set, the dense lightcurves were included twice, thus giving them higher weighting over the sparse data from USNO observations.

The data for all the models presented here will be available on the Database of Asteroid Models from Inversion Techniques (DAMIT, Durech 2008b). This site includes results and data for a growing number of asteroid models. Another catalog of asteroid models, derived from a variety of techniques, can be found on the Poznan Observatory site (Kryszczyńska et al. 2008a). See also Kryszczyńska et al. (2007).

54 Alexandra. Warner observed this asteroid from PDO in January 2008 using a 0.35-m SCT and SBIG STL-9E. The synodic period was found to be 7.028 ± 0.001 h with a lightcurve amplitude of 0.10 ± 0.01 mag. (Figure 1). In addition to the PDO data, Fauerbach observed the asteroid from 2006 December 27 to 2008 January 20. Twelve lightcurves in the UAPC, dating from 1965-1992, were also used to form the dense data set. The final results of the modeling were (preferred solution first):

Period (sidereal)	Lambda	Beta
7.0226456 ± 0.000004 h	$318 \pm 10^\circ$	$+23 \pm 5^\circ$
	$156 \pm 10^\circ$	$+13 \pm 5^\circ$

Belskaya et al (1993) reported solutions of $(160^\circ, +45^\circ)$ and $(290^\circ, +55^\circ)$. The longitude and latitude errors were chosen to include nearly similar solutions in the model search. The period error was found by estimating the error required to produce a 7.5° rotation error over the total time-span of the observations.

The shape model for the $(318^\circ, +23^\circ)$ solution is shown in Figure 2. A test of the solution is to compare the original lightcurve data with the one generated by the model, phase errors in particular. For larger asteroids not likely subject to rotational torque due to thermal radiation (YORP effect), phase errors are likely due to using the wrong sidereal period in the solution. Figure 3 shows the model's curve (black/dark) versus the original data (red/gray) from data in 1965. The agreement is very good.

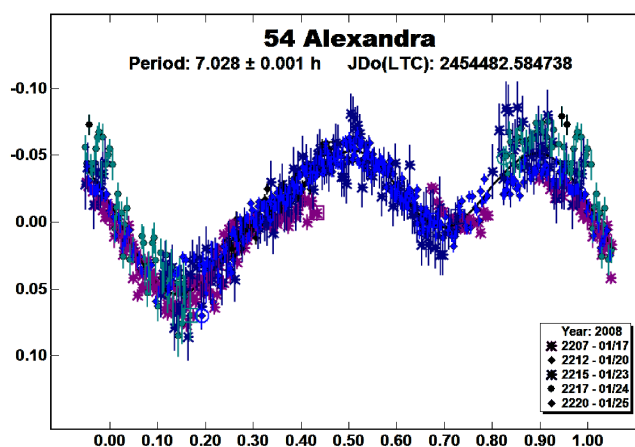


Figure 1. Lightcurve for 54 Alexandra (Warner 2008).

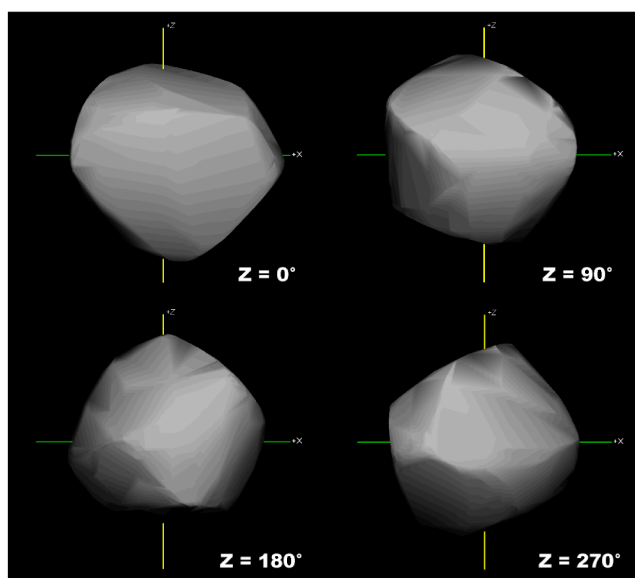


Figure 2. Equatorial view of 54 Alexandra model. The asteroid's north pole is at top. The views are at 90° rotations of the Z-axis.

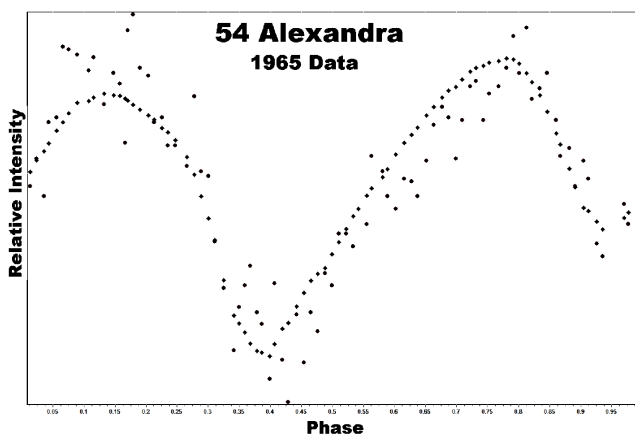


Figure 3. 54 Alexandra model curve (dark) versus 1965 data (light).

167 Urda. This asteroid was observed from PDO in November 2007. Its period and lightcurve were previously reported (Warner 2008b). Data from 16 lightcurves in the UAPC from 1989-1997 were used with the PDO data form the dense lightcurve set. USNO data again formed the sparse data set.

Period (sidereal)	Lambda	Beta
13.06133 ± 0.00002 h	$249 \pm 5^\circ$	$-68 \pm 5^\circ$
	$107 \pm 5^\circ$	$-69 \pm 5^\circ$

Slivan et al (2003) reported an average of two positions to be $(222^\circ, -71^\circ)$.

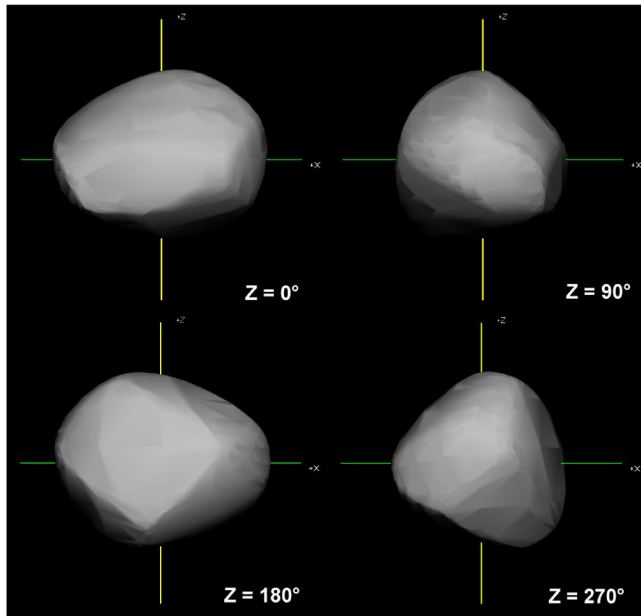


Figure 4. Equatorial view of 167 Urda model. The asteroid's north pole is at top. The views are at 90° rotations of the Z-axis.

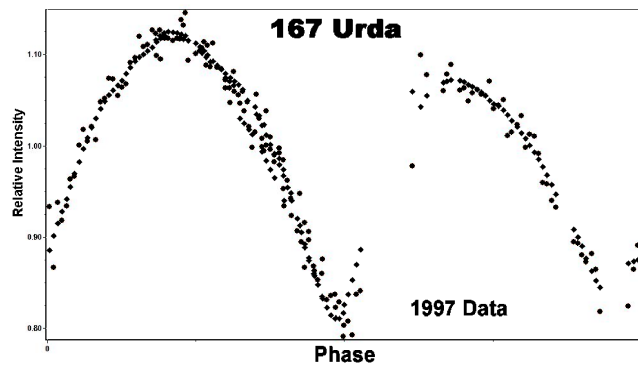


Figure 5. 167 Urda model curve (dark) versus 1997 data (light).

409 Aspasia. This asteroid was observed at PDO in December 2008 using a 0.5-m Ritchey-Chretien and SBIG STL-1001E. The synodic period was determined to be 9.022 ± 0.001 h and the lightcurve amplitude was 0.09 ± 0.01 mag (Figure 6).

Eight lightcurves from 1980-1996 from the UAPC were combined with PDO data to form the dense lightcurve data set. Sparse data was from USNO observations exclusively (Fig. 9). At first, the search by Warner found a “best” solution significantly different from one found by Durech. It was determined that the model search used by Warner was too coarse, allowing better solutions to be overlooked. After modifying the model search code, Warner's best solution (presented here) was nearly identical to that found by Durech. The modeling found two solutions, one being a mirror of the other in longitude, which is a common result when the asteroid's orbital inclination is small.

Period (sidereal)	Lambda	Beta
9.021455 ± 0.000009 h	$177 \pm 10^\circ$	$+15 \pm 5^\circ$
	$3 \pm 10^\circ$	$+30 \pm 5^\circ$

Blanco and Riccioli (1998) reported positions of $(73^\circ, +48^\circ)$ and $(216^\circ, +36^\circ)$.

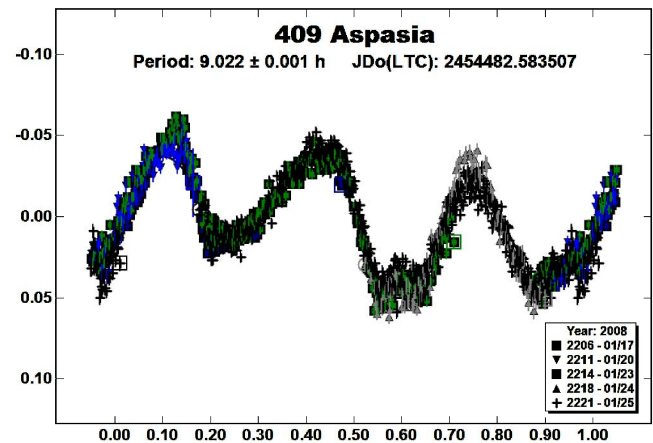


Figure 6. Lightcurve for 409 Aspasia (PDO, 2008).

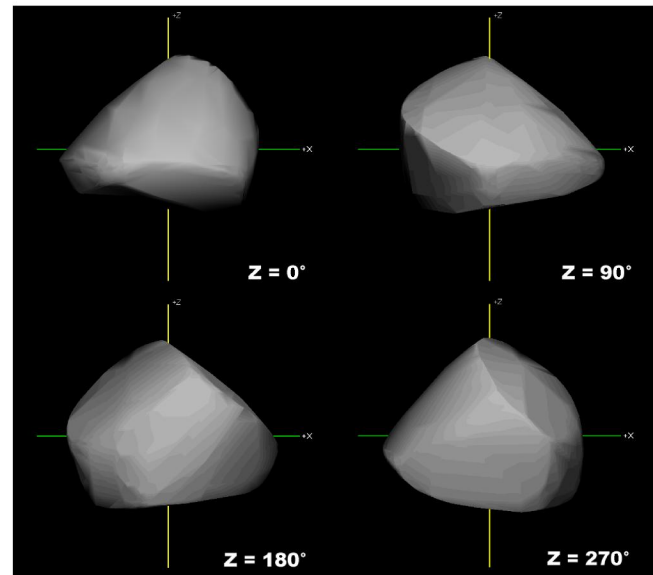


Figure 7. Equatorial view of 409 Aspasia model. The asteroid's north pole is at top. The views are at 90° rotations of the Z-axis.

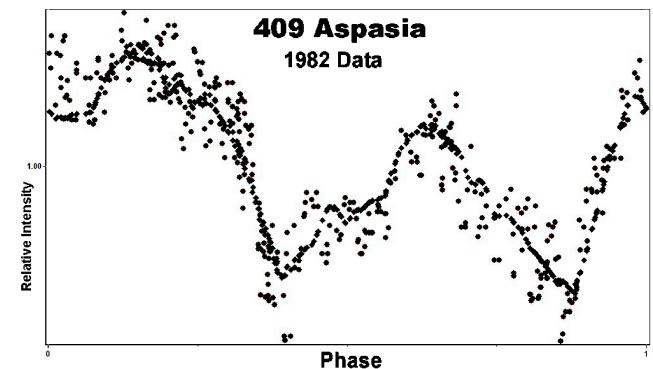


Figure 8. 409 Aspasia model curve (dark) versus 1982 data (light).

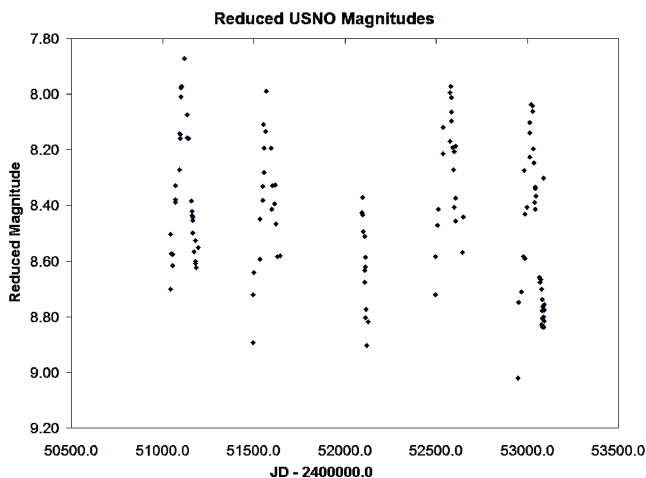


Figure 9. Data for 409 Aspasia from USNO observations. The magnitudes have been reduced to unity Earth-asteroid and Sun-asteroid distances.

1022 Olympiada. This asteroid was observed by Warner in 1999 (Warner 1999) when a period of 4.589 h was reported. That was later revised (Warner 2005) to 3.833 h after a review of the original data. The shorter period was confirmed with a more extensive data set obtained by Warner in 2008 April. Figure 10 shows a lightcurve phased to 3.822 ± 0.006 h based on the 2008 data.

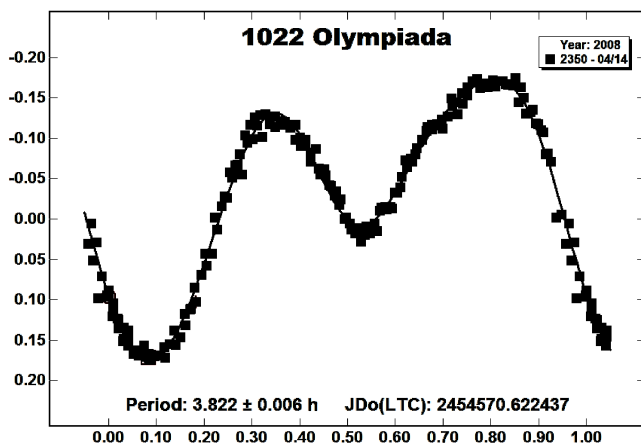


Figure 10. Lightcurve of 1022 Olympiada from PDO in 2008.

The data from the 1999 and 2008 apparitions were combined with sparse USNO data to attempt a shape and spin axis model. Having only two sets of dense lightcurves was an extreme test of the concept of using a limited number of dense curves with a sparse set. The model search found two solutions. The (40, 18) solution theoretical curves fit the actual significantly better, especially in 2008.

Period (sidereal)	Lambda	Beta
3.833594 ± 0.000005 h	$40 \pm 5^\circ$	$+18 \pm 5^\circ$
	$250 \pm 5^\circ$	$+71 \pm 5^\circ$

Neither the DAMIT or Poznan web sites list any previous models for 1022 Olympiada. Figure 11 shows the shape model for the asteroid while Figure 12 shows a fit of the model and 1999 data.

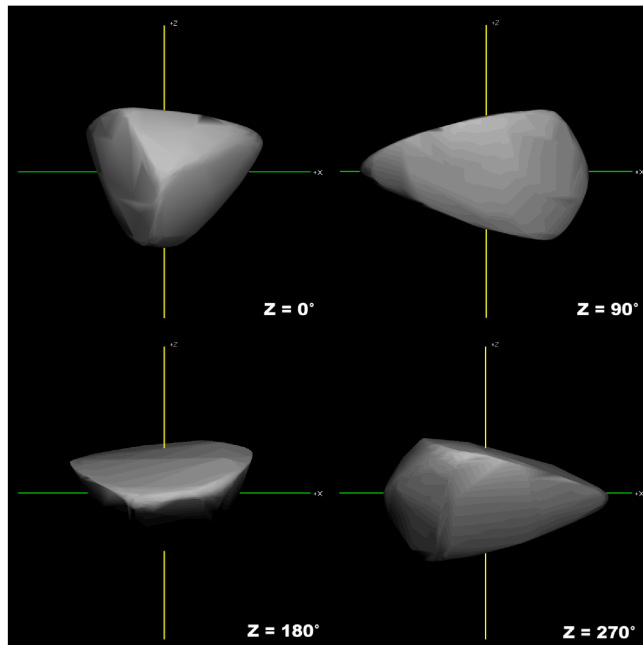


Figure 11. Equatorial view of 1022 Olympiada model. The asteroid's north pole is at top. The views are at 90° rotations of the Z-axis. Note the large “flat” area in the $Z=180^\circ$ view. This may indicate a large crater and/or concavity or it may just be an artifact of the modeling process when using sparse data with a limited number of dense lightcurves.

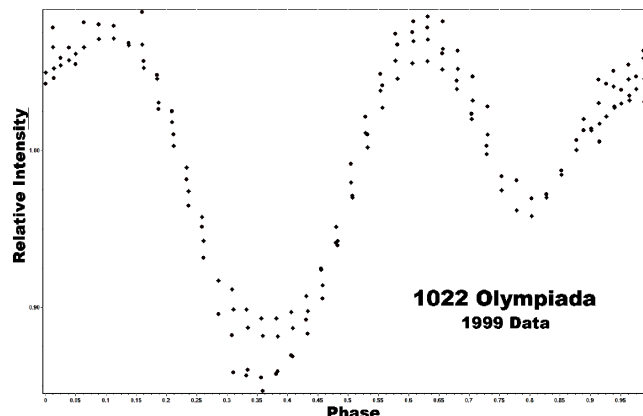


Figure 12. 1022 model curve (dark) versus 1999 data (light).

Conclusions

These four models are examples of what can be done by combining a few dense lightcurves and sparse data from already available sources. It's possible to use dense data from only two apparitions in combination with sparse data, providing the dense data is of higher quality and, preferably, covers a good range of phase angles. Warner has sets of lightcurve data for several asteroids that meet these requirements. Unfortunately, the existing surveys haven't covered any of those asteroids sufficiently to allow a model to be found. It's not often that the professional surveys are lagging behind the backyard astronomer. We hope this paper will serve as inspiration to others to start or continue their work in asteroid lightcurves, keeping in mind that not only are data needed for asteroids with unknown lightcurve parameters but that by working some asteroids just one more time may lead to a successful shape and spin axis model.

Acknowledgements

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A PRELIMINARY SHAPE AND SPIN AXIS MODEL FOR 595 POLYXENA

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Photometric observations made at the Palmer Divide Observatory during the 2006 and 2008 apparitions of the main-belt asteroid 595 Polixena were combined with dense lightcurves from 1993 included in the Uppsala Asteroid Photometric Catalog and a sparse lightcurve based on data from the USNO to determine a preliminary shape and spin axis model. Two solutions dominated the result set, one prograde ($\lambda = 42^\circ$, $\beta = 8^\circ$) and one retrograde ($\lambda = 222^\circ$, $\beta = -4^\circ$). The uncertainty in each coordinate is $\pm 5^\circ$. The sidereal period was found to be 11.794162 ± 0.000023 h.

The outer main-belt asteroid 595 Polixena was observed at the Palmer Divide in March 2008 for two reasons: to determine the correct period for the asteroid and to provide a data set for shape and spin axis modeling. A 0.35 m Meade LX-200GPS telescope was equipped with an SBIG ST-9E and Optec focal reducer to obtain 449 data points from 2008 March 19-22. The pixel scale was approximately 2.5 arcseconds/pixel. All images were 120 s, guided, and unfiltered. The images were processed with dark and flat fields and measured in *MPO Canopus*. Period analysis was also done in *Canopus*.

The period of the asteroid had been previously reported as 11.806 h (Hainaut-Rouelle 1995), 8.5 h (Piironen 1998), 15.89 h (Warner 2007), and 46.32 h (Behrend 2008). The lightcurve from the 2006 apparition by the author had an amplitude of only 0.05 mag (Fig. 1) and so could have easily lead to an ambiguous solution. After the period and amplitude were determined with much more certainty using data from the 2008 apparition ($P = 11.801 \pm 0.001$ h, $A = 0.51$ mag; Fig. 2), the 2006 data were re-examined to see if they would fit the new period. The closest match was found at $P = 12.03 \pm 0.02$ h.

In a forthcoming paper (Durech 2008), it has been shown that a few dense lightcurves (those such as shown in Figs. 1 and 2) combined with so-called “sparse” data sets can often successfully lead to a shape and spin axis model. A “sparse” data set is one comprised of calibrated observations taken over a number of years such that they sufficiently cover the asteroid around its orbit. A check on the AstDys web site (<http://hamilton.dm.unipi.it/cgi-bin/astdys/astibo>) showed that data from the USNO were available for Polixena. Durech (2008) has found that, among the current surveys, only USNO data are of sufficient quality for modeling. Fortunately, Hainaut-Rouelle’s data were also available, being in the Uppsala catalog (Lagerkvist 2001). This made for three sets of dense lightcurves and the one sparse set. *MPO LCInvert*, written by the author, was used for the analysis, the first step of which is to find an accurate sidereal period based on the complete data set. This search can take some time, e.g., more than a day for Polixena. Once the period is found, a search routine looks for the best fit among several initial conditions. The search showed seven solutions that were statistically identical and grouped around two