LIGHTCURVE ANALYSIS OF HILDA ASTEROIDS AT THE CENTER FOR SOLAR SYSTEM STUDIES: 2021 JANUARY-MARCH

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New CCD photometric observations of ten Hilda asteroid members were made from 2021 January through March: 153 Hilda, 190 Ismene, 1202 Marina, 2067 Aksnes, 3990 Heimdal, 6237 Chikushi, (7458) 1984 DE1, 8743 Keneke, and (23186) 2000 PO8. Two of the objects, 3990 Heimdal and 8743 Keneke, are suspected to be in a tumbling state.

CCD photometric observations of Hilda asteroids are made at the Center for Solar System Studies (CS3) as part of an ongoing study of this family/group that 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 Hildas and to find pole and shape models when possible. We also 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 are commonly used for observations. 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.

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	

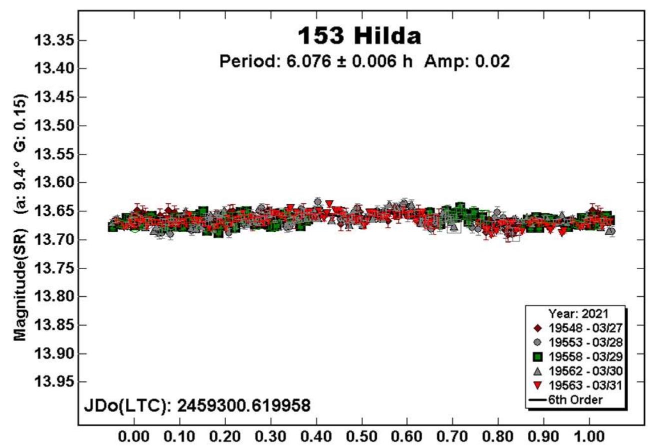
Table I. List of available telescopes and CCD cameras at CS3. The exact combination for each telescope/camera pair can vary due to maintenance or specific needs.

To reduce the number of times and amounts of adjusting nightly zero points, we use the ATLAS catalog r′ (SR) magnitudes (Tonry et al., 2018). Those adjustments are usually ≤ ±0.03 mag. The rare greater corrections may have been related in part to using unfiltered observations, poor centroiding of the reference stars, and not correcting for second-order extinction. Another cause may be selecting what appears to be a single star but is actually an unresolved pair.

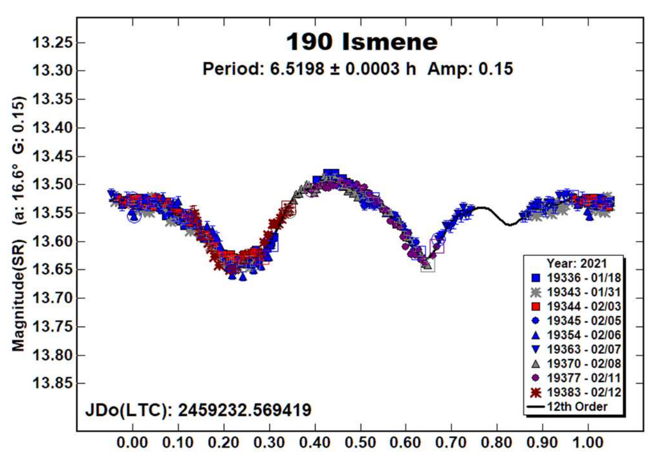
The Y-axis values are ATLAS SR "sky" (catalog) magnitudes. The two values in the parentheses are the phase angle (a) and the value of *G* used to normalize the data to the comparison stars used in the earliest session. This, in effect, made all the observations seem to be made at a single fixed date/time and phase angle, 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*.

<u>153 Hilda</u>. There are numerous references to previous works for the namesake of the Hilda family, e.g., Warner and Stephens (2018), Pilcher and Benishek (2019), Pilcher (2020), and Warner and Stephens (2020a). For those three, the period was very close to 5.958 h and the amplitude ranged from 0.11 to 0.23 mag.

The data from 2021 observations showed a nearly flat lightcurve (0.02 mag) with a slightly longer period of 6.076 h. We used dense lightcurves from Pilcher and Benishek found on the ALCDEF web site and sparse data on the AstDys site for ATLAS, Catalina Sky Survey, and USNO-Flagstaff to generate a model. The results are shown following the references section.

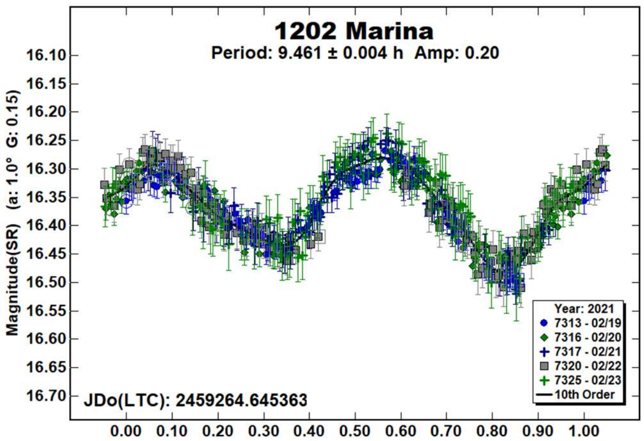


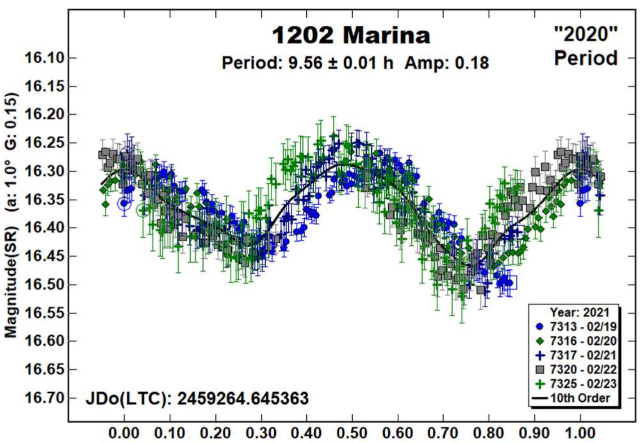
<u>190 Ismene</u>. Dahlgren et al. (1998) found a period of 6.52 h for this 160-km Hilda. Similar results were found by Shevchenko et al (2008) and by us using data from 2019 (Warner and Stephens, 2020a). Our result is in good agreement with those earlier works even though the lightcurve has a small gap near 0.85 rotation phase.



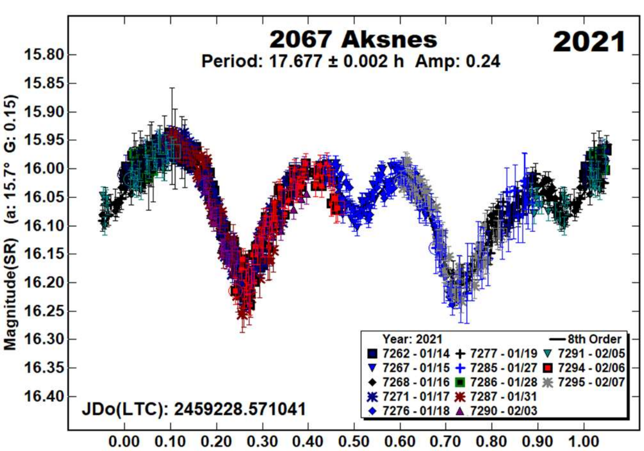
1202 Marina. Dahlgren et al. (1998) found a period of 9.45 h for Marina, which has an estimated diameter of 55 km. We observed it in 2020 and found a period of 9.558 h (Warner and Stephens, 2020b). Durech et al. (2020) derived a shape model with a sidereal period of 9.45833 h and preferred J2000 ecliptic pole of (λ,β) = (54°, -47°).

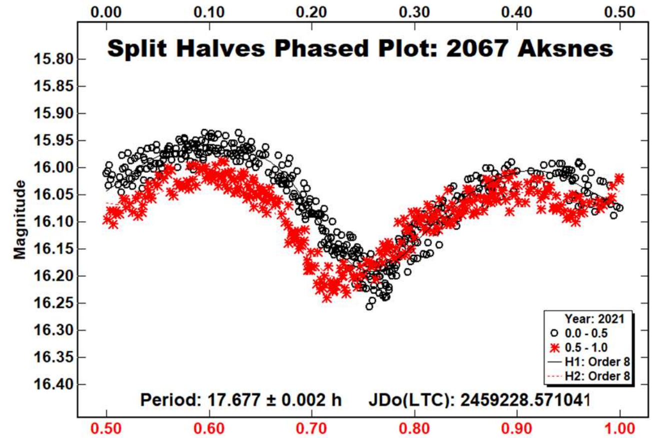
The data analysis found a period of 9.461 h, which is in better agreement with Dahlgren et al. and Durech et al. The fit of our recent data using the shorter period is greatly improved over the one forced to our result from 2020.



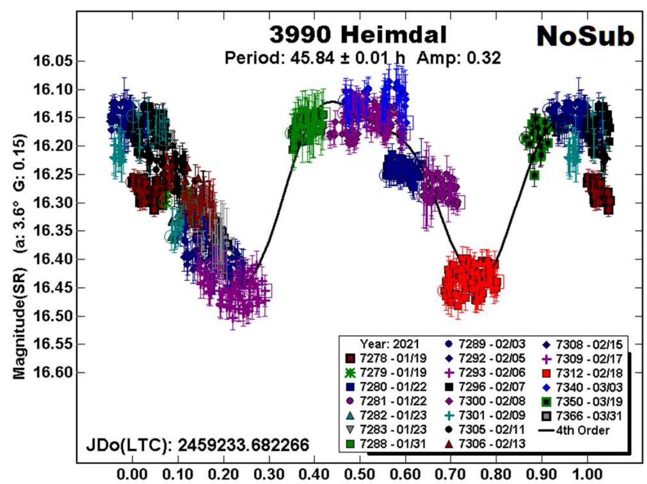


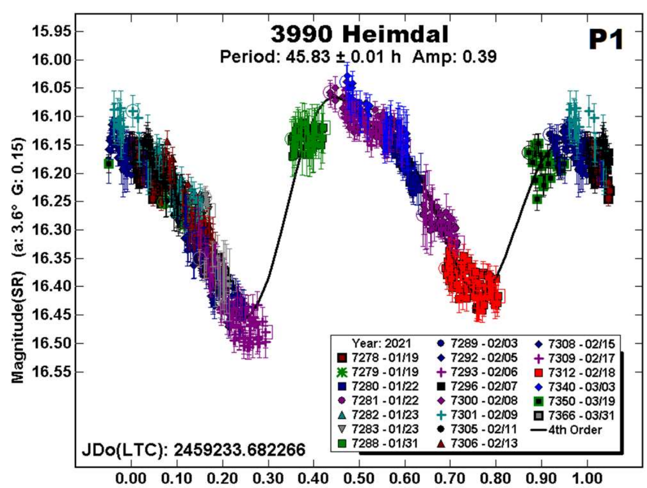
2067 Aksnes. The only previous result was from Dahlgren et al. (1998), who found a period of 17.75 h. Our more extensive data set helped refine the period to one about 0.07 h shorter. The unusual shape was confirmed by the split-halves plot, which showed two distinct parts of the lightcurve.



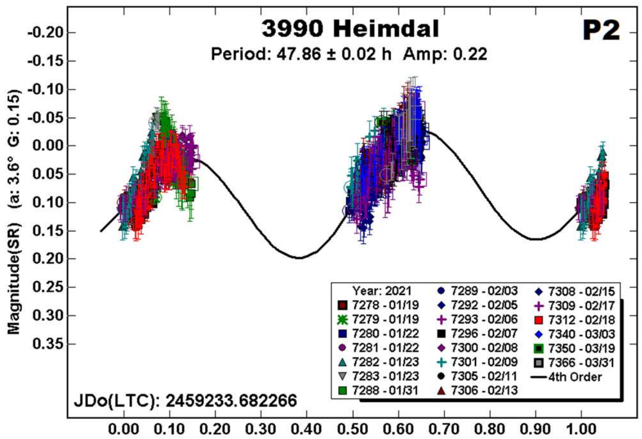


3990 Heimdal. Slyusarev et al. (2012), found only a minimum period of 20 h. Our 2021 observations spanned more than 60 days and had denser covered for most sessions. Finding a single-period solution proved difficult, as seen in the "NoSub" plot. A dual-period search wasn't run until after the session on March 3. It was only after the final observing run on March 31 that an acceptable, but far from perfect, solution could be found, mostly because *MPO Canopus* is not designed to handle the complex relationship of the periods of rotation and precession for tumbling asteroids.



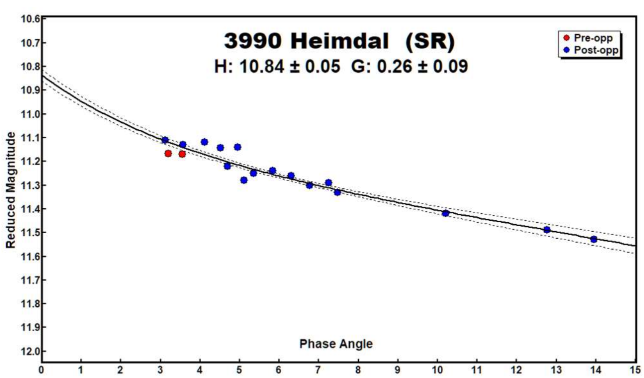


It is very apparent that subtracting P_2 = 47.86 h from the data set leads to a good fit for P_1 = 45.83 h. It's a concern that P_2 is so close to being commensurate with an Earth day and that the rules of thumb for the damping time of tumbler of Hemidal's size indicate that P_1 and/or P_2 are far less than what would be expected (Pravec et al., 2005; 2014). On the other hand, the two periods are consistent with one another if the asteroid is tumbling, i.e., a significantly shorter period for either one would be unlikely.

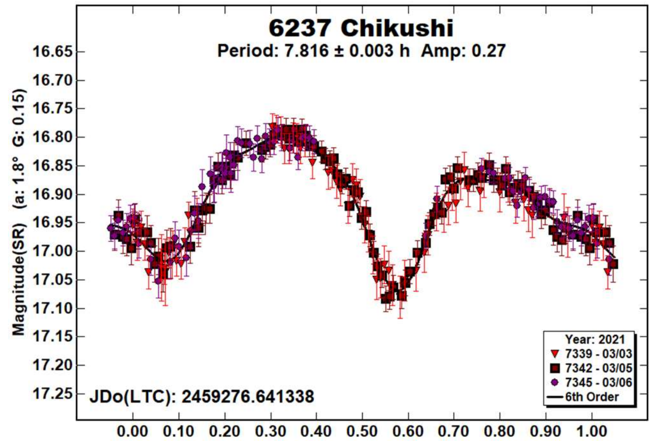


To get the mid-amplitude for each session for H-G phase curve modeling, we used the P_1 plot to find the date and time for a point in each session. Since that plot normalizes all the magnitudes to the first session, the reduced magnitude for a point in P_1 was not used directly. Instead, the offset from the average magnitude of the plot, given by the Fourier analysis, was recorded. For example, if the average of $P1$ = 16.270 and the selected data point in a session had a reduced magnitude of 16.350, a value of +0.08 was recorded.

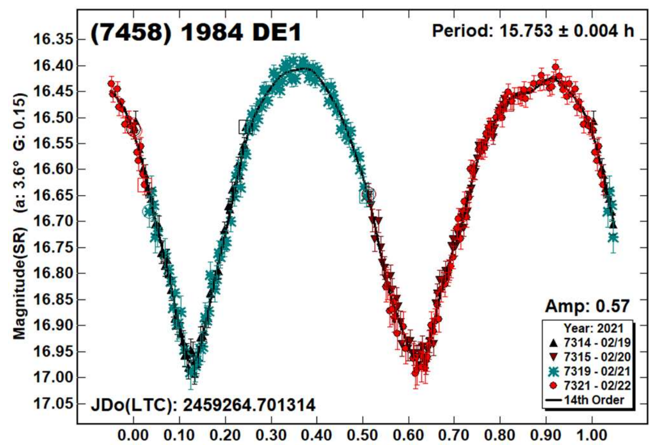
We then plotted the raw data for each session one at a time. The data point corresponding to the saved date/time was found and its correction was applied to its reduced magnitude. This corrected value along with the date and timer were put into the H-G calculator of *MPO Canopus* with the final result being H_{SR} = 10.84 and G_{SR} = 0.26. Assuming V – SR = 0.22 (Warner and Stephens, 2021), this gives H = 11.06. The MPCORB file gives H = 10.88.



<u>6237 Chikushi</u>. Waszczak et al. (2015) used sparse data from the Palomar Transient Factory to find a period of 7.812 h. The result from our most recent dense data set (7.816 h), is very close to theirs as well as the sidereal period (7.81163 h) found by Durech et al. (2020). Our data set from 2017 (Warner and Stephens, 2018) led to 7.787 h. Since it spanned only three days, we consider it statistically the same with our recent result.

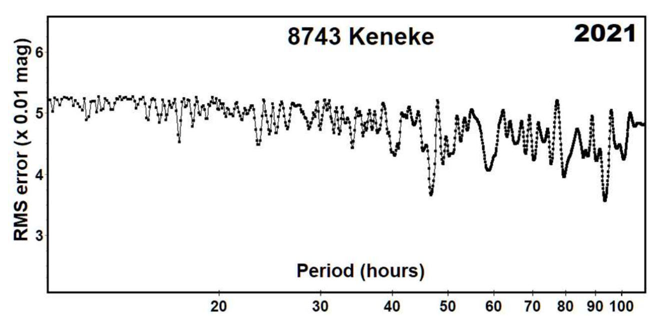


<u>(7458) 1984 DE1</u>. The estimated diameter of this Hilda is 25 km. Waszczak et al. (2015) found a period of 15.651 h and Durech and Hanus (2018) found a sidereal period of 15.7543 h for their model. Our result is in good keeping with the previously reported periods.

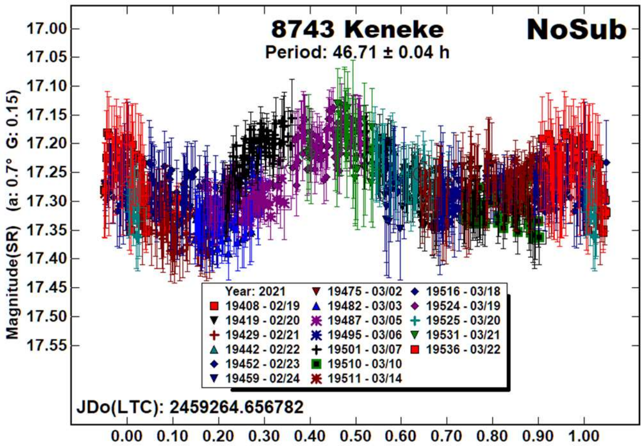


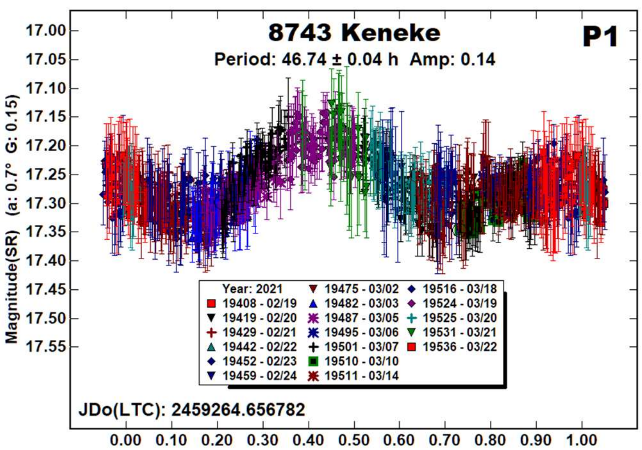
<u>8743 Keneke</u>. Two, very conflicting periods have been reported for this 27 km Hilda. Warner et al. (2017) found a period of 2.769 h while Pál et al. (2020) using data from TESS found 99.3076 h. Our 2021 observations spanned almost a month, Feb 19 - Mar 22, producing the 950 data points used in our analysis.

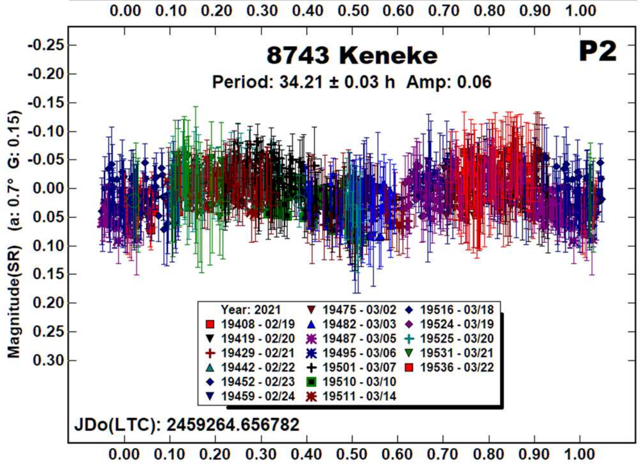
On the face of it, the period spectrum showed two possible periods and, in fact, *MPO Canopus* favored the longer one near 95 h. However, based on the plot at that period and one near 45 h, we worked on the premise that the shorter period was more likely correct.



The "NoSub" plot shows the full data set phased to a period of 46.71 h. Despite the noisy data in a lightcurve with an amplitude of only about 0.20 mag, there were signs of a second period, e.g., session 19487 on March 5. The dual-period search method in *MPO Canopus* eventually found a second period of 34.21 h, which was one a small number of possible solutions but the most probable. Both of these periods are short of what would be expected for the asteroid to be tumbling (Pravec et al., 2005; 2014).

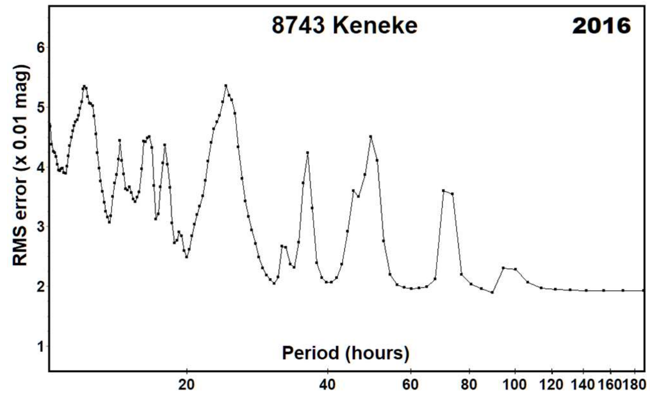


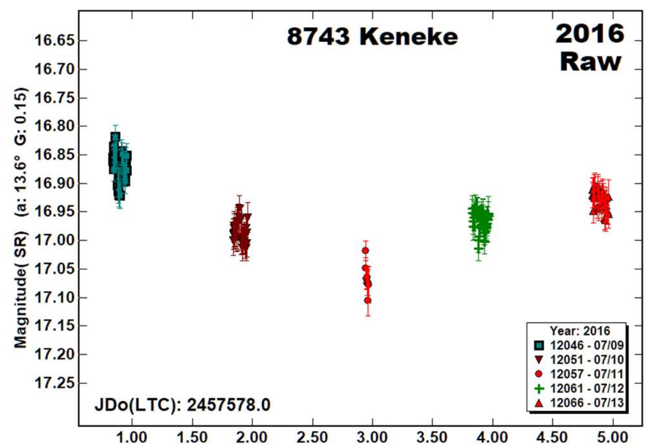


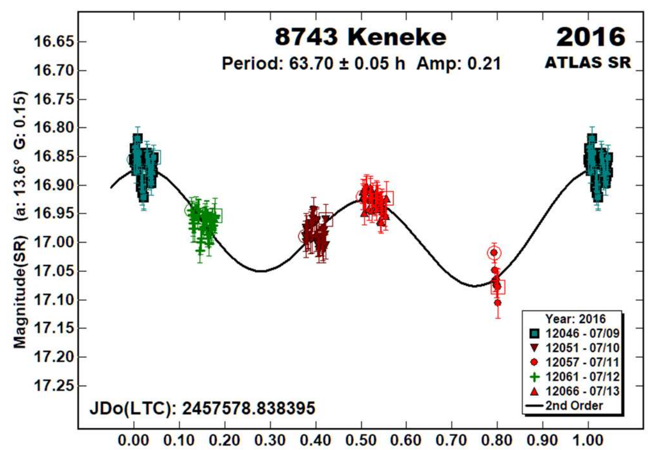


These results prompted another look at the 2016 results. The first step was to use SR magnitudes from the ATLAS catalog for the comparisons and remove any zero point of sets. Despite the very sparse data set obtained in 2016 ("2016 Raw"), there seemed to be a long period component to the data. This was not seen at the time since a catalog with uncertain accuracy was being used.

The period spectrum shows several poorly defined possibilities (broad minimums in the RMS values). The only solution that produced a realistic lightcurve was for 63.7 h which required going down to a second-order analysis in order avoid wild swings in the Fourier model curve. This revised result proved to be very intriguing since it is related in a to the results from 2021 that supports the possibility of the asteroid being in a tumbling state.







A tumbling asteroid lightcurve is defined in part by the sum of integral multiples of the frequencies, i.e.,

$m/f1 + n/f2$

The frequencies for each period are

$f1 = (24/63.7) = 0.376766$
$f2 = (24/34.21) = 0.701549$
$f3 = (24/46.74) = 0.513479$

Number	Name	21yy/mm/dd	Phase	L_{PAB}	B_{PAB}	Period(h)	P.E.	Amp	A.E.
153	Hilda	03/27-03/31	9.4,10.2	150	-8	6.076	0.0006	0.02	0.01
190	Ismene	01/18-02/12	16.6,16.7	50	-6	6.5198	0.0003	0.15	0.01
1202	Marina	02/19-02/23	1.0,1.6	149	4	9.461	0.004	0.20	0.02
2067	Aksnes	01/14-02/07	15.7,17.5	59	-3	17.677	0.002	0.24	0.02
3990	Heimdal	01/19-03/19	*3.6,12.8	125	-10	T45.83	0.01	0.39	0.03
						47.86	0.02	0.22	0.03
6237	Chikushi	03/03-03/06	1.8,2.4	159	5	7.816	0.003	0.27	0.02
7458	1984 DE1	02/19-02/21	3.6,2.9	161	-1	15.753	0.004	0.57	0.02
8743	Keneke	02/19-03/22				T46.74	0.04	0.14	0.02
						34.21	0.03	0.06	0.02
		16/07/09-07/13				63.7	0.9	0.21	0.02
23186	2000 PO8	03/10-03/18	8.9,7.2	194	15	5.012	0.001	0.29	0.02

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

Number	Name	λ1	β1	Period	λ2	β2	Period (h)	a/b ratio	a/c ratio
153	Hilda	**335°**	**-1°**	**5.958538**	155°	-15°	5.958535	1.14	1.4839
23186	2000 PO8	**302°**	**+79°**	**5.011160**	30°	+40°	5.011169	1.2	2.3

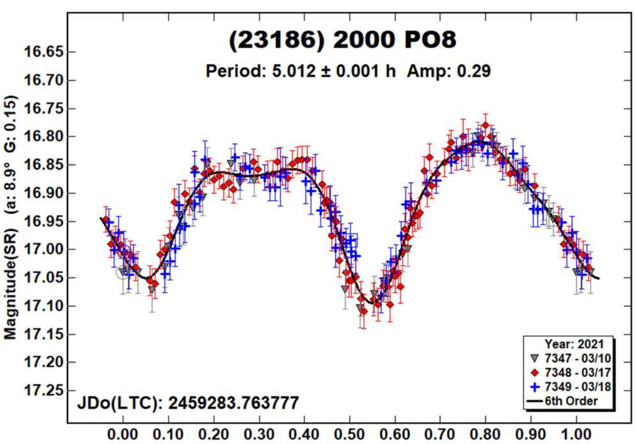
Table III. Results of Pole/Shape modeling. Pole positions are J2000 ecliptic coordinates. The pole error is a circle with a 15° radius centered on the pole. The period error is 1-2 units of the last decimal place. The preferred solution is listed in bold text. The a/b and a/c ratios are from the preferred model.

These give

$f2 - f3 = 0.18807$
$f1 = 2 * (f2 - f3)$; $\Delta = 0.000626$

Therefore, it seems that the three periods are related even when no one period has a simple integral ratio with either of the other two. Even if assuming the asteroid is tumbling, because there are insufficient data, it is not possible to say with certainty that the periods of 45.83 h and 47.86 h are the true periods of precession and rotation.

(23186) 2000 PO8. We observed this asteroid twice before: Warner and Stephens (2018, 5.003 h; 2020b, 5.0165 h). The analysis of the 2021 data gave essentially the same results.



Acknowledgements

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