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LIGHTCURVE ANALYSIS OF HILDA ASTEROIDS AT THE CENTER FOR SOLAR SYSTEM STUDIES: 2017 OCTOBER-DECEMBER

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Lightcurves for 12 Hilda asteroids were obtained at the Center for Solar System Studies (CS3) from 2017 October-December. Preliminary shape and spin axis models are given for seven of the Hildas: 958 Asplinda, 1439 Vogita, 1539 Oterma, 2483 Guinevere, 3561 Devine, 4317 Garibaldi, and 17428 Charleroi. These will serve as good starting points for future modeling.

CCD photometric observations of 12 Hilda asteroids were made at the Center for Solar System Studies (CS3) from 2017 October-December. This is another installment of an on-going series of papers on this group of asteroids, which is located between the outer main-belt and Jupiter Trojans in a 3:2 orbital resonance with Jupiter. The goal is to determine the spin rate statistics of the

group and find pole and shape models when possible. We also we look to examine the degree of influence that the YORP (Yarkovsky–O’Keefe–Radzievskii–Paddack) effect (Rubincam, 2000) has on distant objects and to compare the spin rate distribution against the Jupiter Trojans, which can provide evidence that the Hildas are more “comet-like” than main-belt asteroids.

Table I lists the telescopes and CCD cameras that are combined to make observations. Up to nine telescopes can be used for the campaign, although seven is more common. All the cameras use CCD chips from the KAF blue-enhanced family and so have essentially the same response. The pixel scales ranged from 1.24-1.60 arcsec/pixel. All lightcurve observations were unfiltered since a clear filter can result in a 0.1-0.3 magnitude loss. The exposures varied depending on the asteroid’s brightness and sky motion.

Telescopes	Cameras
0.30-m f/6.3 Schmidt-Cass	FLI Microline 1001E
0.35-m f/9.1 Schmidt-Cass	FLI Proline 1001E
0.35-m f/11 Schmidt-Cass	SBIG STL-1001E
0.40-m f/10 Schmidt-Cass	
0.50-m f/8.1 Ritchey-Chrétien	

Table I. List of available telescopes and CCD cameras at CS3. The exact combination for each telescope/camera pair can vary due to maintenance or specific needs.

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. Catalog magnitudes were usually taken from the APASS (Henden et al., 2009) or CMC-15 (<http://svo2.cab.inta-csic.es/vocats/cmcl5/>) catalogs. The MPOSC3 catalog was used as a last resort. This catalog is based on the 2MASS catalog (<http://www.ipac.caltech.edu/2mass>) with magnitudes converted from J-K to BVRI (Warner, 2007).

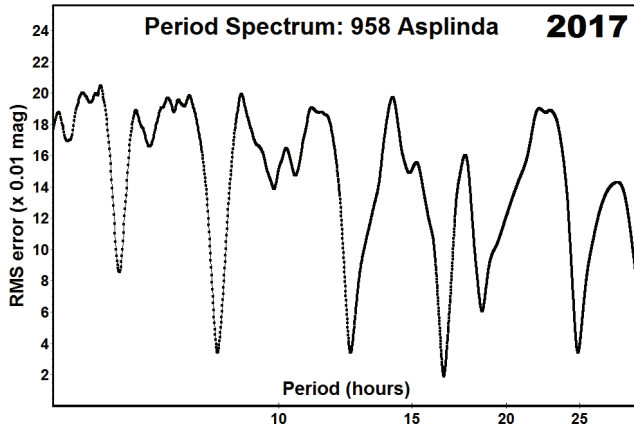
The nightly zero points for the catalogs are generally consistent to about ± 0.05 mag or better, but occasionally reach > 0.1 mag. There is a systematic offset among the catalogs so, whenever possible, the same catalog is used for all observations of a given asteroid. Period analysis is done with *MPO Canopus*, which implements the FALC algorithm by Harris (Harris et al., 1989).

In the 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 $-5 \cdot \log(r\Delta)$ 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 given phase angle, e.g., $\alpha(6.5^\circ)$, using $G = 0.15$, unless otherwise stated. The X-axis is the rotational phase ranging from -0.05 to 1.05 .

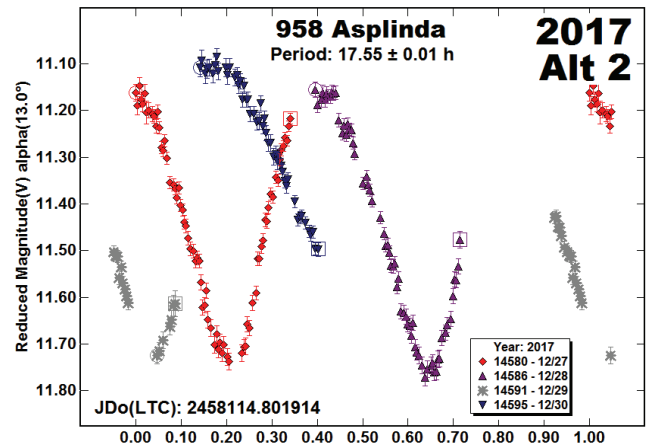
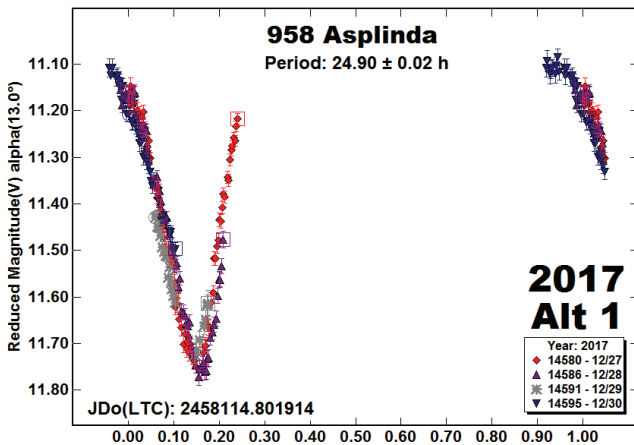
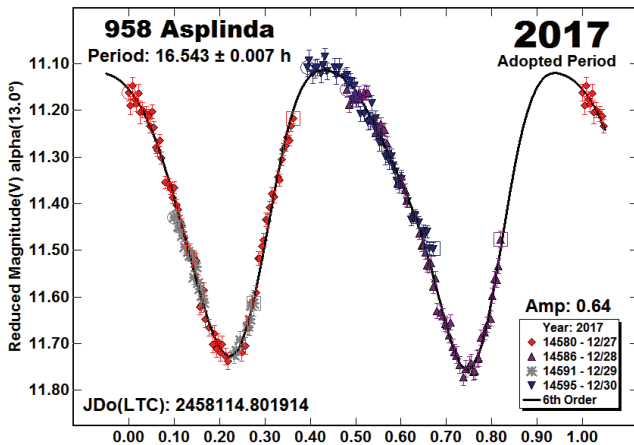
If the plot includes an amplitude, e.g., “Amp: 0.65”, this is the amplitude of the Fourier model curve and *not necessarily the adopted amplitude for the lightcurve*.

For the sake of brevity, only some of the previously reported results may be referenced in the discussions on specific asteroids. For a more complete listing, the reader is directed to the asteroid lightcurve database (LCDB; Warner et al., 2009). The on-line version at <http://www.minorplanet.info/lightcurvedatabase.html> allows direct queries that can be filtered a number of ways and the results saved to a text file. A set of text files of the main LCDB tables, including the references with bibcodes, is also available for download. Readers are strongly encouraged to obtain, when possible, the original references listed in the LCDB for their work.

958 *Asplinda*. Dahlgren et al. (1998) reported a period of 25.3 h and amplitude of 0.57 mag for this 47-km Hilda. Hanus et al. (2013) modeled the asteroid using available dense and sparse data to find a sidereal period of 25.3050 h. Warner et al. (2017b) found a synodic period of 17.55 h and amplitude of 0.18 mag. The asteroid was observed again at CS3 to see if a definitive period could be found.

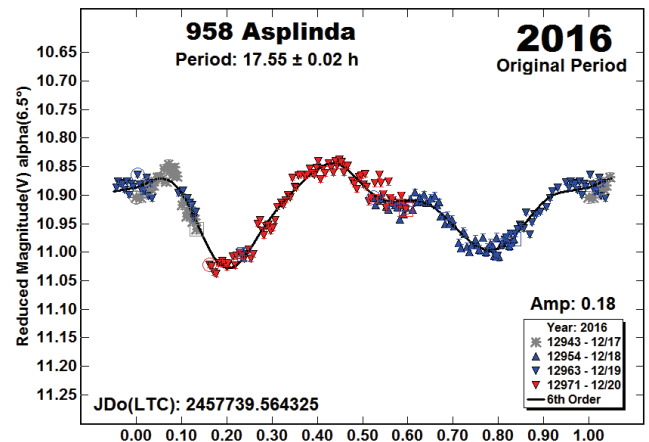
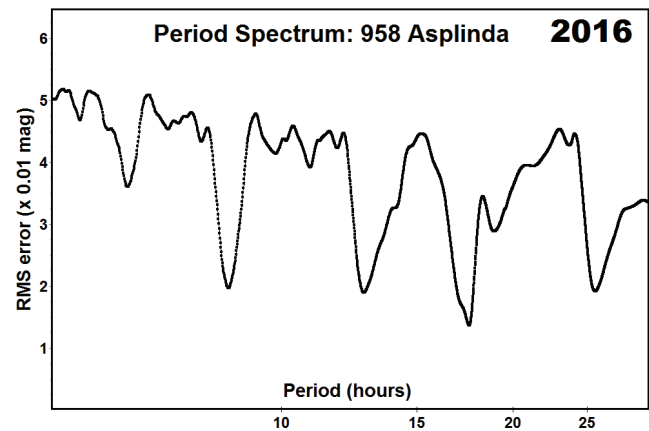


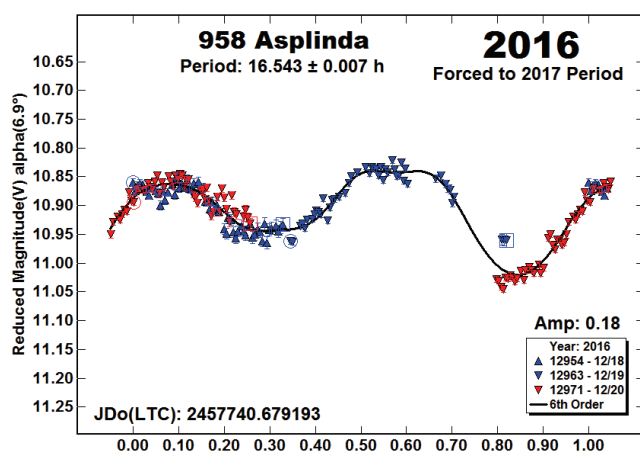
As the period spectrum shows, the 2017 data did not immediately lead to a unique solution. However, they did eliminate the 17.5 hour solution as seen in the “2017 Alt2” plot. A solution near 25 h was possible but, when the data were forced to fit between 25-26 h (“2017 Alt1”), the slopes of the phased lightcurve were unreasonably steep, looking more like they were part of a trimodal solution. Given the amplitude and low phase angle, this was not realistic (Harris et al., 2014).



On the presumption that the period was about 16.5 h, the original data from 2016, obtained by Coley at CS3, were re-examined to see if they could be fit to the shorter period. The period spectrum, when using the original zero points, still favored 17.5 h. However, with only very minor zero point shifts (< 0.03 mag), the data could be fit to the 2017 period. The two caveats were that the session from 2016 Dec 17 was dropped because it didn't fit the shorter period and the data covered the entire lightcurve with the original period but did not with the shorter period.

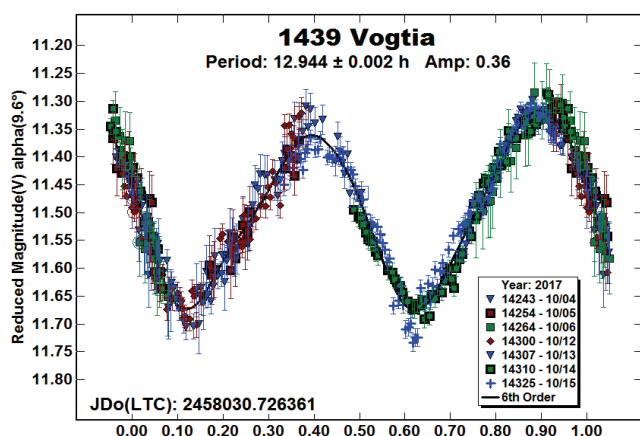
We modeled the shape and spin axis using our two dense data sets (including the 2016 Dec 17 session) and sparse data from the Catalina Sky Survey (CSS) after first doing period searches covering 16-18 h and 25.2-25.5 h. The 16.5 h solution provided a significantly lower χ^2 value.





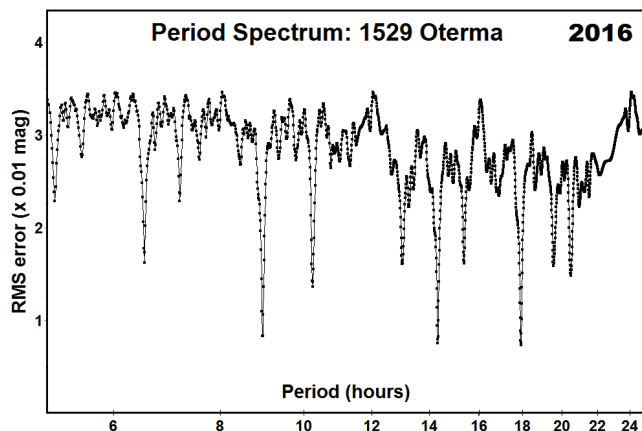
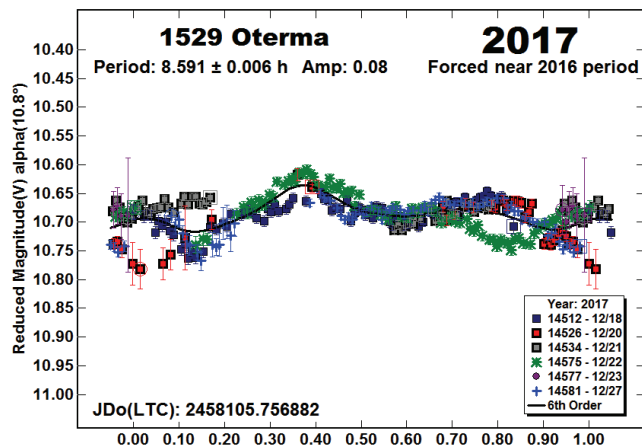
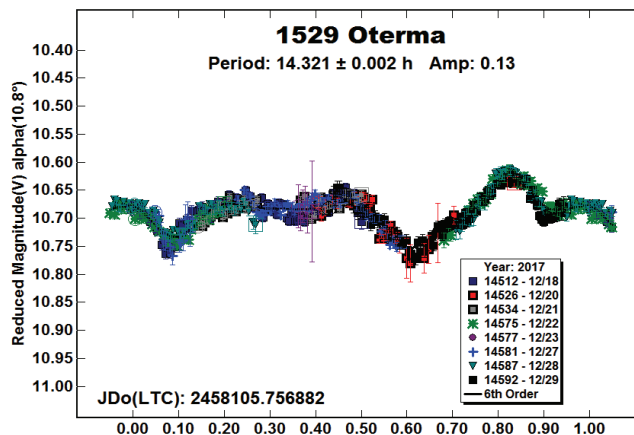
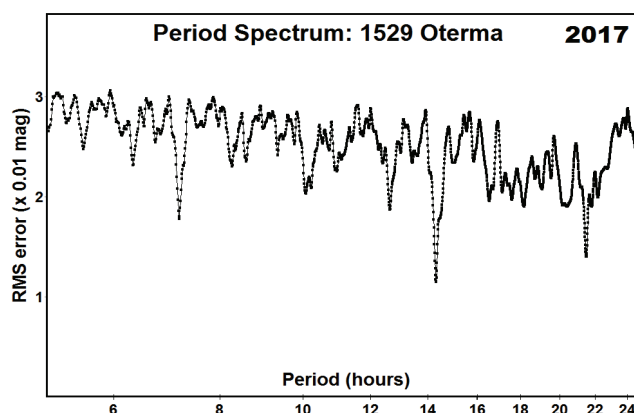
1439 Vogtia. Dahlgren et al. (1998) found a period of 12.95 h, a solution reasonably matched by Warner et al. (2017b) and the one found with our most recent data. In the three cases, the asteroid lightcurve amplitude ranged from 0.33-0.36 mag even though the phase angle bisector was significantly different at two of the apparitions. This implied that the asteroid was elongated and that its pole was nearer to an ecliptic pole than the ecliptic equator.

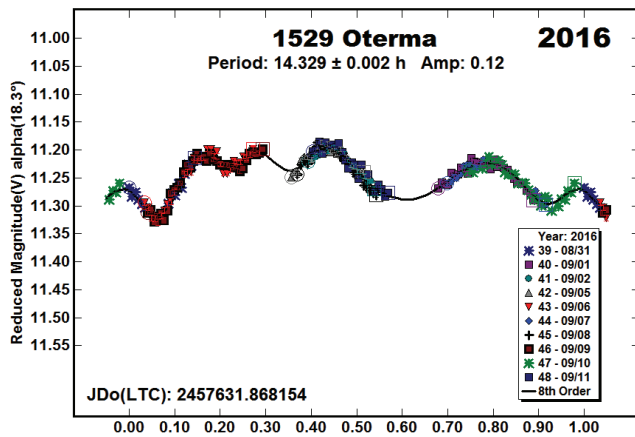
We modeled the asteroid using sparse data from USNO-Flagstaff and CSS as well as our two dense data sets from 2016 and 2017. The period search found a well-constrained solution. However, the pole latitude was near the ecliptic north pole. In such cases, there can be considerable ambiguity in the pole longitude. We found two possible poles where the longitude errors were $\pm 20^\circ$. The latitude errors were smaller, $\pm 10^\circ$ to 15° .



1529 Oterma. This 54-km Hilda was another case of diverging solutions. Dahlgren et al. (1998) found a period of 15.75 h while Warner et al. (2017b) found 8.956 h. The amplitudes were less than 0.2 mag, leaving the possibility that a bimodal lightcurve should not be assumed.

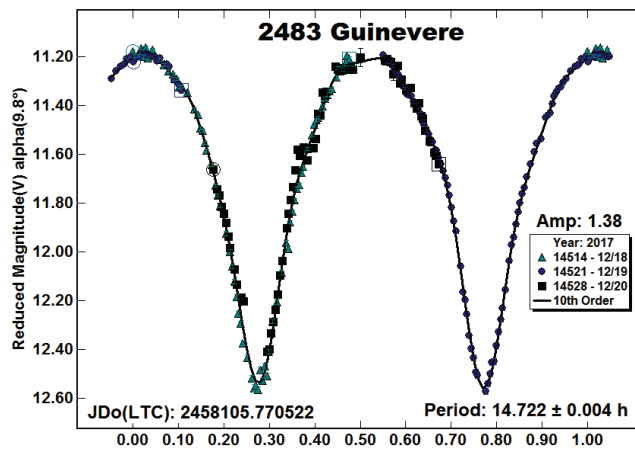
Ditton et al. (2018) found a convincing solution at a third period: 14.298 h. This prompted a second look using the 2016 data CS3 data as well as the more recent observations. We found that the 2017 data provided a good fit to a period almost identical to Ditton et al. (2018). The 2016 solution was not so straightforward. The period spectrum showed several possibilities, with two being the original solution of 8.96 h and the new period of 14.32 h.





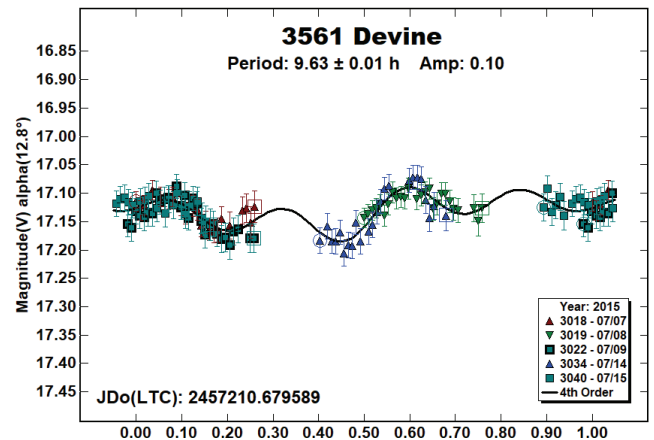
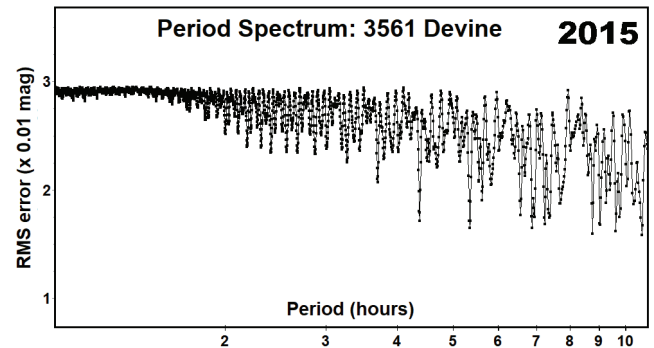
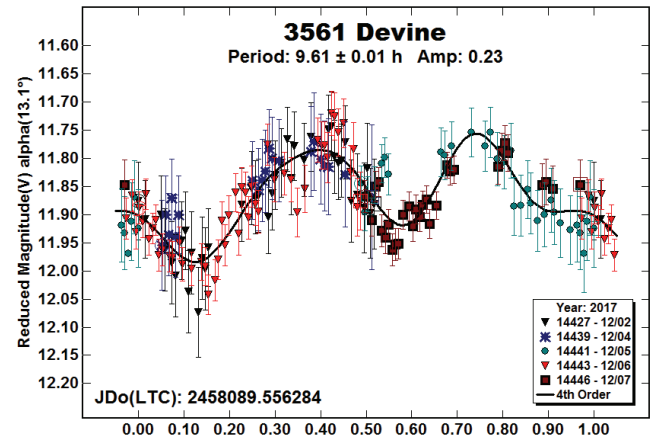
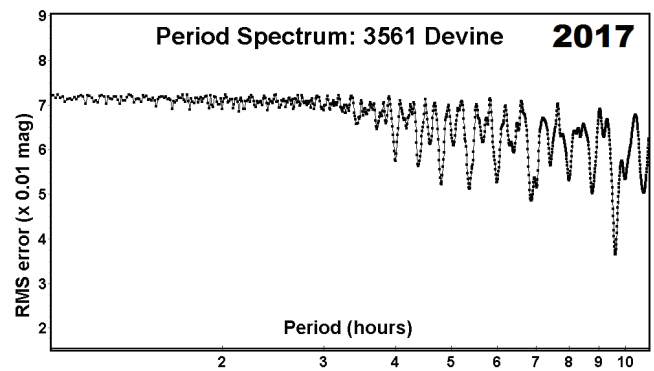
The fit the data to the longer period produces a multimodal lightcurve, which is not unreasonable given the low amplitude and phase angle (Harris et al., 2014). We modeled the asteroid after doing two searches about periods of 8.96 h and 14.32 h, eliminating the likelihood of the period found by Dahlgren et al. (1998). The period solution was weak but it still led to a strong, single pole solution with a negative latitude.

2483 Guinevere. Dahlgren et al. (1998) found $P = 14.733$ h. Durech et al. (2016) modeled the asteroid, finding a sidereal period of 14.73081 h. Our previous result (Warner et al., 2017b) and the one derived from the 2017 data are in good agreement. We used our two dense data sets along with sparse data from CSS to find a model. As shown in Table III, our single pole solution closely matches the longitude of the preferred pole found by Durech et al. (2016). However, our pole has a significantly lower latitude. Even so, ours and the Durech et al. (2016) poles indicate prograde rotation.



3561 Devine. Dahlgren et al. (1998) reported only that the amplitude of the lightcurve was > 0.04 mag. Stephens (2016) found an ambiguous solution that favored 4.376 h but one of 5.354 h could not be excluded. The amplitude was only 0.08 mag during his 2015 July observations. It's worth noting that the two periods differ by one rotation over 24 hours.

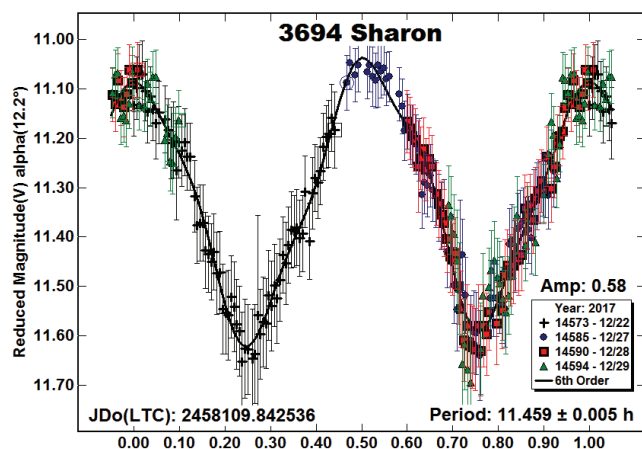
The 2017 data, while somewhat noisy, produced a lightcurve with an amplitude of 0.23 mag and, from the period spectrum, a unique period of 9.61 h. Stephens' 2015 data were re-examined and found to fit a period of 9.63 h, although the shape is multimodal and there are gaps. The revised 2015 period spectrum shows again that several solutions are possible.



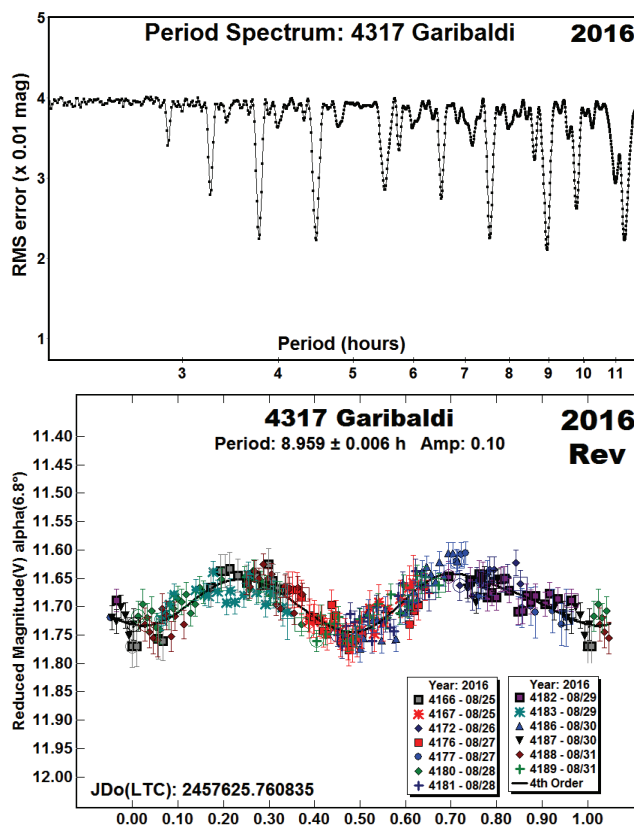
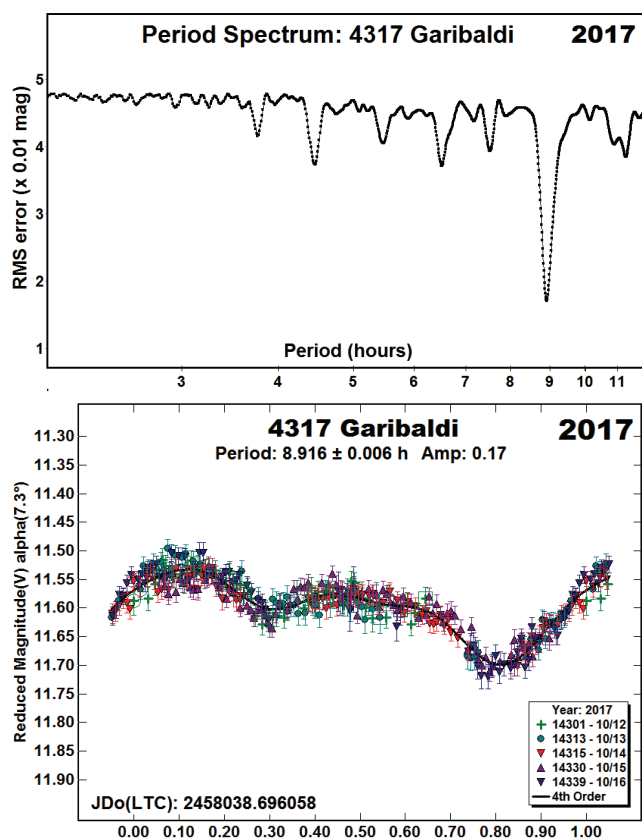
Because of the ambiguities, we modeled the asteroid after doing period searches about 4.4 h and 9.6 h. The lowest χ^2 for a 9.6 period was nearly half of the one for 4.4 h and so we have adopted a synodic period of 9.61 h for the asteroid. The pole search plot found two longitude that differed by about 180° . This is a common

artifact of lightcurve inversion when dealing with objects that have low orbital inclinations. The poles have an error of about $\pm 20^\circ$.

3694 Sharon. Dahlgren et al. (1998) found a period of 11.478 h for this 45-km Hilda. Our result of 11.459 h is in good agreement. There were insufficient dense data to try modeling the asteroid.



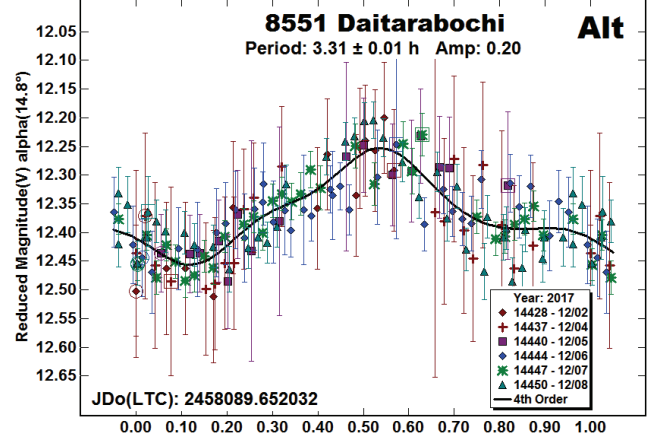
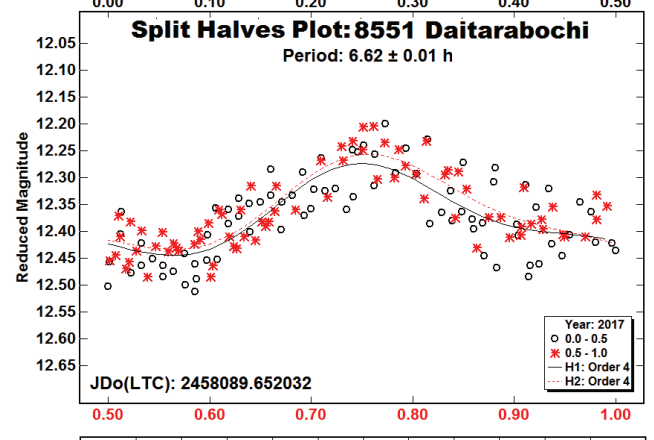
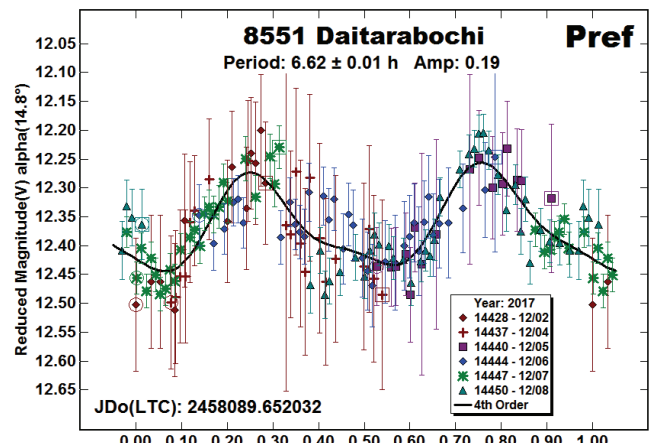
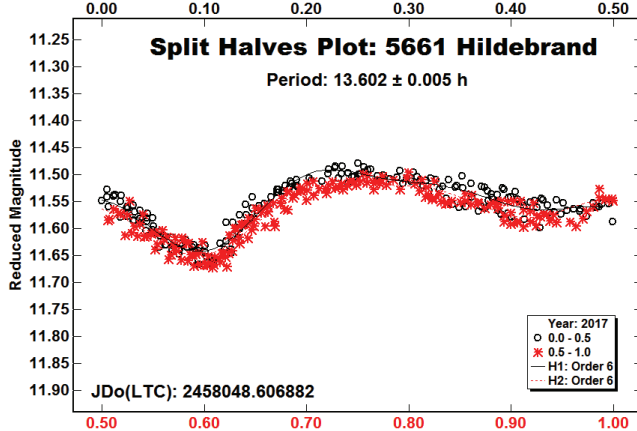
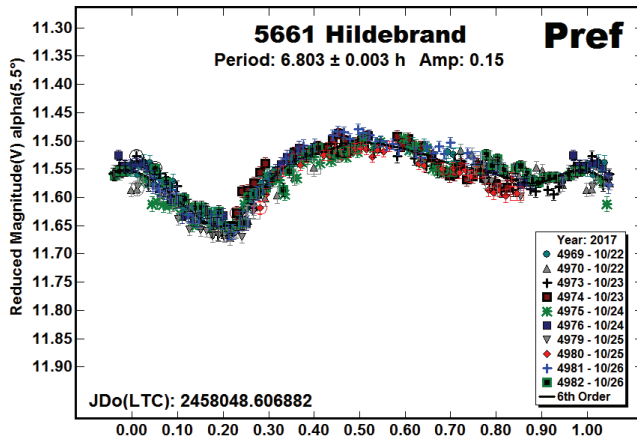
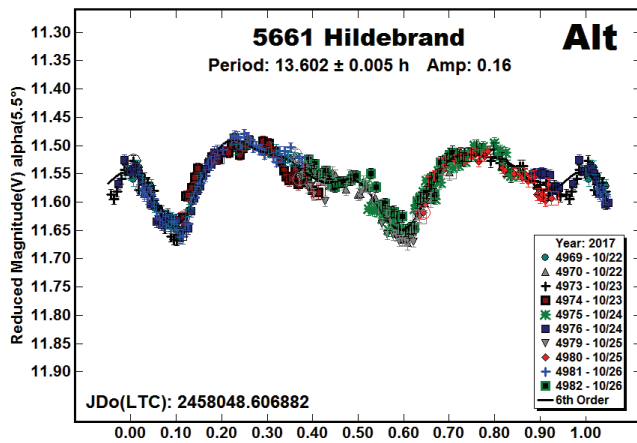
4317 Garibaldi. Dahlgren et al. (1998) reported $P = 28.5$ h, but it is rated $U = 1$ ("probably wrong") in the LCDB. The data from the 2017 campaign led to a period of 8.917 h, which differed from our previous result of 7.539 h from 2016 (Warner et al., 2017a). The data from both apparitions were checked to see if they would fit the opposing period. The result was that the 2016 data could be fit to the longer period but the 2017 data could not be fit to the shorter period.



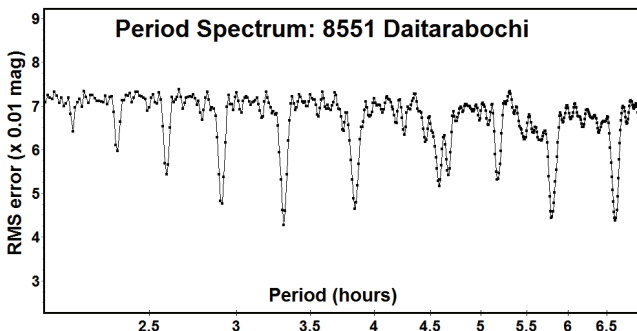
We used the 8.959 h period as the basis for modeling the asteroid. As the pole search plot shows, neither the longitude nor latitude was reliably found. During the 2018-19 apparition, Garibaldi will have a phase angle bisector longitude about 65° from the one in 2016. It's hoped that the addition of a good dense lightcurve set at that time will allow a more constrained pole solution.

5661 Hildebrand. Dahlgren et al. (1998) found a period of 13.61 h. Our 2017 data led to two possible periods, one very similar to that from Dahlgren et al. (1998). That longer period produced a lightcurve that was highly symmetric about the two halves, as seen in the split-halves plot where the second half the lightcurve is superimposed on top of the first half. This technique from Harris et al. (2014) is useful when determining if a half-period solution is possible, as demonstrated by the two halves being nearly identical. In this case, the split-halves plot was essentially the same as the lightcurve for the shorter period.

The Dahlgren et al. (1998) data set was fairly sparse and broken into two consecutive night blocks separated by almost two weeks. This makes it possible (probable) that their solution is the result of a *rotational alias*, i.e., a miscount of the number of rotations over the range of the data. Based on this and the split-halves plot, we have adopted a period of 6.803 h for this work but recognize that the double period cannot be formally excluded.

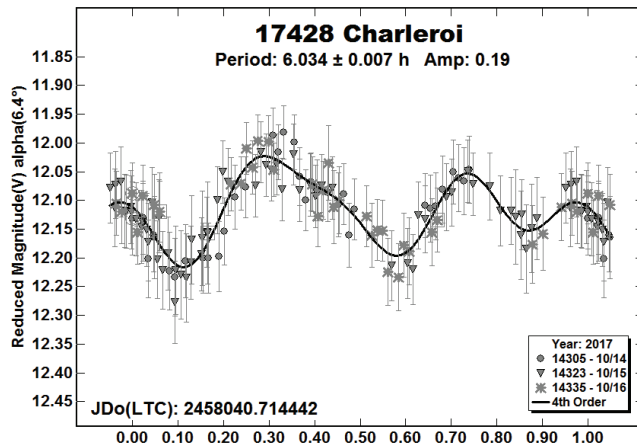


8551 Daitarabochi. This appears to be the first reported period for this 34-km Hilda. The period spectrum shows that the two more likely periods are 6.62 h or the half-period of 3.31 h.

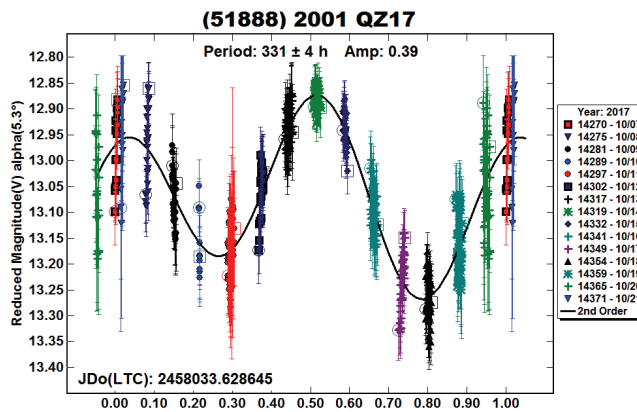
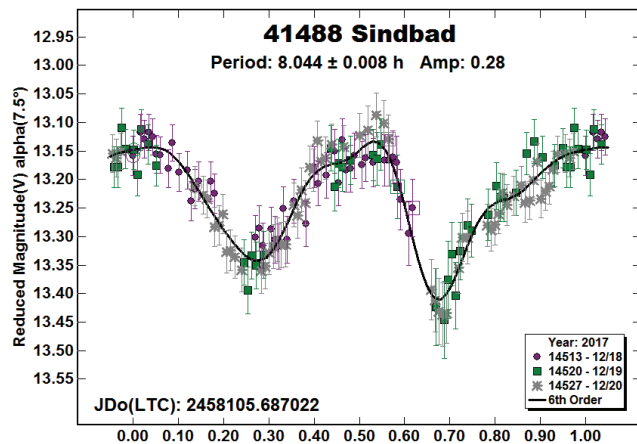


The split-halves plot seems to favor the longer period but, given the noise in the data, the differences in the two halves is not significant. We have adopted 6.62 h for the preferred period but 3.31 h cannot be formally excluded. The estimated diameter of 33 km does not help eliminate the shorter solution. As of 2018 January, there are five asteroids in the LCDB with $D > 30$ km and $P < 3.5$ h.

17428 Charleoi. The period of 6.034 h found from the 2017 data is in good agreement with our previous result of 5.990 h (Warner et al., 2017a). We used our two dense data sets and sparse data from CSS to model the asteroid. The longitude seems to be reasonably established at one of two values separated by about 180° . The latitude is not so well-determined. Our two poles have negative latitudes, indicating retrograde rotation.



41488 Sindbad, (51888) 2001 QZ17. There were no previous entries in the LCDB for either of these Hildas. Sindbad has an estimated diameter of 18 km while 2001 QZ17 is about 15 km. The period for Sindbad is considered secure. The period for 2001 QZ17 is a little less so, although it is almost certainly a very slow rotator. The period makes it a good candidate for tumbling (see Pravec et al., 2014, and references therein). There do seem to be some slight indications of tumbling in that the slope of some of the sessions does not match the slope of the Fourier model curve. However, these small differences are not enough to rate the asteroid even as a possible tumbler.



Shape and Spin Axis Models

The modeling processing using lightcurve inversion has been detailed previously (e.g., Warner et al., 2017b). Briefly, the idea is to find a shape and its orientation such that its modeled lightcurves

Asteroid	Src	Pole	Period (hrs)
958 Asplinda	TW	(228, +33)	16.556100
958 Asplinda	TW	(46, +45)	16.556089
958 Asplinda	H13	(41, +48)	25.3050
958 Asplinda	H13	(226, +35)	25.3050
1439 Vogtia	TW	(255, +71)	12.934244
1439 Vogtia	TW	(76, +67)	12.934239
1529 Oterma	TW	(59, -71)	14.339108
2483 Guinevere	TW	(16, +42)	14.730644
2483 Guinevere	D16	(19, +70)	14.73081
3561 Devine	TW	(95, -38)	9.622158
3561 Devine	TW	(261, -28)	9.622160
4317 Garibaldi	TW	(164, +28)	8.933050
17428 Charleroi	TW	(329, -35)	5.989413
17428 Charleroi	TW	(145, -49)	5.989415

Table II. The Src column gives the source for the results: TW, this work; H13, Hanus et al., 2013; D16, Durech et al., 2016. The Pole column gives the ecliptic longitude and latitude of the asteroid's north pole. The Period column gives the sidereal period, in hours. If there is more than one solution, the preferred one is in bold text. The period error is on the order of 1-2 units in the last decimal place. For single solutions, the pole

closely match the original data. It is generally “easier” to model NEAs because a single apparition can cover a wide range of phase angle bisector longitudes and phases, which are critical in finding a reliable solution. Main-belt asteroids usually require data from at least three oppositions at different phase angle bisector longitudes before a reliable model can be developed. This is even when using sparse data from surveys such as from the Catalina Sky Survey in Arizona (<https://catalina.lpl.arizona.edu/>).

In the PAB longitude plot, green circles represent dense lightcurves while red squares represent sparse data from one or more of the surveys. The green line in the period plot lies 10% above the lowest χ^2 value. An ideal solution has a well-defined shape with only one data point below the line. In the pole plot, dark red represents a solution that is more than 10% above the lowest χ^2 value. A “perfect” solution is when there is only one dark blue region and all the others are dark red. The solid black line in the lightcurve plots is the model lightcurve and the red dots are the original data.

In most models presented here, the period solution is far from being unique, which is critical to the subsequent steps. The only way to improve the solution is to obtain data from even further back in time and/or the future so that the data cover a longer time span. This, of course, presumes data of sufficient quality. The sparse data are often the only source of extended data. Unfortunately, in some cases here, the original sparse data set showed much higher scatter than usual and so a number of observations had to be removed. This shortened the date range of observations considerably.

Acknowledgements

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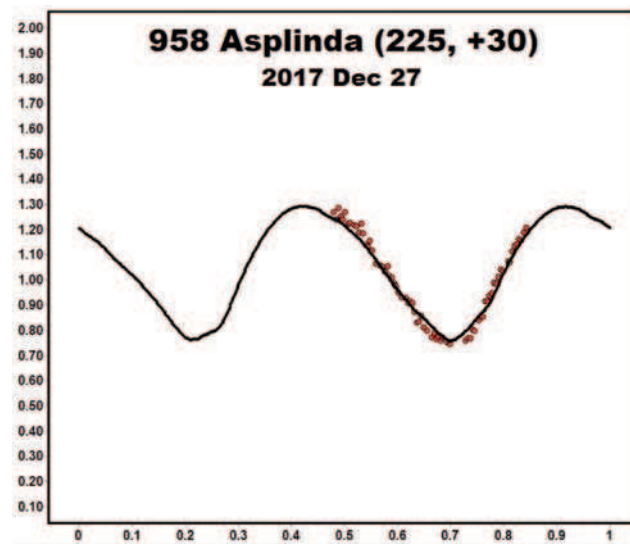
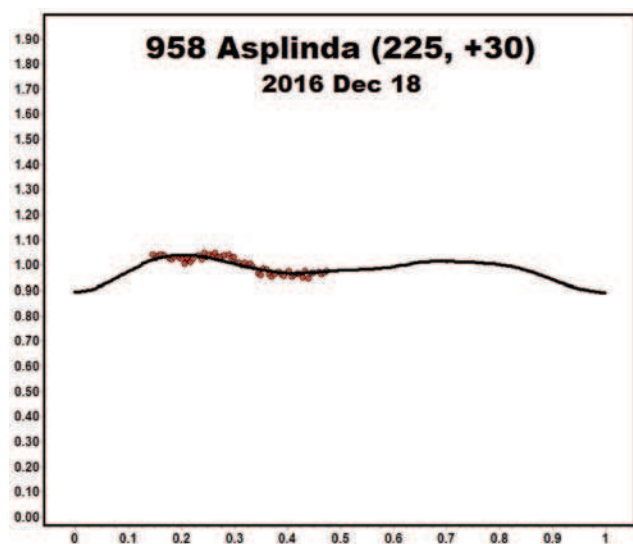
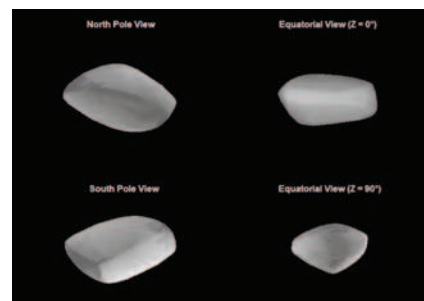
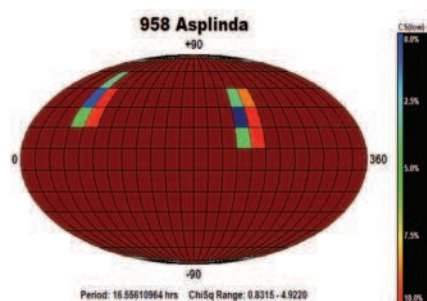
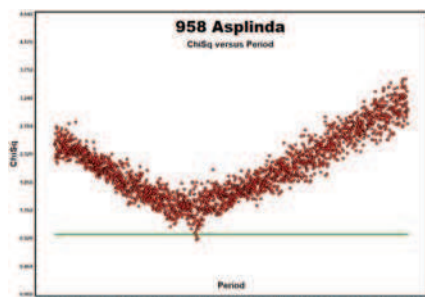
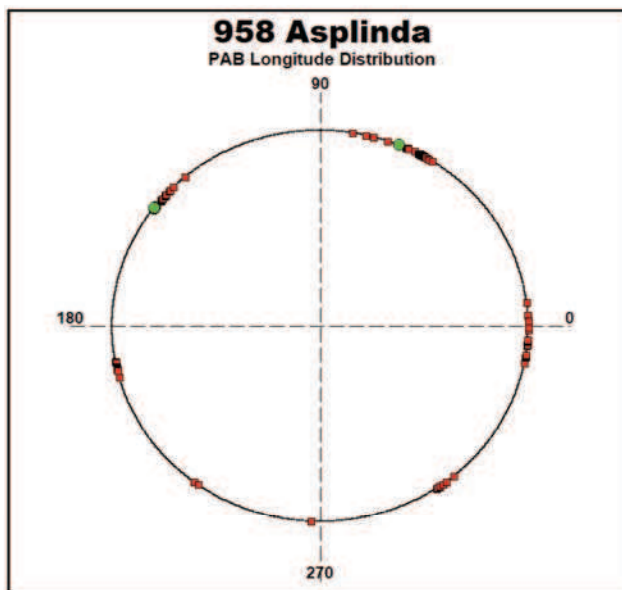
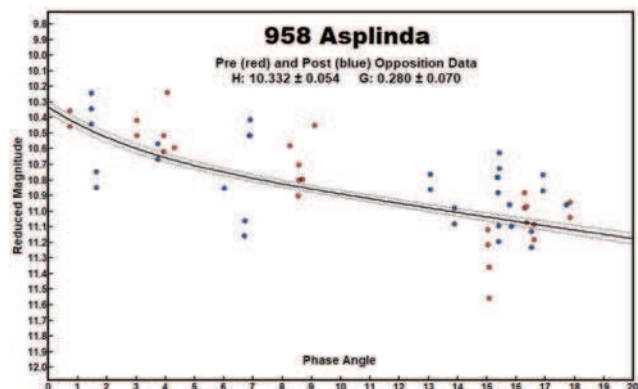
Number	Name	2017 mm/dd	Pts	Phase	L _{PAB}	B _{PAB}	Period(h)	P.E.	Amp	A.E.
958	Asplinda	12/27-12/29	205	13.1, 12.7	143	3	16.543	0.007	0.64	0.02
1439	Vogtia	10/04-10/15	432	9.6, 7.1	48	1	12.944	0.002	0.36	0.02
1529	Oterma	12/31-12/31	250	9.6, 0.0, 7.1	0	0	14.329	0.002	0.12	0.01
1529	Oterma	12/18-12/29	524	10.8, 8.3	127	4	14.321	0.002	0.13	0.01
2483	Guinevere	12/18-12/20	250	9.9, 9.2	112	-3	14.721	0.006	1.37	0.03
3561	Devine	12/04-12/07	172	13.3, 13.6	15	-10	9.61	0.01	0.23	0.02
3694	Sharon	12/22-12/29	250	12.3, 11.2	144	-1	11.459	0.005	0.58	0.03
4317	Garibaldi	08/25-08/31	254	6.8, 5.5	359	-8	8.959	0.006	0.1	0.01
4317	Garibaldi	10/04-10/16	357	9.1, 6.3	45	1	8.917	0.005	0.17	0.01
5661	Hildebrand	10/22-10/26	386	5.5, 5.1	36	15	13.6	0.005	0.16	0.01
8551	Daitarabochi	12/04-12/08	800	14.9, 15.2	8	-9	6.62	0.01	0.19	0.03
17428	Charleroi	10/14-10/16	130	6.4, 6.0	47	5	6.034	0.007	0.19	0.02
41488	Sindbad	12/18-12/20	147	7.5, 8.1	66	-11	8.044	0.008	0.28	0.02
51888	2001 QZ17	10/07-10/21	508	5.4, 9.8	216	1	331	4	0.39	0.03

Table III. Observing circumstances. The phase angle (α) is given at the start and end of each date range. L_{PAB} and B_{PAB} are each the average phase angle bisector longitude and latitude (see Harris *et al.*, 1984).

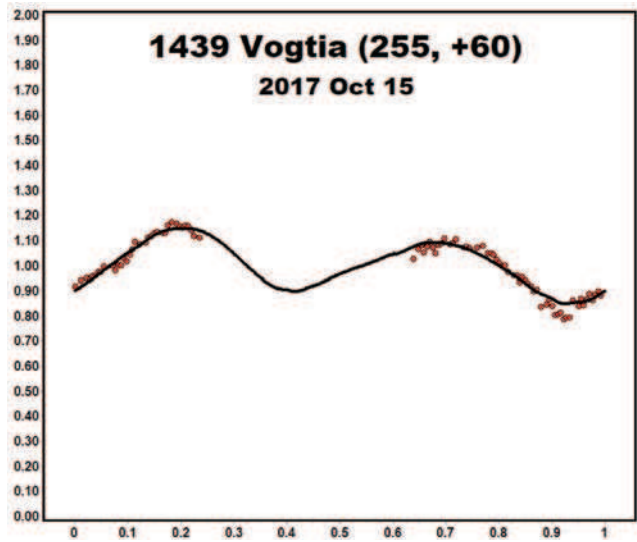
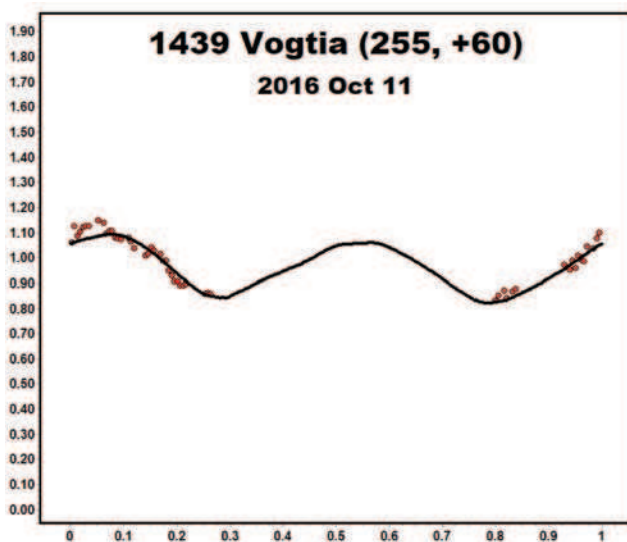
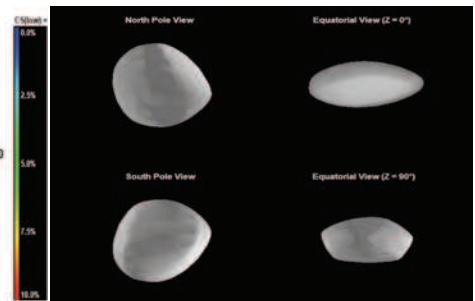
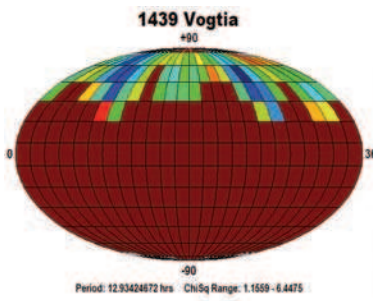
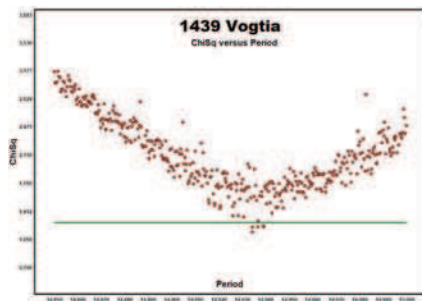
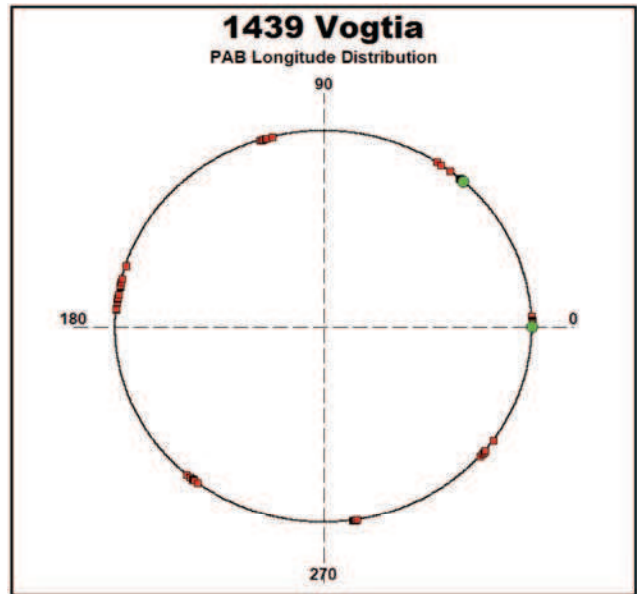
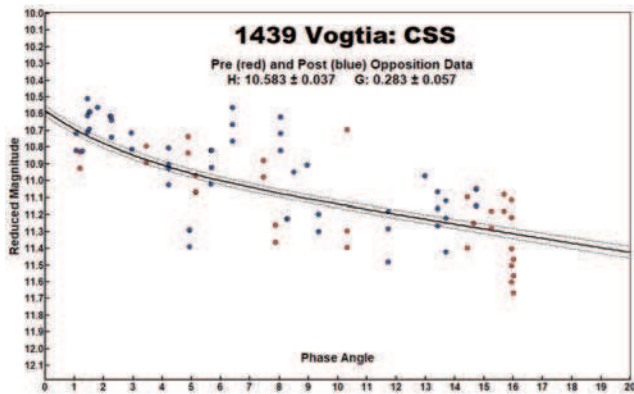
which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation. (<http://www.ipac.caltech.edu/2mass/>)

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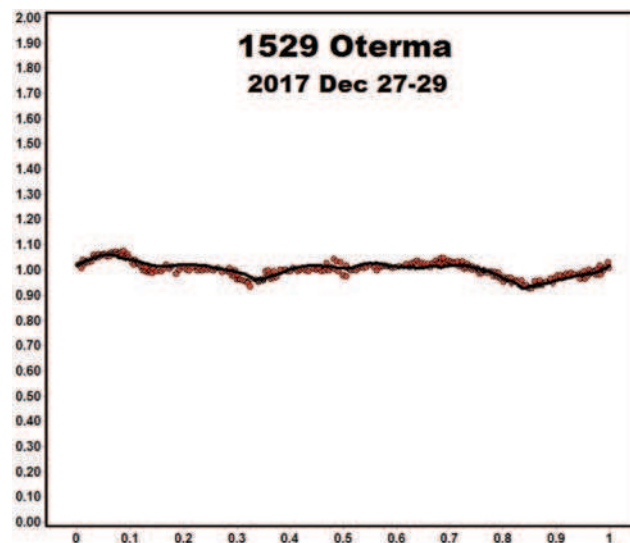
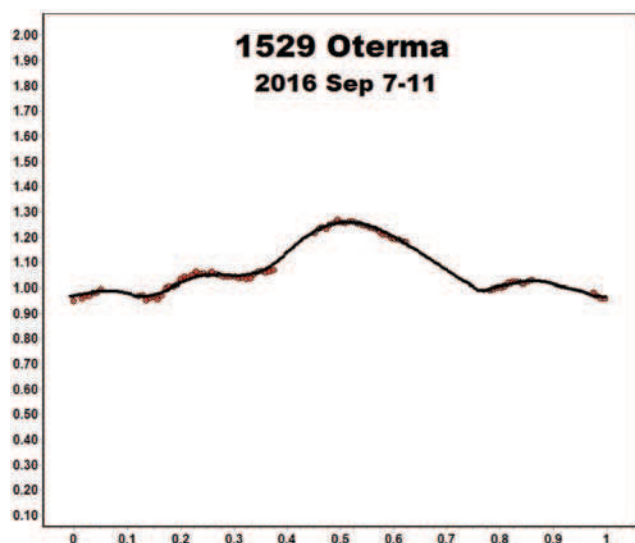
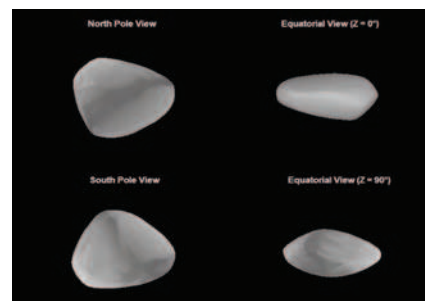
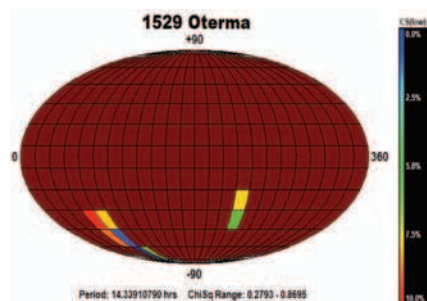
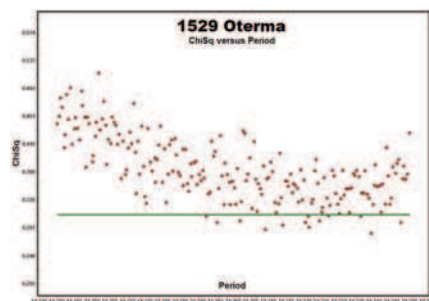
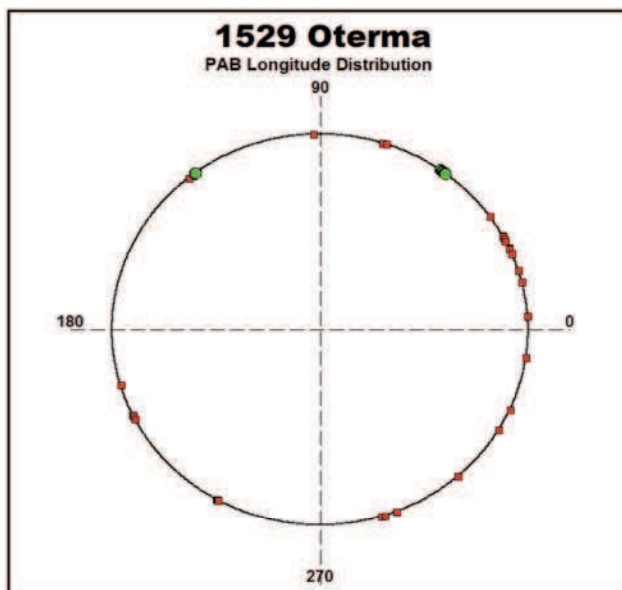
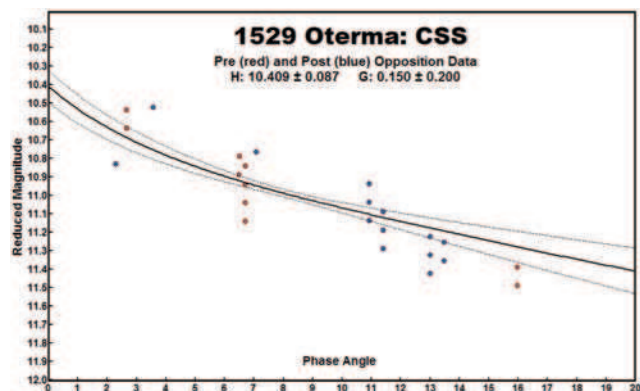
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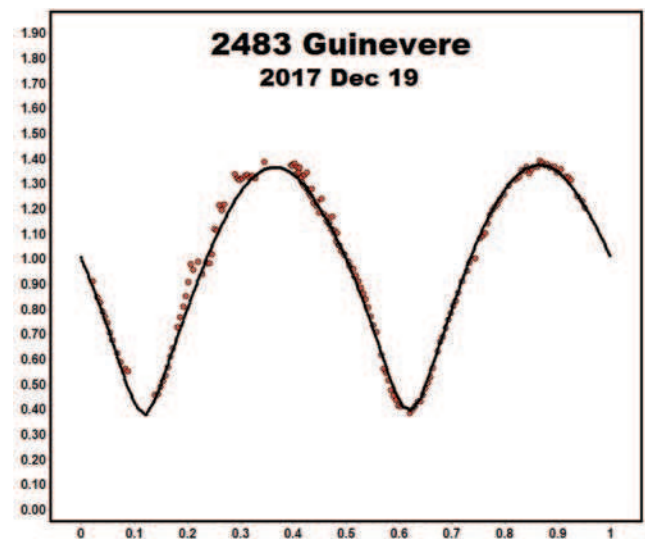
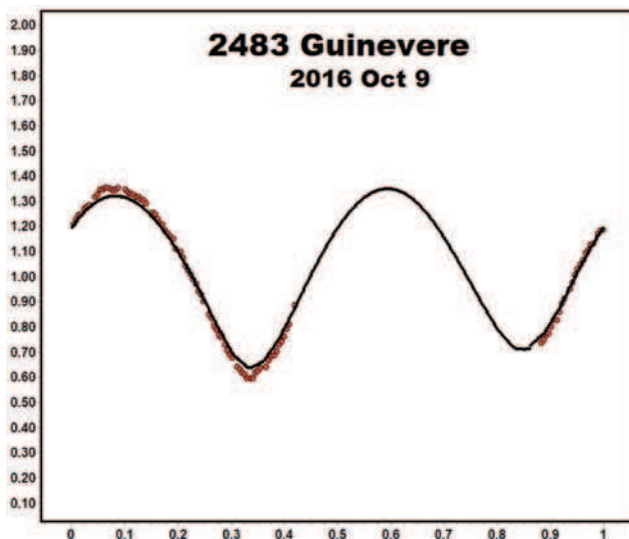
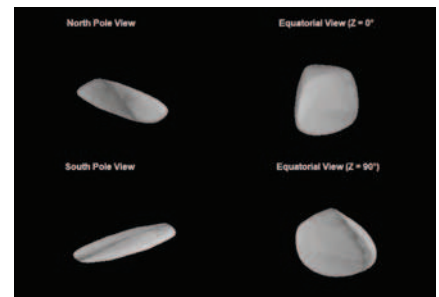
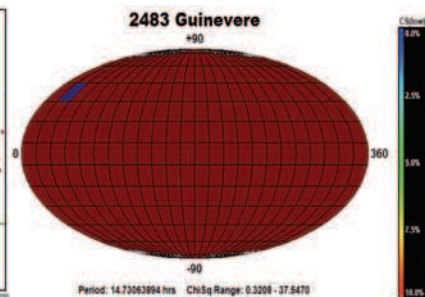
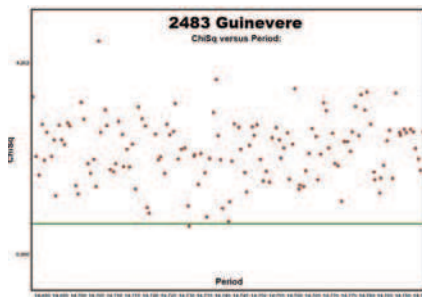
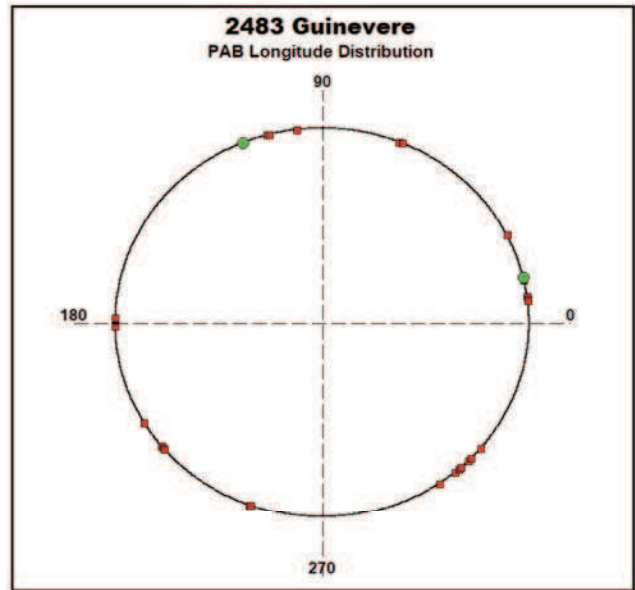
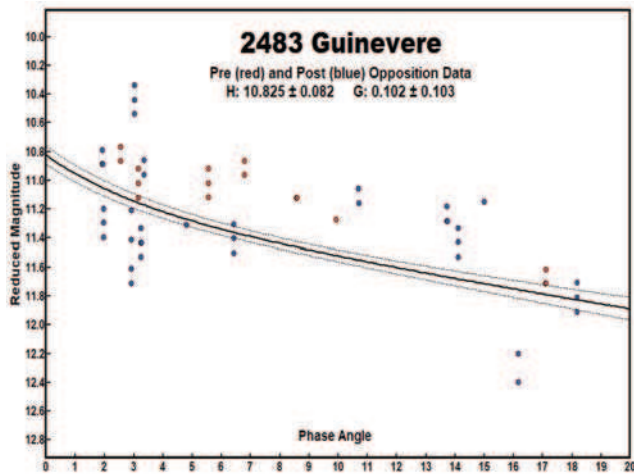
Inversion modeling plots for 958 Asplinda. This model has two likely solutions that differ mostly by about 180° ecliptic longitude. The large flat areas on the model could indicate concavities.



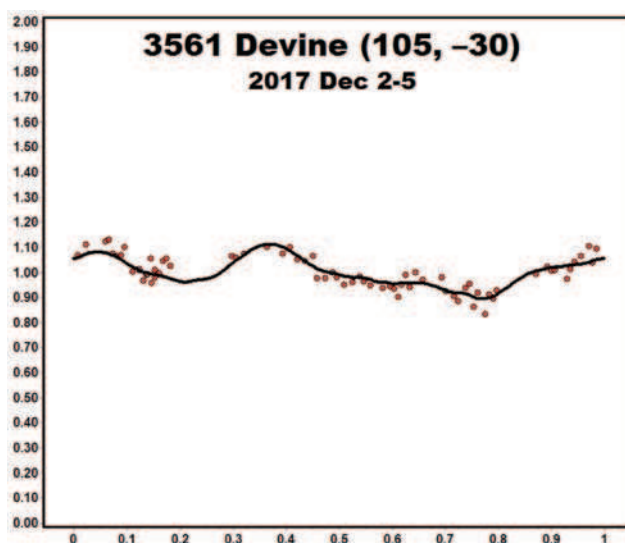
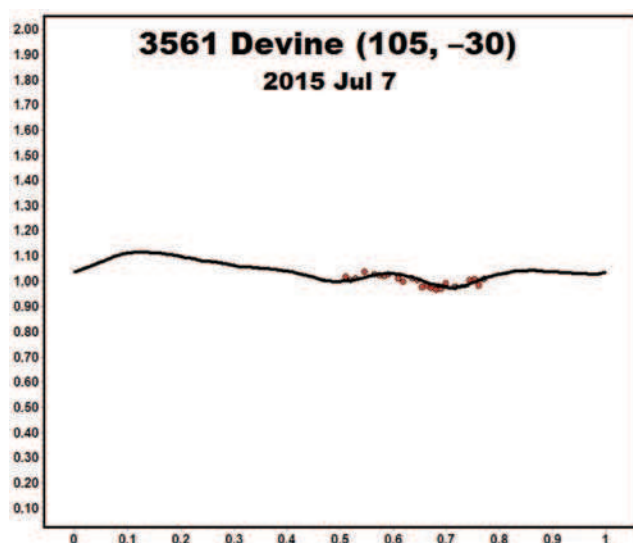
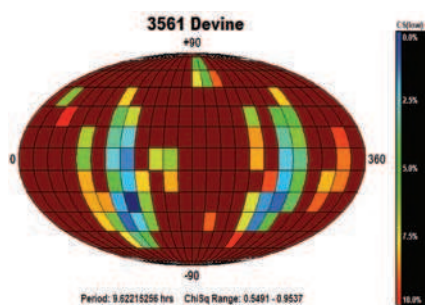
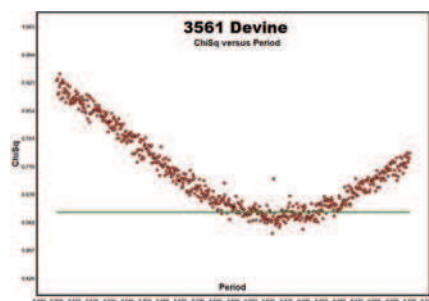
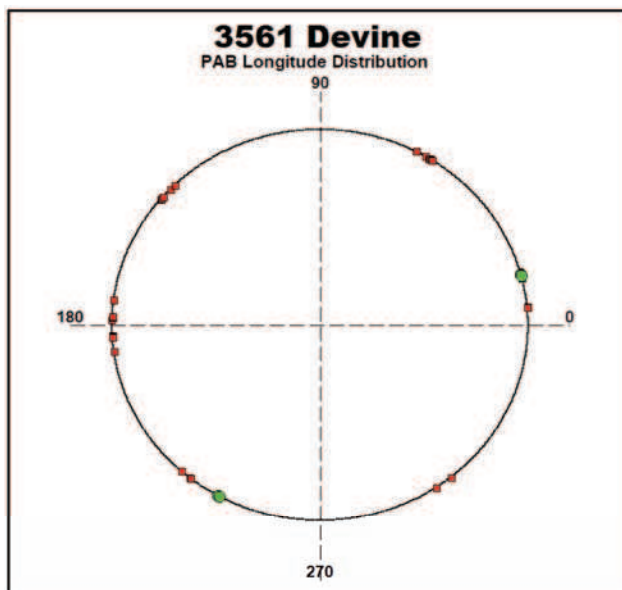
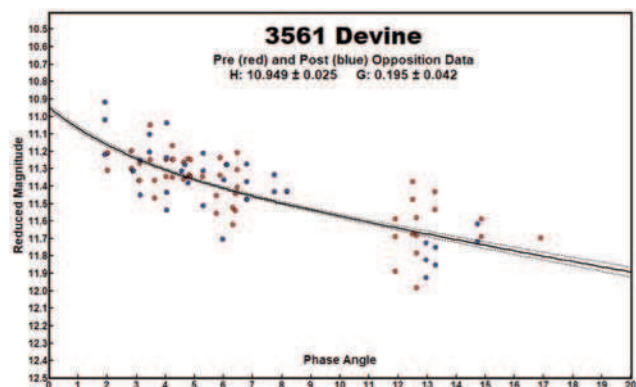
Inversion modeling plots for 1439 Vogtia. When the asteroid's pole is close to one of the ecliptic poles, it's common to have considerable ambiguity in the longitude. In this case, two solutions were favored: the one with the lowest χ^2 in the pole search is shown here.



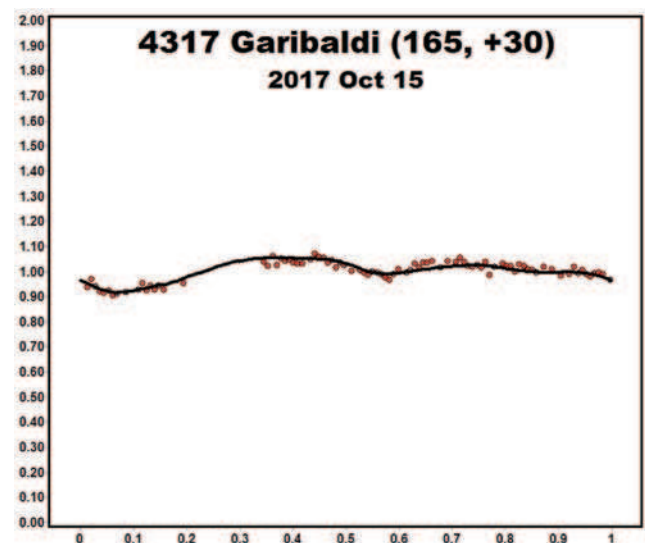
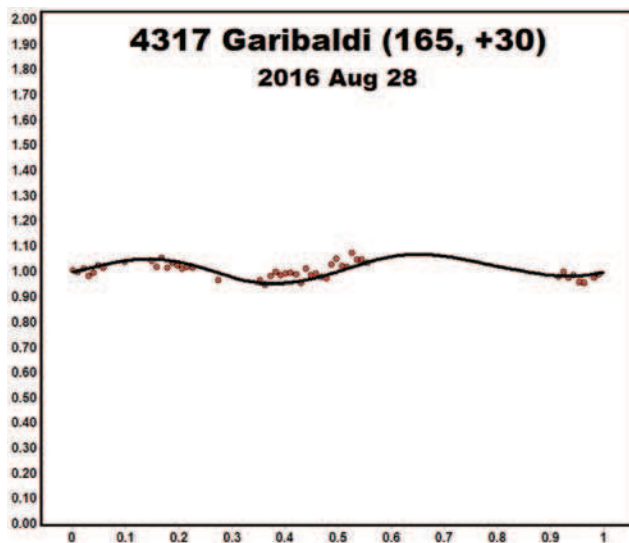
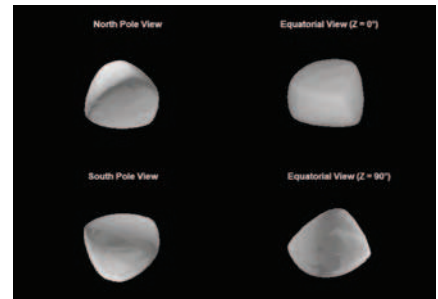
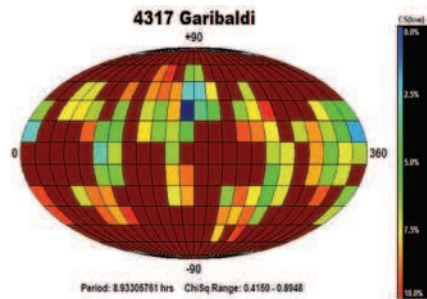
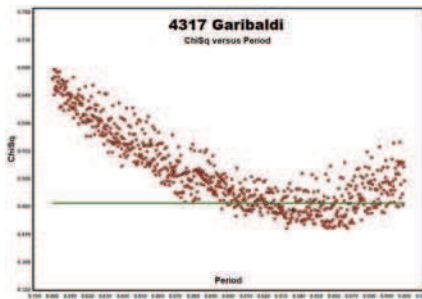
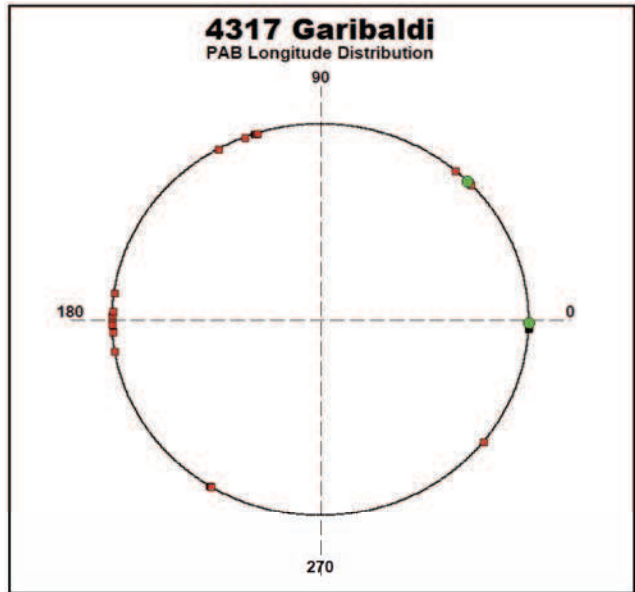
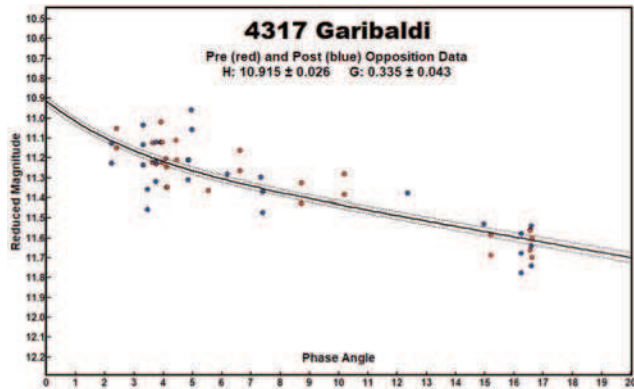
Inversion modeling plots for 1529 Oterma. The period solution is weak, mostly due to very noisy and limited sparse data. Under these circumstances, the subsequent pole solution is surprisingly unambiguous. Additional observations are strongly encourage to allow confirming and then refining the solution.



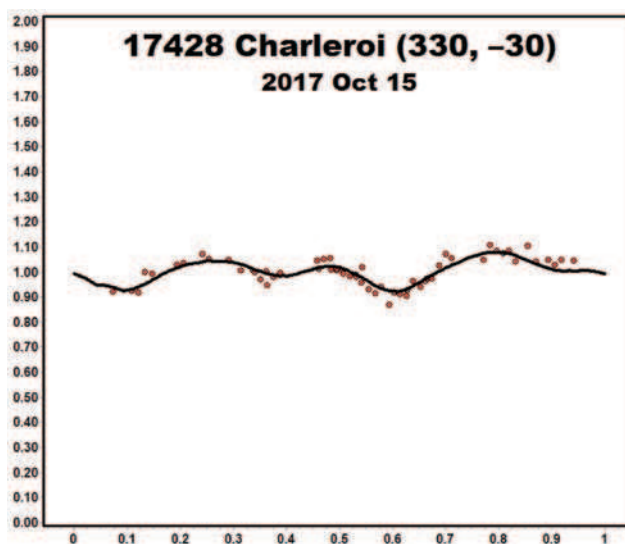
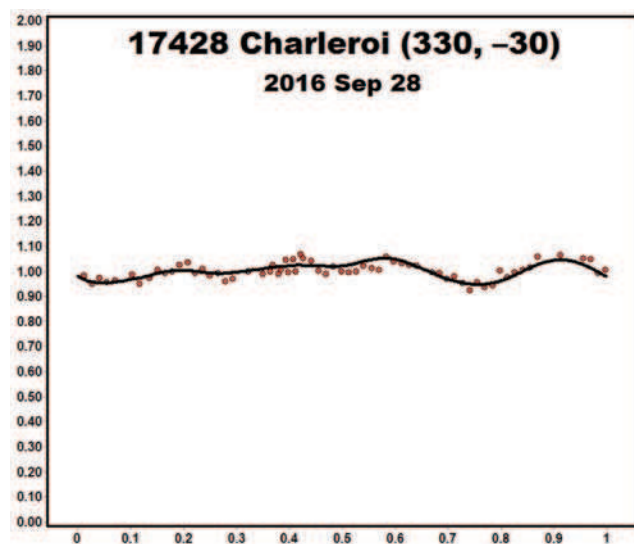
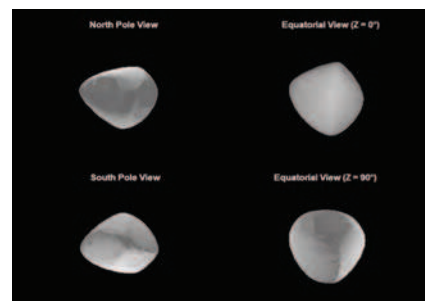
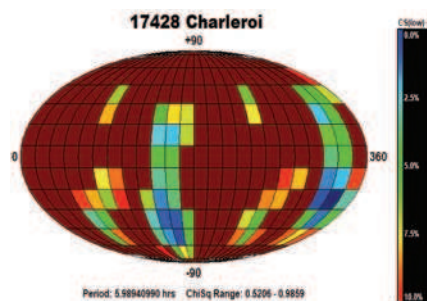
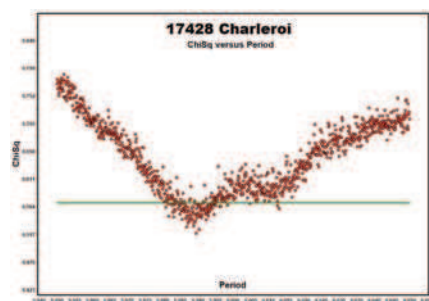
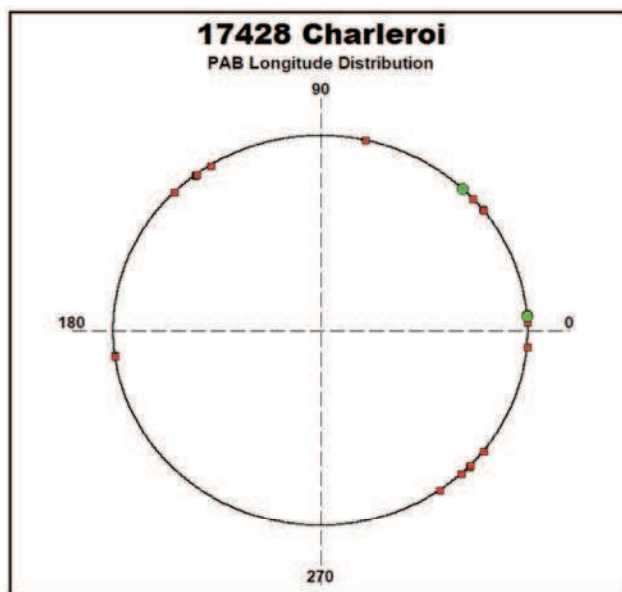
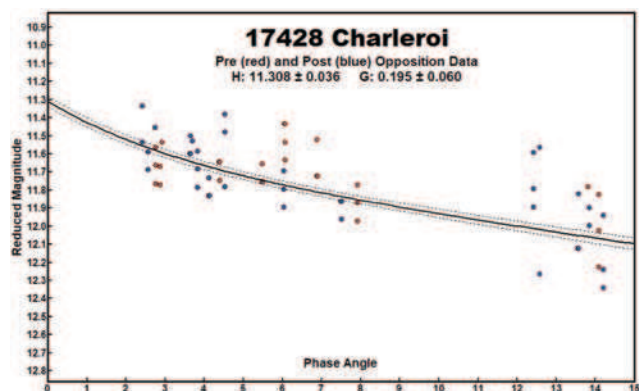
Inversion modeling plots for 2483 Guinevere. Only a small part of the range in the period search is shown so that the lowest x_2 value would be visible. The entire plot at normal scale is a narrow flat line with large scatter. Despite the problems with the period, this model has one solution. The positive latitude indicates that the asteroid has a prograde rotation. The model curve for 2016 doesn't quite have enough amplitude. Here again, additional observations are needed to check these results.



Inversion modeling plots for 3561 Devine. This model is poorly constrained in both longitude and latitude. The two adopted solutions have negative latitudes, indicating retrograde rotation. As expected, the data are not a tight fit to the model lightcurve.



Inversion modeling plots for 4317 Garibaldi. This model is very ambiguous with no outstanding preference in period or pole longitude/latitude. The low amplitudes at each apparition do support the adopted model shape of a nearly spheroidal body.



Inversion modeling plots for 17428 Charleroi. The large number of 10% solutions in the period search show the need for more data, either further back in time or in the future. This model favors two, mirrored longitudes but the latitude is poorly constrained. The adopted solutions both have negative latitudes and so imply retrograde rotation.