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LIGHTCURVE ANALYSIS FOR NINE NEAR-EARTH ASTEROIDS OBSERVED BETWEEN 2009 - 2023

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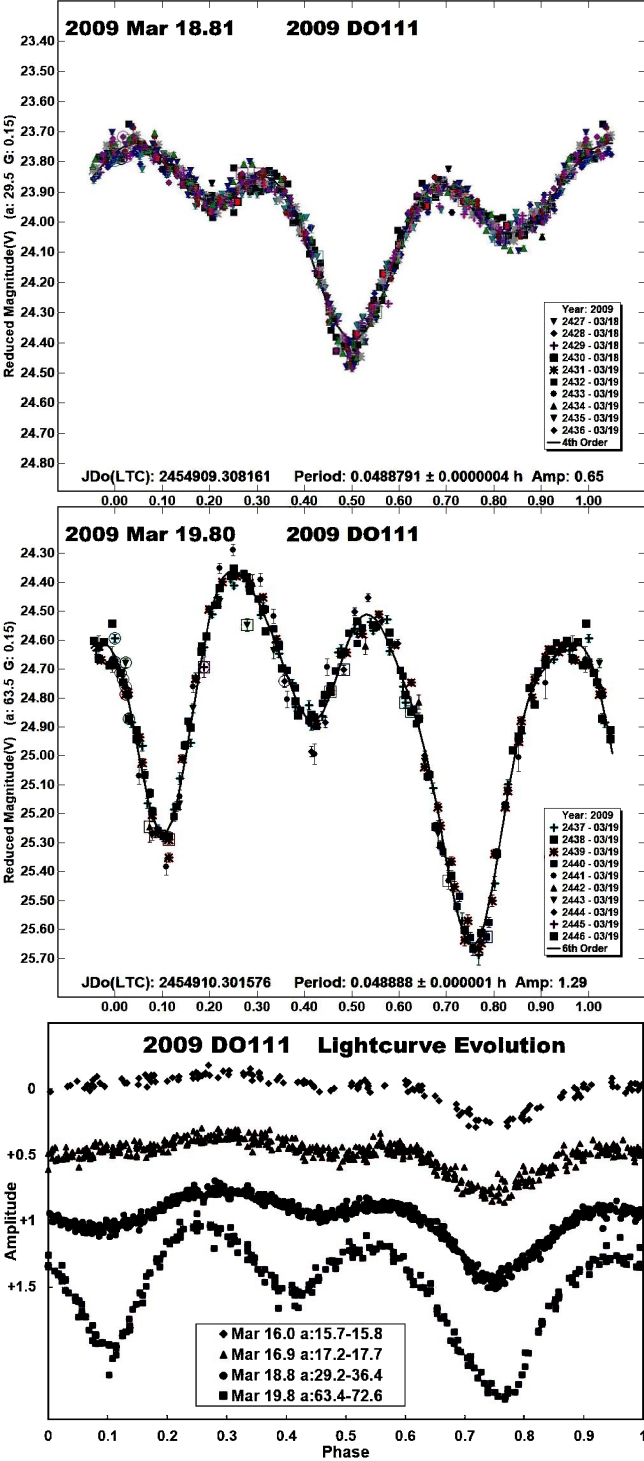
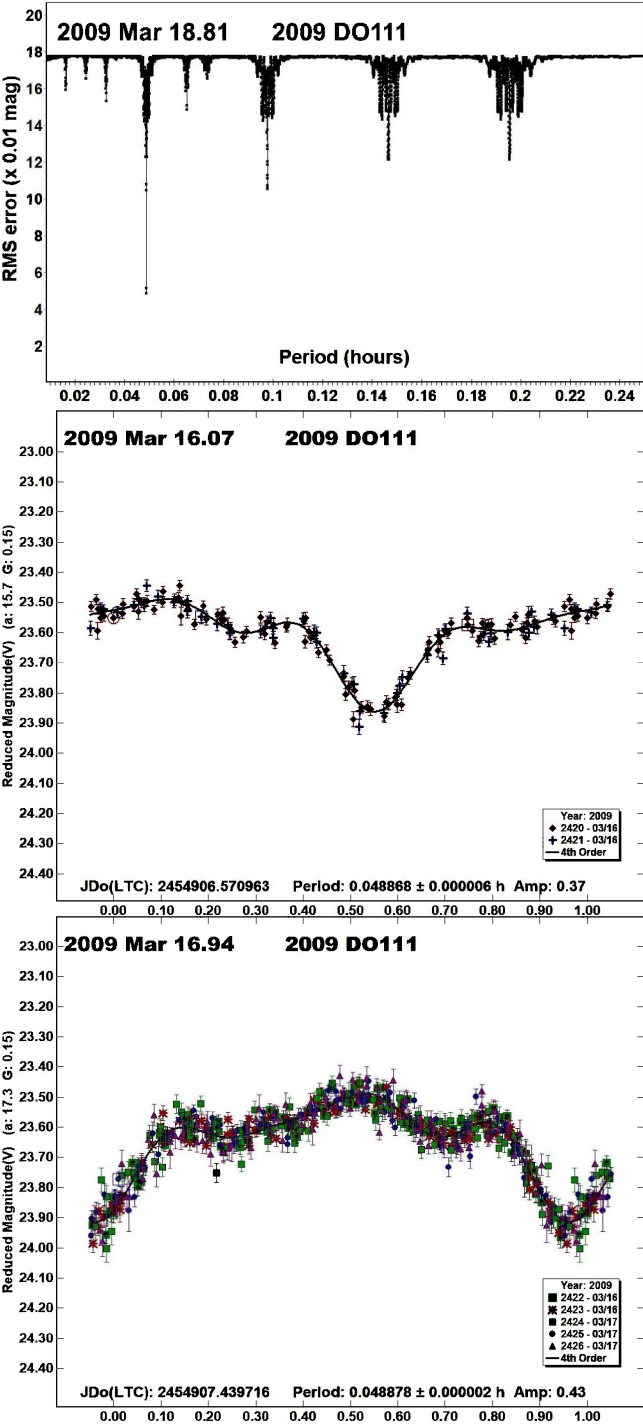
Lightcurves and amplitudes for 9 near-Earth asteroids observed from Great Shefford Observatory during close approaches between 2009 - 2019 and August - November 2023 are reported. All are fast or superfast rotators, seven having periods less than 4 minutes, with 2023 TC7 having a period of 12.7 seconds. One has a reliably detected tumbling rotation and another is a possible tumbler.

Photometric observations of near-Earth asteroids during close approaches to Earth in 2009 - 2019 and August - November 2023 were made at Great Shefford Observatory using a 0.40-m Schmidt-Cassegrain and Apogee Alta U47+ CCD camera. All observations were made unfiltered and with the telescope operating with a focal reducer at f/6. The 1K×1K, 13-micron CCD was binned 2×2 resulting in an image scale of 2.16 arc seconds/pixel. All the images were calibrated with dark and flat frames and *Astrometrica* (Raab, 2023) was used to measure photometry using APASS Johnson V band data from the UCAC4 catalogue (Zacharias et al., 2013). *MPO Canopus* (Warner, 2023), incorporating the Fourier algorithm developed by Harris (Harris et al., 1989) was used for lightcurve analysis.

No previously reported results have been found in the Asteroid Lightcurve Database (LCDB) (Warner et al., 2009), from searches via the Astrophysics Data System (ADS, 2023) or from wider searches unless otherwise noted. All size estimates are calculated using H values from the Small-Body Database Lookup (JPL 2023b), using an assumed albedo for NEAs of 0.2 (LCDB readme.pdf file) and are therefore uncertain and offered for relative comparison only.

2009 DO111. This Apollo made a very favourable approach to 1.2 Lunar Distances (LD) from Earth on 2009 Mar 20.2 UTC, nearly 1 month after discovery (Tubbiolo et al., 2009) and will not come closer before 2146. It was followed on four nights, observations starting on 2009 Mar 16.07, 16.94, 18.81 and 19.80 UTC as it brightened from 15th to 12th magnitude on its approach. Reductions from each night produced very similar period spectra, period determinations of 0.04889 h = 176 s and trimodal lightcurves. A representative period spectrum is given from the night of 2009 Mar 18.81, all the minima are related, either integer multiples or small integer fractions (3/2, 4/3, 2/3, 1/2, 1/3) of the best fit period. Independent lightcurves are given for the four nights, for each the Y-axis has been forced to 1.4 magnitudes to aid comparison of the changing amplitude (increasing from 0.37 to 1.29 magnitudes) as the phase angle increased from 16° to 73°. Small zero-point corrections have been made to sessions in the individual lightcurves to minimise scatter in the curves, RMS values of the adjustments for the four nights Mar 16.1, 16.9, 18.8 and 19.8 are 0.01, 0.04, 0.07 and 0.05 respectively. A 'Lightcurve Evolution' plot is given, aligning the deepest minima apparent on each separate night and displacing each night by 0.5 magnitudes vertically to avoid overlap. The key indicates the dates and range of phase angles each covers.

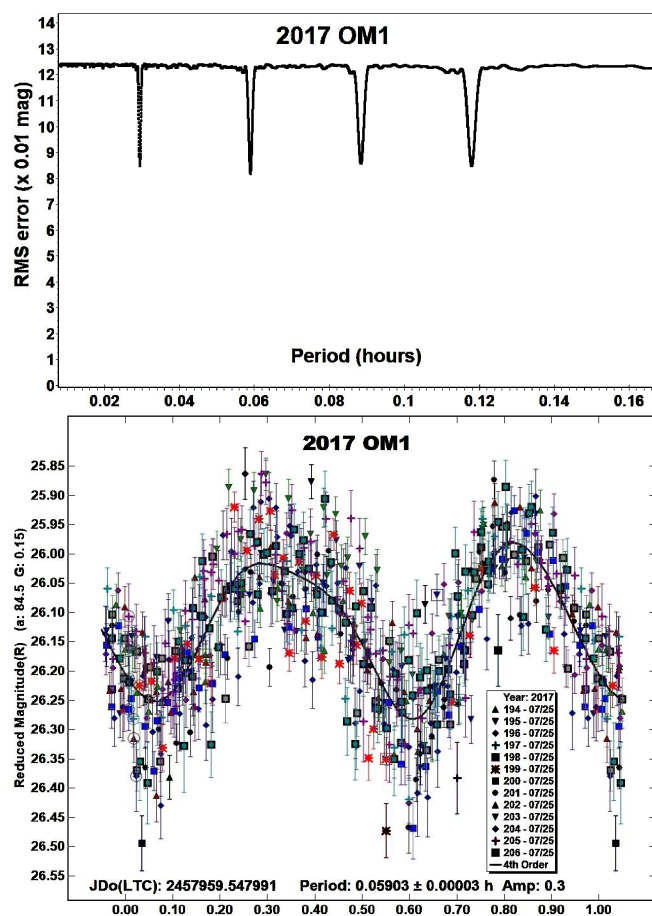
A number of other results for 2009 DO111 have been published previously and are listed here together with the dates covered by the respective lightcurves: 2009 Mar 19.9 (Behrend, 2009web), 2009 Mar 16-18 (Koehn et al., 2014), 2009 Mar 17.0 (Vaduvescu et al., 2017) and 2009 Mar 17.31 & Mar 18.27 (Skiff et al., 2019). The lightcurves presented here are in good agreement with these earlier works for their respective dates of coverage. Behrend notes that tumbling may be present, to be re-analysed. Koehn notes that their result suffers from lightcurve smoothing. The same data was then re-analysed and refined in the Skiff paper. Vaduvescu provides a well-defined lightcurve but remarks that their coverage is insufficient to test the tumbling supposition. There is no evidence of tumbling in the four lightcurves presented in the current paper.



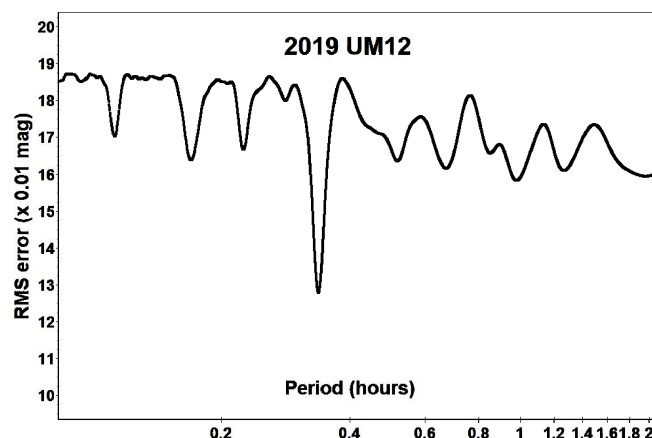
A summary of the data collection circumstances is given in Table I.

Start date	Exp. len (s)	Data points	Span (h)	Observed for (h)
2009 Mar				
Mar 16.07	12	150	2.2	0.64
Mar 16.94	4, 6	498	4.5	1.31
Mar 18.81	4, 6	783	8.8	1.94
Mar 19.80	1.5, 2	249	2.9	0.60

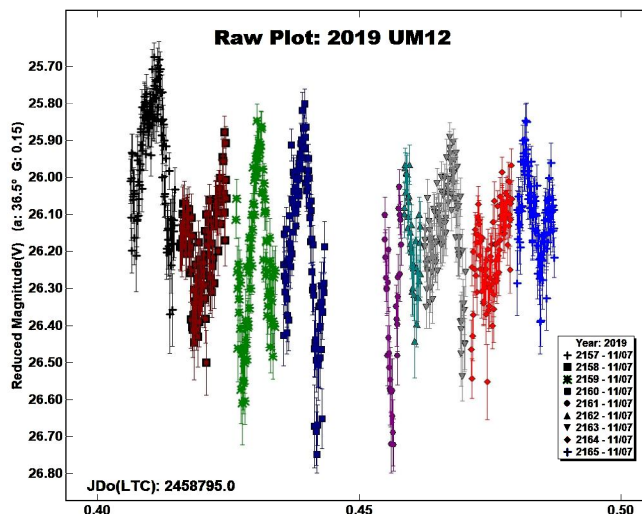
Table I. 2009 DO111 data collection circumstances, listing for each date the exposure lengths used (seconds), number of data points, the number of hours from the first to last data point and the number of hours of continuous observation.



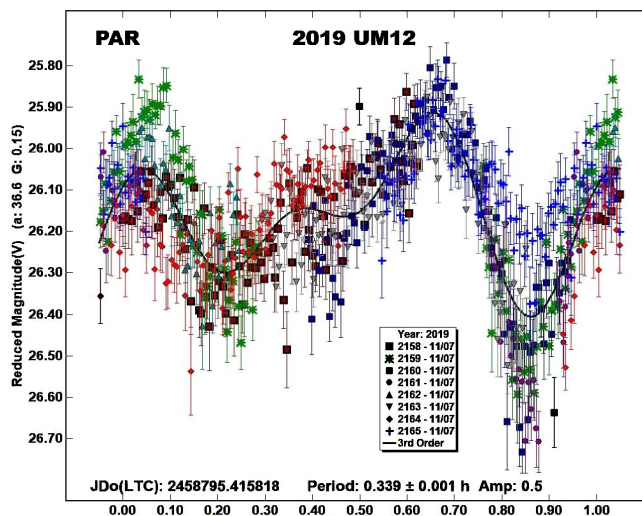
2019 UM12. This Apollo was discovered by the Mt. Lemmon Survey on 2019 Oct 29, 10 days before it passed Earth at 1.3 LD (Bulger et al., 2019). It is listed in the SBDB with $H = 24.7$, suggesting a dia. of ~ 34 m. It was observed for 1.9 h while it was still inbound, starting on 2019 Nov 7.91 UTC when it was 15th mag and large variations in magnitude were obvious within a few minutes. A raw plot of the measurements shows maxima approximately every 10 minutes, suggesting a ~ 20 -minute bimodal period. However, maxima and minima vary in height and attempts to determine the lightcurve with *MPO Canopus* are unsatisfactory, systematic trends indicating that 2019 UM12 is probably tumbling.



The period spectrum locates the dominant period around 0.339 h = 20.3 minutes but also indicates a number of less well-defined minima but no coherent solution for tumbling or non-principal axis rotation can be found.



The first session (marked as 2157 in the raw plot) appears anomalously bright by ~ 0.17 magnitudes, this may be a consequence of tumbling, but potentially more likely is a zero-pointing issue at the start of the observing run. A best fit principal axis rotation (non-tumbling) solution is given marked as PAR rejecting the first session. It is likely that 2019 UM12 is tumbling, with principal period ~ 0.339 h, there are deviations from the main period and a secondary period in the range 0.2 - 0.5 h may be present but this is not established, so it is expected that it may be given a PAR rating of -2 (deviations from a single period are seen but the second period is not resolved) on the scale defined in Pravec et al. (2005).



2023 TM3. This was a Catalina Sky Survey discovery from 2023 Oct 8 which made an approach to 0.4 Lunar Distances (LD) on Oct 10.54 UTC (Bacci et al., 2023). The SBDB lists it as an Aten with $H = 26.9$, indicating an approximate diameter of 12 m and both Sentry (JPL, 2023a) and NEODyS (NEODyS, 2023) list it as a virtual impactor with multiple low probability potential impacts starting in 2082. It was observed for 2.0 h starting at 2023 Oct 10.04 UTC and 770 photometric measurements were obtained. 2023 TM3 was within 1.3 LD and its apparent motion increased from 92 to 124

LIGHTCURVES FOR THREE KORONIS FAMILY ASTEROIDS

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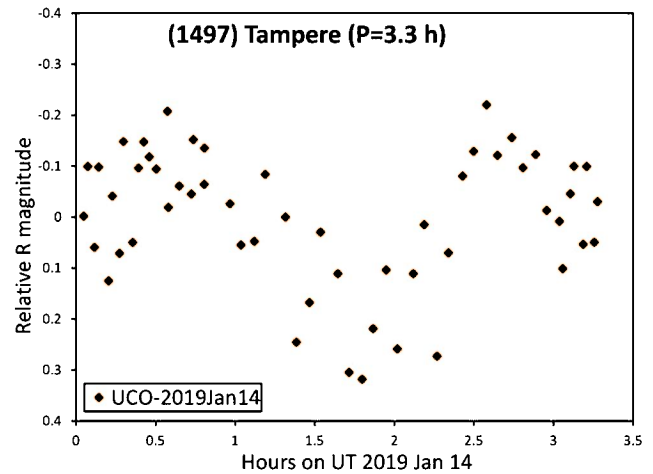
(Received: 2024 January 15)

We present photometry for three Koronis family asteroids, with new synodic rotation periods for two objects with no previously published dense lightcurves: (2470) Agematsu: 2.7952 ± 0.0007 h; and (3856) Luts kij: 7.992 ± 0.0002 h. The lightcurve for (1497) Tampere is consistent with the previously published period.

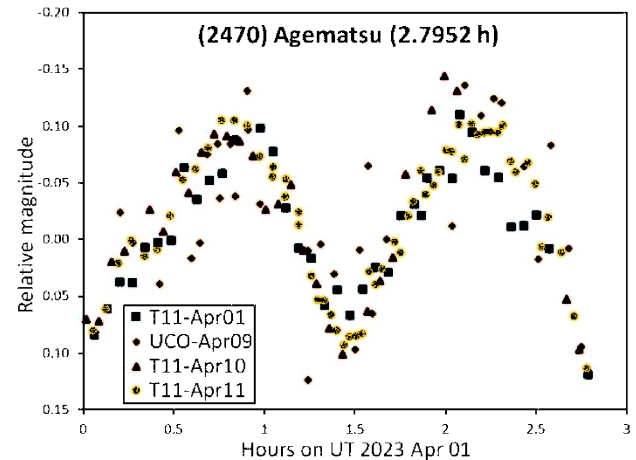
Members of the Koronis family have been shown to possess strongly anisotropic spin vectors clustered in two directions (Slivan, 2002). Thermal radiation torques by the YORP mechanism (Rubincam, 2000) may dominate collisional evolution of asteroid spins for sufficiently small objects of diameter $\lesssim 30$ km in the main asteroid belt. Because YORP torques are more relevant for smaller objects, we continue our project (Wilkin et al., 2022; Wilkin et al., 2023) to increase the sample of known spins for koronis family objects (Slivan et al., 2003; Slivan et al., 2023b). Targets were chosen using the Koronis family web tool (Slivan, 2003), specifically, from the shape/spin list: (1497) Tampere, and from the quality $Q < 3$ list needing more accurate periods: (2470) Agematsu and (3856) Luts kij.

Imaging observations were obtained using four telescopes including the Union College Observatory (UCO) and remote access through the networks iTelescope.net (T11, T21) and Telescope.Live (SPA-2; see Table I). Observation dates and telescopes used are given by the figure legends. All observations used a red filter but specific filters varied by observatory due to availability. Exposure times were 240s and binning 2×2 on all cameras. Images were processed for bias, dark, and twilight flat field corrections. We used *AstroImageJ* software (Collins et al., 2017) to process the Union College images and to perform photometry on all images. NASA Horizons ephemerides (NASA, 2024) were used to apply light-time corrections and to obtain parameter values for phase and phase angle bisector appearing in Table II.

1497 Tampere. Rotation period and lightcurves were published by Slivan et al. (2023a), who obtained synodic period of 3.30237 ± 0.00015 h. Our single night in 2019 yielded a lightcurve consistent with the previous period and amplitude 0.45 ± 0.06 mag in R.



2470 Agematsu. No published periods or lightcurves were found in the lightcurve database (LCDB, Warner et al., 2009). We performed imaging observations on two telescopes and four nights in April, 2023. Relative magnitudes for a given night were shifted to produce a self-consistent composite. The composite lightcurve results in an estimated period of 2.7952 ± 0.0007 h.



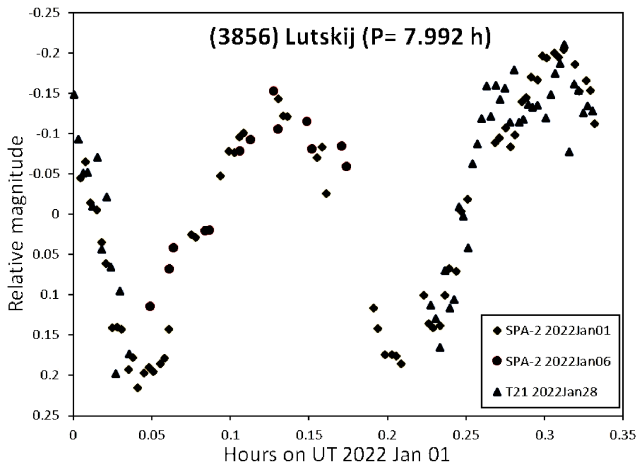
3856 Luts kij. No published periods or lightcurves were found in the lightcurve database (LCDB, Warner et al., 2009). We observed remotely on three nights in early 2022 using two telescopes. Relative magnitudes for a given night were shifted to produce a self-consistent composite. The lightcurve is doubly-periodic at a period of 7.992 ± 0.002 h. The amplitude, 0.42 ± 0.03 mag, is sufficiently large that we may exclude the possibility of a singly-periodic lightcurve at one half that period, or a quadruply-periodic lightcurve at double the given period (Harris et al., 2014). Recently, a sparse-survey period has been given by Ďurech and Hanuš (2023) using GAIA DR3 photometry. Their result, 7.9934 h, with unspecified error, is consistent with ours.

Name	Site	Telescope	Camera	Array	Filter	FOV(')	Scale(''/pix)
UCO	Schenectady, NY	0.51-m RC f/8.1	SBIG STXL-11002	2004×1336×9μm	R	30×20	0.93
T11	Beryl Junction, UT	0.50-m CDK f/6.8	FLI-PL11002M	4008×2672×9μm	R	36×54	0.81
T21	Mayhill, NM	0.43-m CDK f/6.8	FLI-PL6303E	3072×2048×9μm	R	33×49	1.92
SPA-2	Oria, Spain	0.70-m RC f/8	FLI-PL16803	2048×2048×9μm	r'	29×29	0.86

Table I. Telescopes and Cameras. UCO = Union College Observatory; RC=Ritchey-Chrétien; CDK = Planewave Corrected Dall-Kirkham Astrogaph. The primary and secondary mirrors of UCO were shifted in early 2021 along with a resurfacing, yielding a slightly altered image scale. Prior to 2021, the image scale was 0.87''/pix.

Number	Name	yyyy mm/dd	Phase	L _{PAB}	B _{PAB}	Period(h)	P.E.	Amp	A.E.	Grp
1497	Tampere	2019 01/14–01/29	1.7	118	0	3.3	0.3	0.45	0.06	Kor
2470	Agematsu	2023 04/01–04/11	*2.6, 2.6	196	4	2.7952	0.0007	0.15	0.02	Kor
3856	Lutskij	2022 01/01–01/29	4.7, 14.7	90	2	7.992	0.002	0.42	0.03	Kor

Table II. Observing circumstances and results. The phase angle is given for the first and last dates. If preceded by an asterisk, the phase angle reached an extremum during the period. LPAB and BPAB are the approximate phase angle bisector longitude/latitude at mid-date range.



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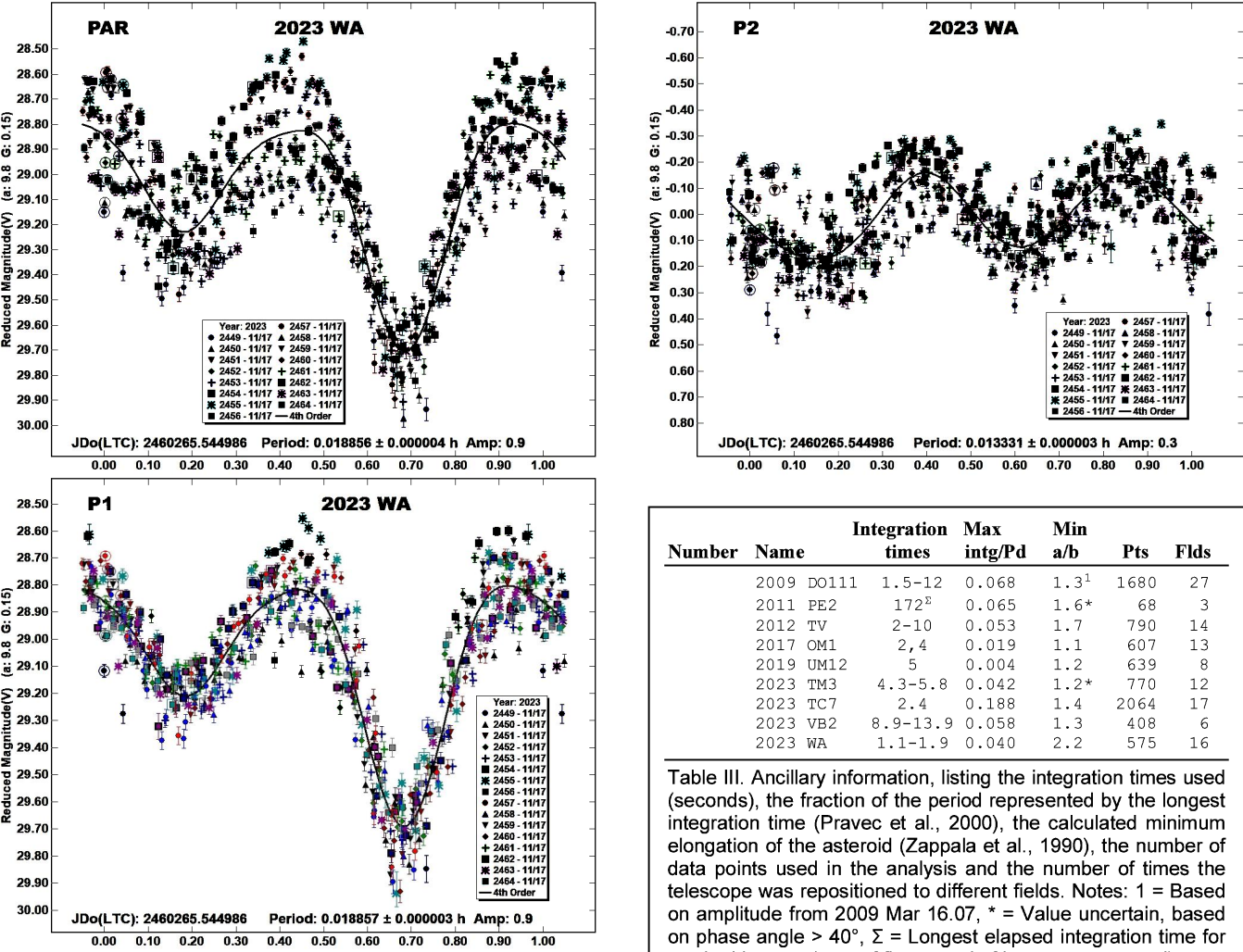
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Number	Name	yyyy mm/dd	Phase	L _{PAB}	B _{PAB}	Period(h)	P.E.	Amp	A.E	PAR	H
2009	DO111	2009 03/18-03/19	29.2-36.4	173	16	0.0488791	0.0000004	0.65	0.04		22.9
2011	PE2	2011 08/09-08/09	52.1-51.9	341	13	0.740	0.004	1.3	0.3		23.1
2012	TV	2012 10/06-10/07	4.0-9.8	15	-3	0.052611	0.000001	0.72	0.05		25.2
2017	OM1	2017 07/25-07/25	84.6-87.5	342	18	0.05903	0.00003	0.3	0.1		23.4
2019	UM12	2019 11/07-11/07	36.5-38.2	26	1	0.339	0.001	0.5	0.2	-2	24.7
2023	TM3	2023 10/10-10/10	44.9-46.1	36	12	0.038429	0.000006	0.5	0.1		26.9
2023	TC7	2023 10/14-10/14	*9.0-23.3	19	8	0.0035401	0.0000001	0.6	0.1		26.9
2023	VB2	2023 11/06-11/07	16.3-17.9	39	-7	0.06661	0.00002	0.5	0.1		28.2
2023	WA	2023 11/17-11/17	11.0-15.1	48	-1	0.018857	0.000003	0.89	0.15	-3	28.5
						0.013331	0.000003	0.33	0.15		

Table II. Observing circumstances and results. The phase angle is given for the first and last date. If preceded by an asterisk, the phase angle reached an extrema during the period. L_{PAB} and B_{PAB} are the approximate phase angle bisector longitude/latitude at mid-date range (see Harris et al., 1984). Amplitude error (A.E.) is calculated as $\sqrt{2} \times$ (lightcurve RMS residual). PAR is the expected Principal Axis Rotation quality detection code (Pravec et al., 2005) and H is the absolute magnitude at 1 au from Sun and Earth taken from the Small-Body Database Lookup (JPL, 2023b).



Number	Name	Integration times	Max intg/Pd	Min a/b	Pts	Flds
2009	DO111	1.5-12	0.068	1.3 ¹	1680	27
2011	PE2	172 ²	0.065	1.6*	68	3
2012	TV	2-10	0.053	1.7	790	14
2017	OM1	2, 4	0.019	1.1	607	13
2019	UM12	5	0.004	1.2	639	8
2023	TM3	4.3-5.8	0.042	1.2*	770	12
2023	TC7	2.4	0.188	1.4	2064	17
2023	VB2	8.9-13.9	0.058	1.3	408	6
2023	WA	1.1-1.9	0.040	2.2	575	16

Table III. Ancillary information, listing the integration times used (seconds), the fraction of the period represented by the longest integration time (Pravec et al., 2000), the calculated minimum elongation of the asteroid (Zappala et al., 1990), the number of data points used in the analysis and the number of times the telescope was repositioned to different fields. Notes: 1 = Based on amplitude from 2009 Mar 16.07, * = Value uncertain, based on phase angle > 40°, Σ = Longest elapsed integration time for stacked images (start of first to end of last exposure used)

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