

LIGHTCURVES, SIDEREAL ROTATION PERIOD, SPIN POLE, AND CONVEX MODEL SHAPE OF KORONIS FAMILY MEMBER (1443) RUPPINA

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Rotation lightcurves of Koronis asteroid family member (1443) Ruppina were observed during its consecutive apparitions in 2015, 2016, and 2017–18, the latter yielding an improved synodic rotation period of 5.8796 ± 0.0002 h. In combination with the previously published lightcurves recorded in 2007 and 2014 the resulting data set is confirmed to be sufficient to unambiguously determine the sidereal rotation period, and the corresponding results for spin vector and convex model shape are presented.

Koronis family member (1443) Ruppina was observed during three apparitions between 2015 and 2018 as part of an ongoing program to study rotation properties of the family's brighter objects (Slivan et al., 2008). Lightcurve observations of Ruppina have been previously reported by Neugent and Slivan (2008), Arredondo et al. (2014), Stephens (2018), and Stephens and Warner (2020); the corresponding four independent determinations of the synodic rotation period all agree. The latter paper also presents an analysis for sidereal period and spin vector whose outcome is discussed at length by Slivan (2021; this issue).

The program of observations reported here was designed specifically to build a lightcurve data set that would be demonstrably sufficient for sidereal period and spin vector analyses, in part by improving the determination of the synodic rotation period (Slivan, 2012) and by assembling a suitable progression of epoch intervals (Slivan, 2013). The lightcurves from the two apparitions that had been published prior to the observations reported here served as a starting place, establishing an epoch interval of length five apparitions apart.

The observations were made during Ruppina's three consecutive apparitions in 2015, 2016, and 2017–18, using a series of CCD cameras at the Cassegrain focus of the the 0.61m Sawyer telescope at the Whittin Observatory in Wellesley, MA. Nightly observing information is summarized in Table I, and details about the instruments used are given in Table II. Image integrations were 240 s using an *R* filter. The observing strategy used to calibrate the lightcurves to standard magnitudes is described by Slivan et al. (2008), as are the procedures used for image processing and measurement. The resulting lightcurves were reduced for light-time and to unit distances.

2015 apparition: (Fig. 1, top panel) This viewing aspect had not yet been observed. Lightcurves were observed on two nights which together cover about 2/3 of the rotation phase, sufficient to record an amplitude, and also to measure an epoch interval of one apparition with respect to the lightcurves from 2014.

2016 apparition: (Fig. 1, center panel) This viewing aspect at an ecliptic longitude about 100° different from that in 2015 had not yet been observed. A lightcurve was observed on a single night covering just over 1/2 of the rotation phase, sufficient to record an amplitude, and also to measure an epoch interval of two apparitions with respect to 2014.

2017–18 apparition: (Fig. 1, bottom panel) At this viewing aspect near the reflex of that in 2015, lightcurves observed on six nights recorded complete coverage in rotation phase, and define an epoch interval of three apparitions with respect to 2014. The data span a 113-night interval in order to maximize the precision of the derived synodic rotation period. The improved period of 5.8796 ± 0.0002 h is consistent with the previously published periods and has been used to fold all of the lightcurves presented in Fig. 1.

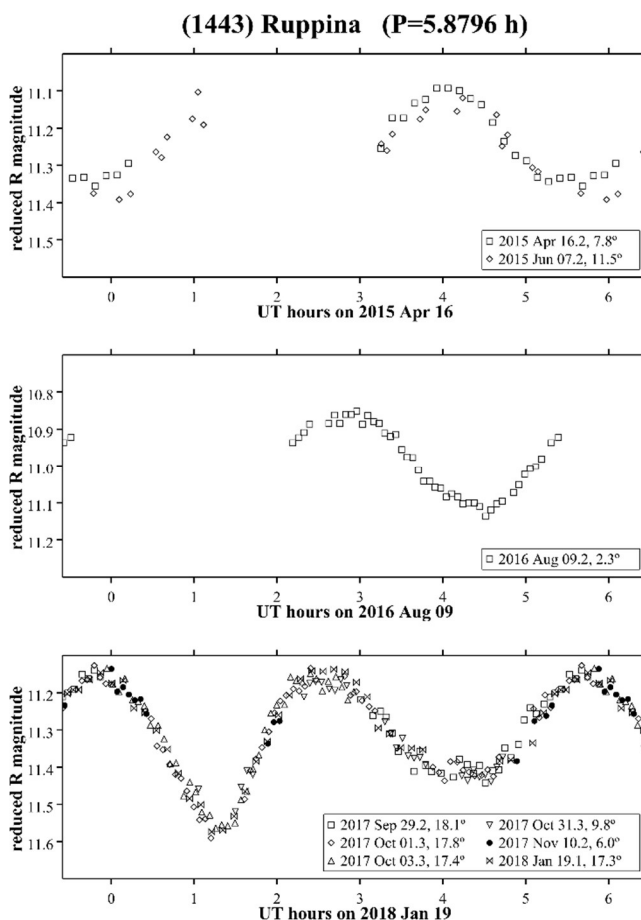


Figure 1. Folded composite lightcurves of (1443) Ruppina showing one rotation period plus the earliest and latest 10% repeated. (Top panel) 2015 apparition; both nights are calibrated to *R* magnitudes and reduced for changing solar phase angle using the MPC adopted value of $G = 0.15$ for the slope parameter. (Center panel) 2016 apparition. (Bottom panel) 2017–18 apparition; the nights of uncalibrated relative photometry have been shifted in brightness for best fit to the Jan 19 calibrated *R* lightcurve.

Applying the “sieve algorithm” of Slivan (2013) to the epochs measured from these lightcurves, in combination with epochs from the lightcurves recorded in 2007 and 2014 (Neugent and Slivan, 2008; Arredondo et al., 2014), confirms that these five apparitions (Table III) are sufficient to unambiguously count rotations over the entire data set—there is only one possible solution for the sidereal rotation period (Fig. 2) which indicates that the data are suitable to credibly attempt analysis for the spin pole.

Sidereal Photometric Astrometry (SPA) (Slivan, 2014; Drummond et al., 1988) locates a single merged pole region surrounding the north ecliptic pole (Fig. 3, left panel) with a corresponding sidereal period of 5.87941 h. Having thus determined that the rotation is prograde, convex inversion (CI) (Kaasalainen et al., 2001) trial poles were then run for the north ecliptic hemisphere (Fig. 3, right panel). Even though this lightcurve data set from only five apparitions is sufficient to determine an unambiguous sidereal period and prograde rotation, the trial pole fits from CI do not fully resolve the pole location, identifying instead two pairs of symmetric possible pole regions. Agreement with the SPA pole region distinguishes the correct solution regions as the pair closest to the north ecliptic pole. A summary of the analysis results is presented in Table V, and graphs of the P_1 solution model lightcurve fits to the entire data set used are presented in Fig. 4. As is discussed in a companion paper (Slivan, 2021; this issue) the pole results reported here differ markedly from those of Stephens and Warner (2020). Finally, a rendering of the P_1 CI model shape is shown in Fig. 5, mindful that any model shape based on a limited lightcurve data set such as that used here is necessarily very coarse.

UT date	Inst. ID	Observer(s)
2015 Apr 16	Ap8p	Slivan
2015 Jun 07	Ap8p	Slivan, Kurzner
2016 Aug 09	Ap8p	Slivan
2017 Sep 29	SBIG	Miller, Gordon, Sheraden Cox
2017 Oct 01	SBIG	Slivan, Shi
2017 Oct 03	SBIG	Sheraden Cox, Gordon
2017 Oct 31	SBIG	Gordon, Zdanky, Sheraden Cox
2017 Nov 10	SBIG	Sheraden Cox
2018 Jan 19	FLI	Slivan

Table I: Nightly observing information. Columns are: UT date, instrument ID (see Table II), and observers.

Inst. ID	CCD camera	FOV (')	Bin	Scale ("/pix)
Ap8p	Apogee AP8p	19×19	2×2	1.2
SBIG	SBIG STL-1001	16×16	1×1	0.9
FLI	FLI-PL23042	20×20	2×2	1.2

Table II: Cameras used. Columns are: instrument ID, CCD camera, detector field of view, image binning used, and binned image scale.

Years observed	Number of apparitions	λ_{PAB} observed (°)
2007–2018	5	62, 69, 147, 226, 322

Table III: Summary of lightcurve data set used for the period, pole, and shape analyses. Columns are: years spanned by the lightcurves, the number of different apparitions observed, and a list of the ecliptic longitudes of the phase angle bisector near the mid-date of the observations from each apparition.

Epoch pair index	Interval (d)	Interval (app.)	Epochs source apparitions
0	415.9	1	2016, 2017–18
1	417.0	1	2014, 2015
2	481.1	1	2015, 2016
3	897.0	2	2015, 2017–18
4	898.1	2	2014, 2016
5	1314.0	3	2014, 2017–18
6	2300.0	5	2007, 2014
7	2717.0	6	2007, 2015
8	3198.1	7	2007, 2016
9	3614.0	8	2007, 2017–18

Table IV: Time intervals between lightcurve epochs used to identify the ranges of possible sidereal periods. Columns are: the epoch pair index label used in Fig. 2, the interval length rounded to 0.1 d, the corresponding integer count of elapsed apparitions, and identification of the apparitions from which the defining epochs were measured.

sidereal period: 5.8794084 ± 0.0000014 h				
		λ (°)	β (°)	ε (°)
spin poles and	P1	160 ± 3	+79 ± 5	11
obliquities:	P2	358 ± 3	+79 ± 5	11
model axial ratios: a/b ~ 1.2; b/c undetermined				

Table V: Summary of period, pole, and model shape results. The error for the sidereal period was calculated for the CI pole location using SPA, and the errors for the pole coordinates are given in degrees of arc and were estimated based on the chi-square distribution of the CI fits to trial poles. The spin obliquities ε are the angles between the orbit pole and the spin poles. The a/b axial ratio is a necessarily coarse estimate, and b/c cannot credibly be determined for this object whose viewing aspects are always close to equatorial.

Acknowledgments

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Number	Name	yyyy mm/dd	Phase	L_{PAB}	B_{PAB}	Period(h)	P.E.	Amp	A.E.
1443	Ruppina	2015 04/16–06/07	*7.8, 11.5	226	+2			0.25	0.02
1443	Ruppina	2016 08/09	2.3	322	+1			0.26	0.02
1443	Ruppina	2017 09/29–2018 01/19	*18.1, 17.3	62	–2	5.8796	0.0002	0.43	0.03

Table V: Observing circumstances and results. Solar phase angle is given for the first and last dates; an asterisk indicates that the phase angle reached a minimum within that interval. L_{PAB} and B_{PAB} are the phase angle bisector longitude and latitude at mid-date range.

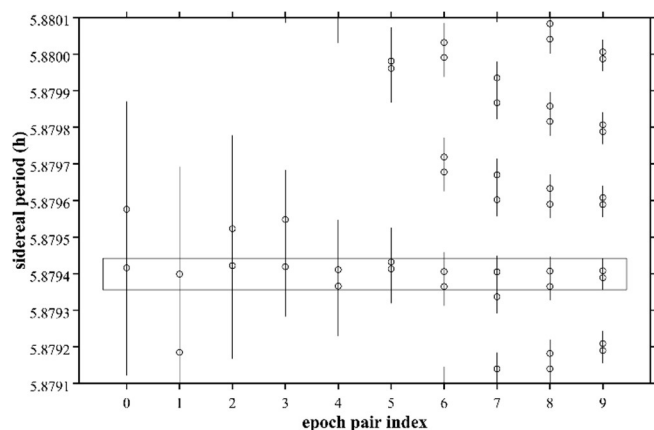


Figure 2: Confirmation of unambiguous sidereal rotation counting of (1443) Ruppina, based on epochs measured from the lightcurves from the five observed apparitions, 2007 through 2017–18. The synodic constraint is the improved period 5.8796, adopting $2.5\sigma = 0.0005$ h, and the epoch measurement adopted errors are 15 min which is $1.5\times$ the maximum observed asymmetry of the timing of the extrema in the composite lightcurves. Each horizontal coordinate index corresponds to the time interval between a pair of epochs as detailed in Table IV, ordered with longer intervals to the right. Open circles and vertical bars represent sidereal periods and period ranges, respectively, calculated from every possible number of rotations that could elapse during the interval. The thin horizontal rectangle identifies the single range of periods, 5.879356 to 5.879442 h, that is allowed by all ten time intervals.

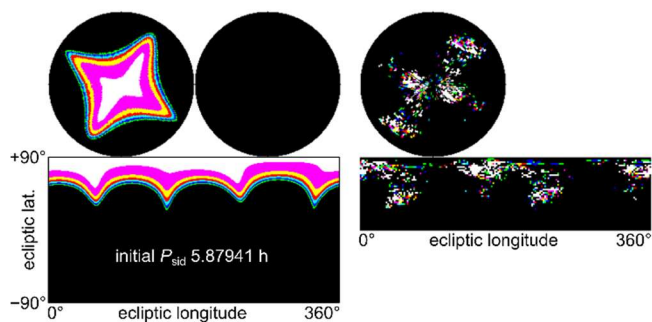


Figure 3: Contour graphs of the “goodness of fit” of trial poles for (1443) Ruppina. (Left panel) From SPA analysis of epochs measured from the lightcurves from the five apparitions observed from 2007 to 2017–18. Trial pole resolution is 1° and best-fit regions are colored white. In the lower half of the graph the celestial sphere is projected on a rectangular grid of ecliptic longitude and latitude. The same data in a polar format undistorted near the ecliptic poles appear in the upper half of the graph, where north- and south-hemisphere views are plotted separately. For Ruppina a single merged prograde pole region is found surrounding the north ecliptic pole. (Right panel) Similar to the left panel, but from CI analysis, for only the north ecliptic hemisphere, with a trial pole resolution of 2° , and using for clarity a color map which highlights only the regions of best fit. Two pairs of symmetric possible pole regions are found; the adopted pair is closest to the ecliptic pole as distinguished by using the SPA graph at left.

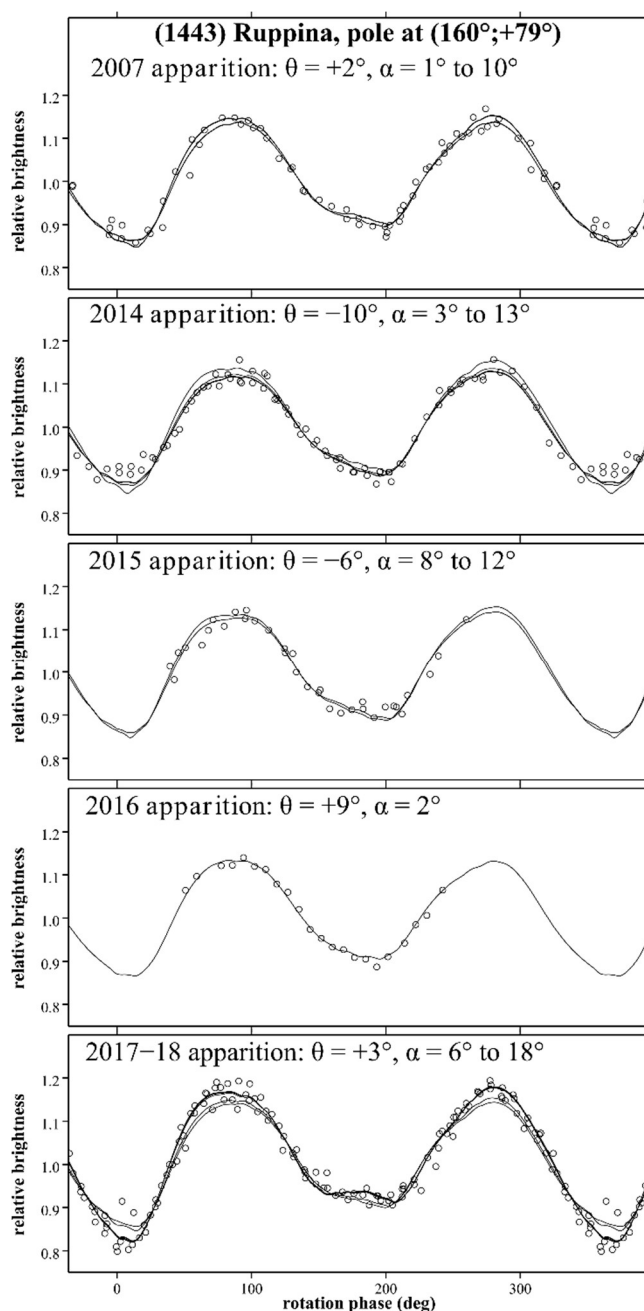


Figure 4: Lightcurve fits for (1443) Ruppina with pole P_1 , plotted at identical vertical scales as brightness vs. sidereal rotation phase, with open circles for observed brightnesses and solid curves for the model. Changes in the lightcurve shape during the course of the observations appear as non-overlapping model curves. θ is the sub-PAB latitude and α is the included range of solar phase angles.

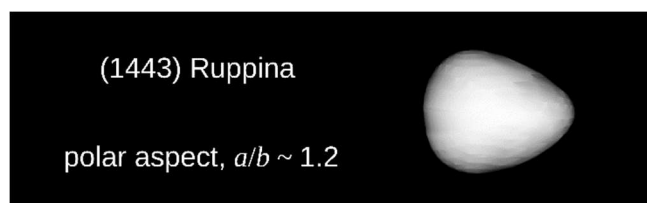


Figure 5: P_1 model rendering of (1443) Ruppina, fully illuminated using an artificial scattering law to better visualize the shape. In absence of information in the lightcurves to scale the model along the polar axis, only the pole-on view shown is constrained.

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

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New CCD photometric observations of the Hilda member 1038 Tuckia were made at the Center for Solar System Studies in 2021 February and March. Analysis of the resulting data indicate that the asteroid may be in non-principal axis rotation (NPAR), i.e., tumbling.

CCD photometric the Hilda asteroid 1038 Tuckia were 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.

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.

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.

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 $\leq \pm 0.03$ 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.