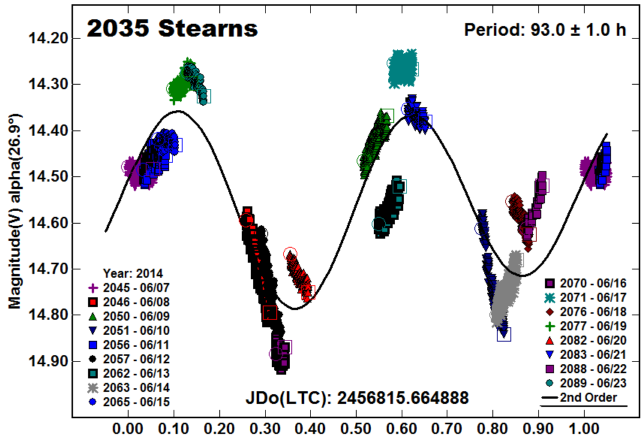

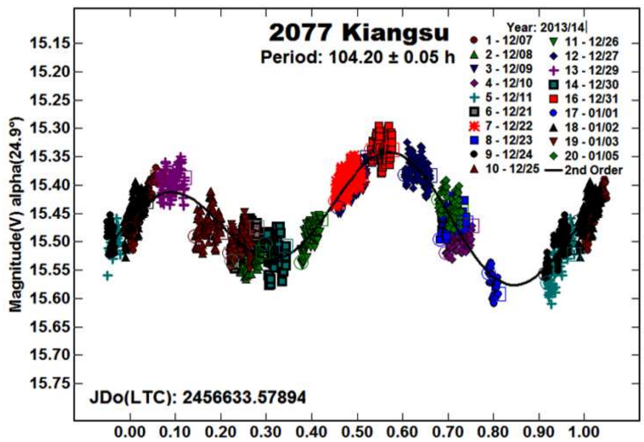

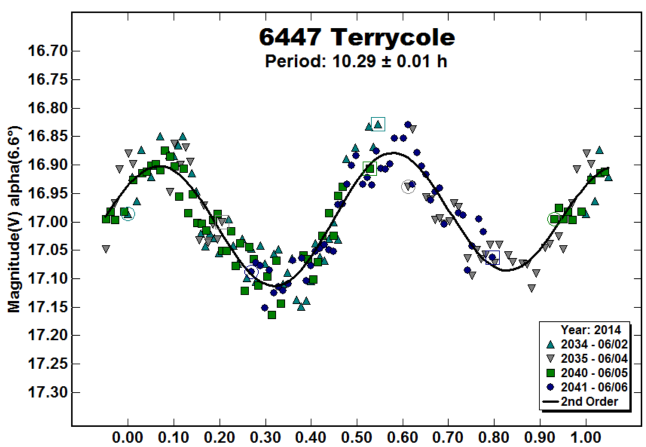

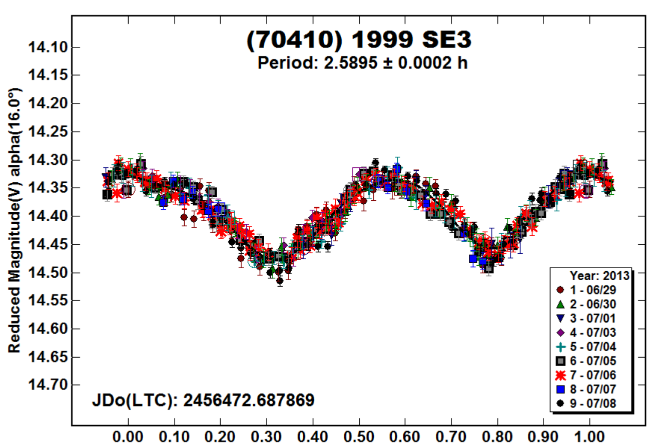

ROTATION PERIOD, SPIN AXIS, AND SHAPE MODEL FOR MAIN-BELT ASTEROID 92 UNDINA

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CCD photometry observations of 92 Undina in 2014 April found a synodic rotation period of 15.933 ± 0.002 h and lightcurve amplitude of 0.16 ± 0.01 mag. An attempt was made to model the spin axis and shape for the asteroid using a combination of dense lightcurves from three apparitions and sparse data from two survey programs. The results were inconclusive other than to indicate that the pole latitude is not far removed from the ecliptic plane and rotation is probably retrograde.

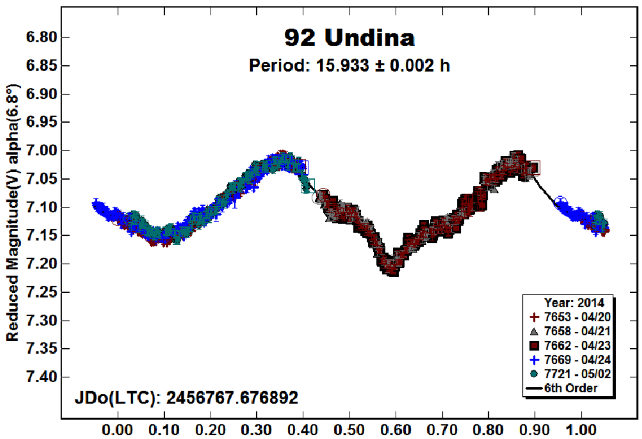
CCD photometry observations of the main-belt asteroid 92 Undina were made in 2014 April and May at the Center for Solar System Studies-Palmer Divide Station. A 0.3-m *f*/9.4 Schmidt-Cassegrain was used along with a Finger Lakes Instrumentations MicroLine-1001E operating at –30° C. The 1024x1024 array of 24-micron pixels provided a field of view of about 30x30 arcminutes and a plate scale of 1.7 arcsec/pixel. All images were guided and taken without a filter. Exposures were 60 seconds in early April and decreased to 45 seconds in late April and early May to avoid saturation. Dark frames and flat fields were applied in *MPO Canopus*.

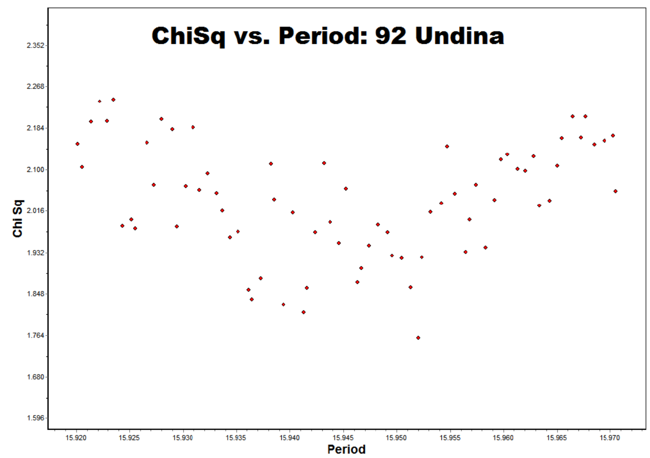
Measurements were done using *MPO Canopus,* which was used to produce and apply the master dark and flat-field frames. The Comp Star Selector utility in *MPO Canopus* found up to five comparison stars of near solar-color to be used in differential photometry. Catalog magnitudes were taken from the APASS catalog (Henden *et al.,* 2009) since these are derived directly from reductions based on Landolt standard fields. Period analysis was also done using *MPO Canopus*, which implements the FALC algorithm developed by Harris (Harris *et al.,* 1989).

In the lightcurve plots below, the "Reduced Magnitude" is Johnson V as indicated in the Y-axis title. These are values that have been converted from sky magnitudes to unity distance by applying –5*log (rΔ) 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. The horizontal axis is the rotational phase, ranging from –0.05 to 1.05.

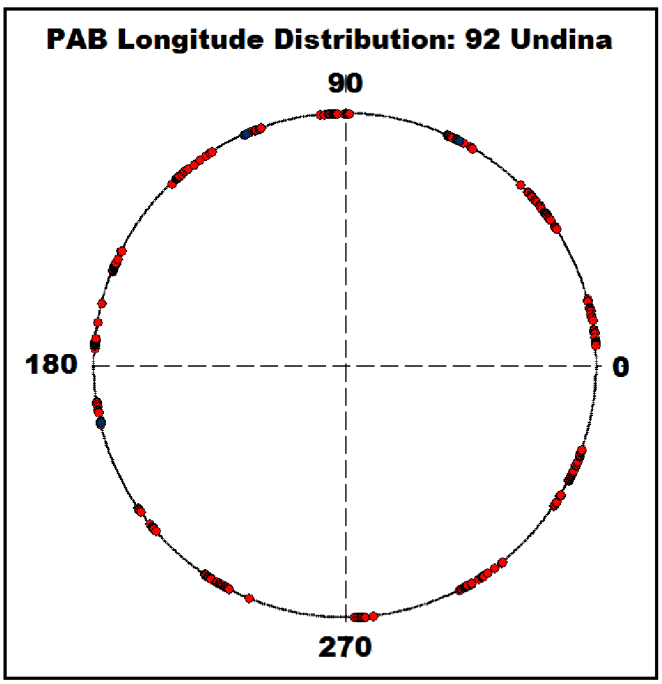
Synodic Rotation Period (2014)

This was the third apparition at which this asteroid was worked by the author (Warner, 2007; 2012). The most recent period of *P* = 15.933 h is in good agreement with the earlier results as well as those from Schrober *et al.* (1979).





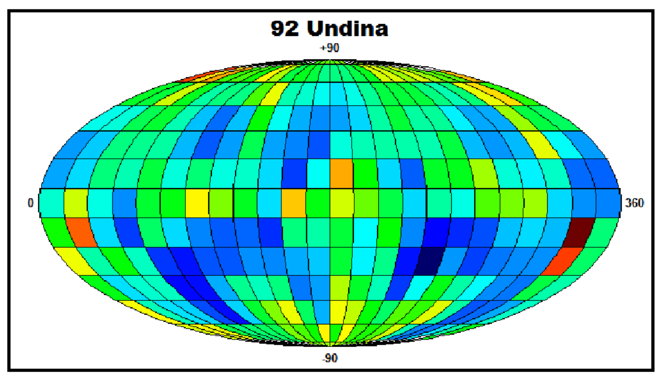
An earlier attempt to model the asteroid's spin axis (Warner, unpublished) found $P_{SIDEREAL}$ = 15.93612 h with a pole of (4°, 50°) or (190°, 73°) ecliptic coordinates. The addition of a third apparition, each with a different phase angle bisector longitude (see Harris *et al.*, 1984) from the others, prompted a new search that included sparse data from USNO-Flagstaff and the Catalina Sky Survey. The first figure below shows the distribution with red data points representing sparse data and blue points representing the dense lightcurves. The view is from the north ecliptic pole.



Generally, a search for the synodic period should cover at least ± 5% of the average synodic period *if all the lightcurves are rated U = 3 under the LCDB system* (see Warner *et al.*, 2009 and updated documentation on-line for the U rating system). Introducing lesser quality data, or when the synodic periods are significantly different, requires expanding the search range. With a large number of data points, this can result in a search that takes several *days* on a single PC. In this case, all the results covered a relatively small range and the data were of higher quality. To save time, the period search was limited to the range of 15.87-16.00 hours, or about centered on a 15.94 h average. Even so, the search required almost 24 hours of uninterrupted computing time.

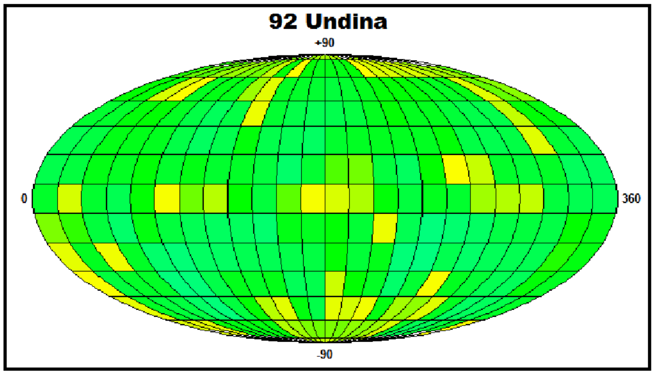
The plot showing the χ^2 value versus the period shows that the search did find a minimum, but it is poorly defined. The most likely cause is the generally low amplitude of the asteroid lightcurve and the noise in the sparse data at half (or more) the amplitude level. There was one period with a noticeably lower χ^2 value at 15.95198047 h. Generally, modeling will be more successful if the *second lowest* χ^2 value is at least 1.1x the lowest value. In this search, more than a dozen periods had χ^2 that met the *10-per cent rule*. Despite the less than ideal results, it was decided to continue with modeling by searching for the lowest χ^2 value among 312 discrete, fixed pole positions, but allowing the period to float.

In the two pole search plots below, scaling goes from dark blue for lowest χ^2 to red for higher values, the highest value being dark red.



The first plot uses a *relative scale*, i.e., the colors are scaled to fit the actual range of the χ^2 results. The scaling is based on log(χ^2), which compresses the colors at the extremes and spreads them out in the mid-range values. Ideally, the hope is for a small "island of blue" in the middle of a sea of greens to reds. This was not the case here. Instead, there are two blue regions south of the ecliptic, indicating retrograde rotation, and some smaller groups of bluish areas north. From this, and a review of the χ^2 values, it seems likely that the asteroid is in retrograde rotation and that the spin axis favors the ecliptic plane more than the pole.

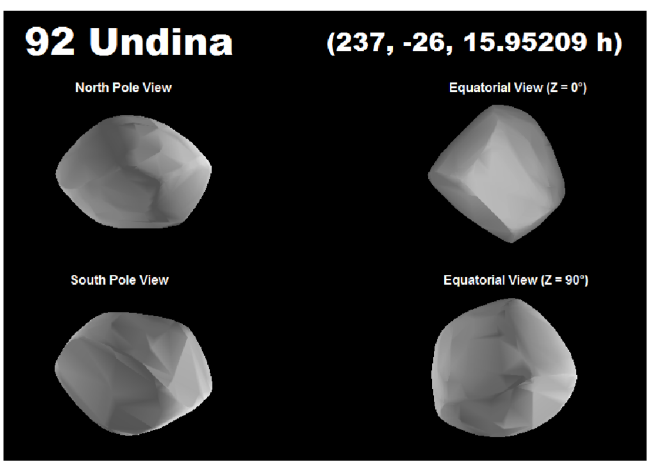
It should be noted that the lightcurve inversion process often results in at least two solutions, usually differing by 180° in longitude. Sometimes the longitudes are about the same but the latitudes are mirrored on either side of the ecliptic equator. A third possibility is a *double-mirroring*, where the longitudes *and* latitudes are reflected, thus creating four possible solutions.



A secondary check of the pole solution is on an *absolute scale*, where the colors range from blue to red using a fixed scale $0 < \chi^2 < 5$; all solutions $\chi^2 \geq 5$ are red. The choice of an upper cutoff of 5 is mostly arbitrary, based on experience when modeling with and without sparse data. The hope is still to see a small island of bluish colors on a sea of other colors well towards red. In the plot for 92 Undina, the plot shows little variation, an indication that the pole solution is not particularly strong.

With the results so far, the search for a shape model proceeded knowing that whatever came out would be, at best, a good guess. All the χ^2 values following the *10-per cent rule*, with two exceptions, had negative latitudes (retrograde rotation) and were generally grouped around 240° (lowest χ^2) and 60° longitude. Follow up searches that allowed the longitude, latitude, and period to float were centered on (240°, –30°) and (60°, –45°) ecliptic longitude and latitude. The initial period was the one found for the selected discrete pole.

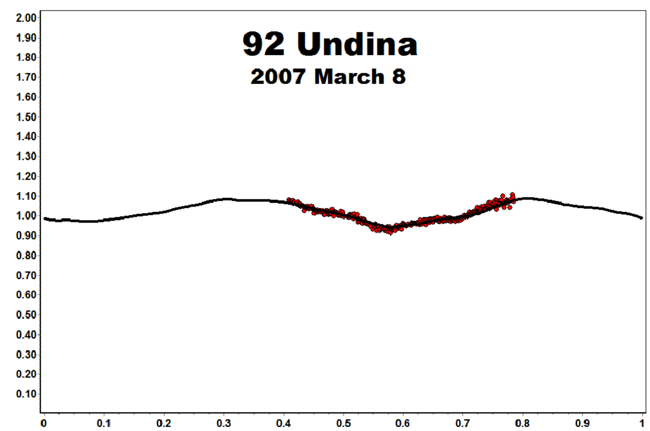
The final results were (237°, –26°, 15.95209 h) and (69°, –45, 15.95196 h). The first one is adopted for this work on the basis that it produced a more likely shape, but one that is still probably wrong.

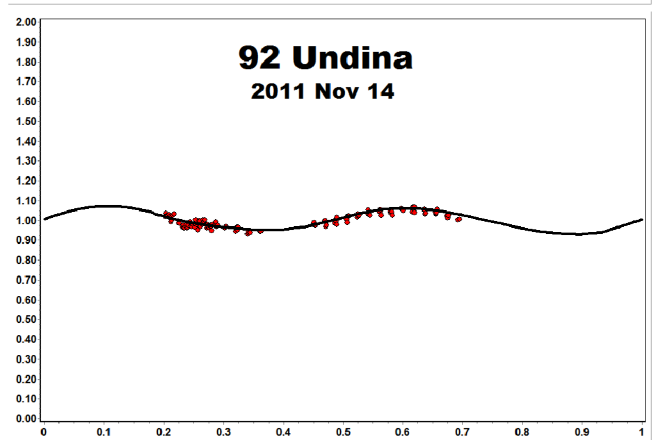


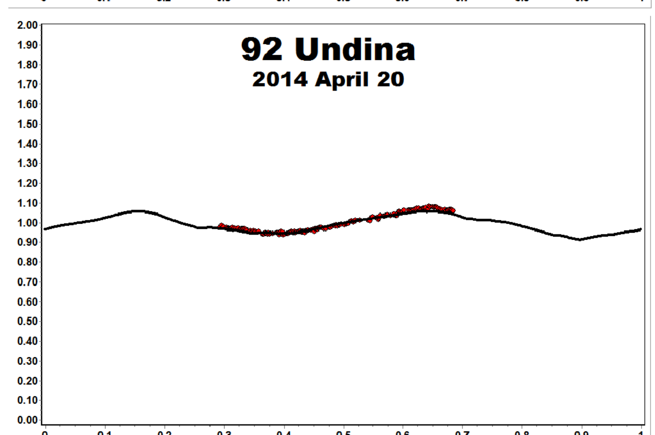
On the left are views of the asteroid model for the adopted solution from its north and south poles. The upper-right shows an equatorial view at 0° rotation. At lower right is an equatorial view at +90° rotation. The axis ratios are: a/b: 0.954, a/c: 0.880, and b/c: 0.923. Either a/c or b/c should be > 1.0. For the second candidate (69°, –45°, 15.95196 h), the ratios were even smaller.

Assuming the estimated size of the asteroid is correct, the adopted solution fits reasonably well with a pole found by Shepard *et al.* (2014) that indicated the subradar observations in 2011 were at a latitude of 45 ± 10°. The solution here would give about 54°.

Naturally, the model lightcurve for a given date should match data obtained on that date. This is another check of the results. Despite the abnormal shape, the model lightcurves matched the data very well at the three apparitions.







Conclusions

The spin axis and shape models presented here are a good start, but not definitive. Given the generally low amplitude of the asteroid, it may not be possible to do much better, i.e., the inversion process relies on the lightcurves from different viewing aspects and phase angles to have sufficient differences to build an unambiguous model.

One problem, the initial one, was that the sidereal period could not be well-defined. Slivan (2012, 2013) discussed the issues involved in finding a unique sidereal period using an analytical approach. Anyone attempting modeling should keep these two papers at hand. As mentioned before, sparse data are of best use when the noise (scatter) is not a significant fraction of the asteroid's lightcurve amplitude (see, e.g., Durech *et al.*, 2011; Hanus and Durech, 2012).

Acknowledgements

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ROTATION PERIOD OF 227 PHILOSOPHIA IS RE-EVALUATED

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We previously published a rotation period of 52.98 hours for 227 Philosophia (Pilcher and Alkema, 2014, *Minor Planet Bulletin* **41**, 188). By adjusting instrumental magnitudes of the observations reported there by 0.03 or less, we obtain equally good fits to 26.476 hours with a monomodal lightcurve and 52.955 hours with a bimodal lightcurve, amplitude 0.12 magnitudes. We prefer the shorter period because the two sides of the longer period lightcurve are nearly identical.

Earlier period determinations for 227 Philosophia are by Bembrick et al. (2006), 18.048 hours; Behrend (2006), 26.138 hours; Alkema (2013), 17.181 hours. In a lightcurve far more dense than any previously obtained, we (Pilcher and Alkema, 2014) reported a rotation period of 52.98 hours, with a slightly asymmetric bimodal lightcurve. By adjusting the instrumental magnitudes of the observations reported in this reference by 0.03 or less, we find equally good fits to 26.476 hours with a monomodal lightcurve (Figure 1) and 52.955 hours with a very symmetric bimodal lightcurve (Figure 2). A symmetric bimodal lightcurve can be produced only by an object whose shape is highly symmetric over a 180 degree rotation. This is unlikely for a real asteroid. We therefore prefer the 26.476 hour period, although the longer period cannot be ruled out. The formal error of ± 0.001 hours is unrealistic. We believe the real error is probably near ± 0.01 hours, or even larger.

The data obtained by Alkema (2013) provided a good fit to a nearly symmetric bimodal lightcurve of period 53.12 hours, although with incomplete phase coverage, and published by Pilcher and Alkema (2014). Following an instrumental magnitude adjustment, we are able to provide a good fit of these data to a monomodal lightcurve with period 26.560 hours (Figure 3), compatible with the 26.476 hours found in the more dense lightcurve.

<u>Future work.</u> It often occurs that an asteroid with a monomodal lightcurve at some oppositions has a bimodal lightcurve at a subsequent opposition at a different celestial longitude. We recommend that 227 Philosophia be observed at a future opposition. We can be fully confident that the period is near either 26.5 hours or 53 hours. The observer at the future opposition needs only to look for possible bimodal behavior in a 26.5 hour lightcurve. Its presence will definitively resolve the ambiguity in the current period determination, but if the bimodal behavior at 26.5 hours is absent, the period will still be ambiguous. Dates and declinations of future maximum elongations from the Sun are: 2015 Apr. 30, -28 degrees, southern hemisphere observers please