LIGHTCURVE ANALYSIS FOR FIVE MAIN BELT ASTEROIDS

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Photometric observations of five main-belt asteroids were obtained from 2014-2023. We derived the following rotational synodic periods: 435 Ella, 4.62267 ± 0.0007 h; 1105 Fragaria, 5.426 ± 0.001 h; 1248 Jugurtha, 12.191 ± 0.002 h; 2343 Siding Spring, 2.10633 ± 0.00003 h; 7055 Fabiopagan, 4.1684 ± 0.016 h. Sideral periods were found for 435 Ella, 4.6228035 ± 5×10^{-7} h, 1105 Fragaria, 5.4314465 ± 2×10^{-6} h; 1248 Jugurtha, 12.190522 ± 5×10^{-5} h; 2343 Siding Spring, 2.106505 ± 2×10^{-6} h: 7055 Fabiopagan, 4.168785 ± 5×10^{-6} h.

We report on the photometric analysis result for five main-belt asteroids made by the Asociación Valenciana de Astronomía (AVA). This work was done from the Astronomical Center Alto Turia (CAAT, MPC J57) located in Aras de los Olmos, Valencia, Observatorio Zonalunar (MPC J08), and Vallbona Observatory with MPC code J67, operated by members of the Valencian Astronomy Association (AVA, *http://www.astroava.org*). This database shows graphic results of the data, mainly lightcurves with the plot phased to a given period.

Observatory	Telescope (meters)	CCD
C.A.A.T. (J57)	0.45 DK	SBIG STL-11002
Zonalunar (J08)	0.20 NW	QHY6
Vallbona (J67)	0.25 SCT	SBIG ST7-XME

Table I. List of instruments used for the observations.

In this article, we focused on asteroids for which we had data from several appearances, both obtained by us and from data published in the Asteroid Data Exchange Format web site (ALCDEF; *https://alcdef.org*). The hope was to be able to calculate the rotation periods with greater accuracy.

Images were measured using *MPO Canopus* (Bdw Publishing) with a differential photometry technique. The comparison stars were restricted to near solar-color to minimize color dependencies, especially at larger air masses. The lightcurves show the synodic rotation period. The amplitude (peak-to-peak) that is shown is that for the Fourier model curve and not necessarily the true amplitude.

In a second step we used the method given by Slivan (2012; 2013, Eqs. 3-5, implemented on *http://www.koronisfamily.com*). With this method, from the maximum lux of different apparitions, we tried to limit the error intervals to know exact number of rotations of the asteroid, which univocally leads us to know its sidereal period. This is a valid method for data of the "dense" type, obtained continuously during an entire observation session.

In a third step we use the software *MPO LC Invert (*Bdw Publishing), which uses the inversion method described by Kaasalainen and Torppa (2001) and Kaasalainen et al. (2001). This software uses the code written by J. Durech based on the original FORTRAN code written by Kaasalainen to implement the period Scan. The advantage of this method is that it allows the use of "dense" data such as we obtained together with "sparse" data available in databases from Catalina, Usno, Atlas, Palomar, etc.

This is an iterative method that, based on an initial estimate of the period given by the lightcurve, finds the local minimum of χ^2 and gives the corresponding solution. The procedure starts with six initial poles for each trial period and selects the period that gives the lowest χ^2. If there is a clear minimum in χ^2 when plotted as a function of the period, we can assume it as a correct solution, but is not always a clear one. We include only those asteroids that gave an unambiguous result.

The range of periods to be scanned is reduced, since we know the synodic period of the asteroid, having solved the lightcurves for several apparitions. This saves time in calculations. When making the calculation, weighted coefficients were used to take into account the density of the data. We assigned a value of 1 to "dense" data and a value of 0.3 for "sparse" data.

Error estimates in the inversion method are not obvious. The smallest separation, ΔP, of the local minima (Kaasalainen et al. 2001) in the period parameter space is roughly given by

$$\Delta P \approx 0.5 \text{ x } P^2/\Delta t$$

where Δt is the full epoch range of the data set. This derives from the fact that the maxima and minima of a double sinusoidal lightcurve for periods P and P ± ΔP are at the same epochs after Δt time.

As stated by Kaasalainen et al. (2001), "The period error is mostly governed by the epochs of the lightcurves. If the best local χ^2 minimum of the period spectrum is clearly lower than the others, one can obtain an error estimate of, say, a hundredth part of the smallest minimum width ΔP since the edge of a local minimum ravine always lies much higher than its bottom".

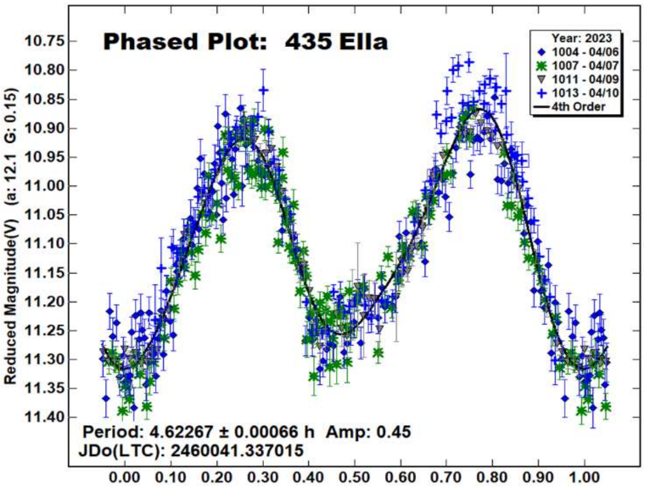
Durech et al. (2016) proposes an estimate of error of

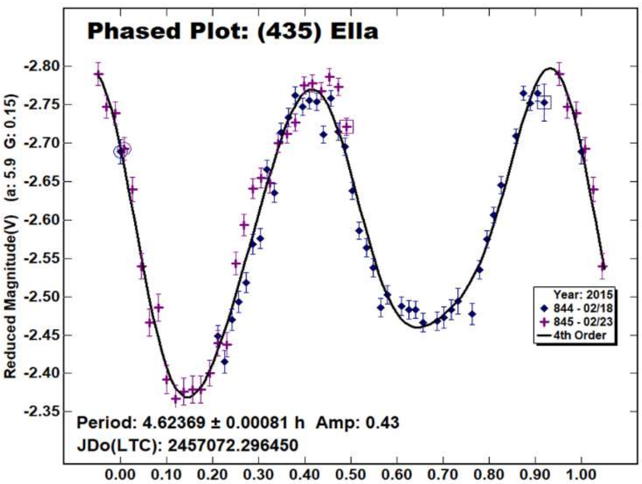
$$\Delta P \approx (1/10 \text{ x } 0.5) \text{ x } P^2/\Delta t$$

1/10 means that the period accuracy is 1/10 of the difference between local minima in the periodogram.

Once the period and period error were determined, we made a final adjustment with the Slivan method in order to find the best period approach.

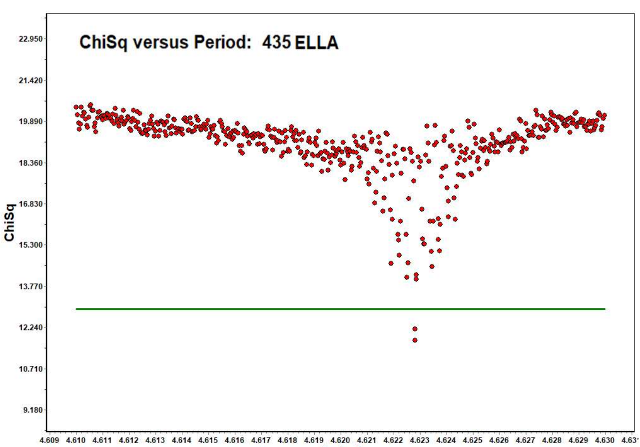
<u>435 Ella</u>. This inner main-belt asteroid was discovered on 1898 Sep 11 by M.F. Wolf and A. Schwassmann, at Heidelberg. We made observations on 2023 Apr 6-10. From our data, we derived a synodic rotation period of 4.62267 ± 0.0007 h and an amplitude of 0.45 mag Observations from 2015 Feb 8-23 led to a period of 4.624 ± 0.008 h with an amplitude of 0.44 mag, Dose (2020), whose data are available on the ALCDEF site, found a 4.622 h period. Marciniak et al. (2012) found 4.622802 looking for the spin axis.





We tried the method given by Slivan for data from 2020-2023, which were the closest-in-time apparitions in the data set. Unfortunately, the errors were too large to reach a unique solution.

We used *MPO LCInvert* with data from surveys Catalina (536 points, 2003/11/21 - 2023/3/28), Palomar (117 points, 2015/1/50 - 2022/5/13), USNO (200 points, 1998/9/14 - 2013/8/10), and Atlas (962 points, 2017/7/29 - 2023/3/25) with a weight of 0.3 and all the dense data referred were given a weight of 1.0. The result is a sidereal period of 4.622853 h.



A generic estimate of period error is given by

$$P_{err} = 10/360 \times P^2/T$$

where P is the period and T is the total time range of the data. The based on the 2020-2023 is 4×10^{-5} h. We again used the Slivan method with maximum lightcurve times of

2015 Feb 23: JD 2457077.38572020
2020 May 19: JD 2458988.7799
2023 Apr 10: JD 2460045.3379

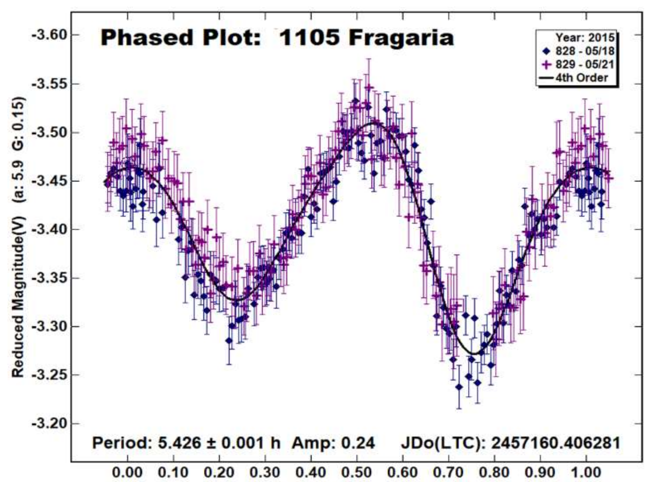
The new error of 0.00004 h gives an unambiguous solution of 4.6228035 ± 0.0000007 h with an amplitude of 0.24 mag. Marciniak et al. (2012) found a period of 4.622802 h.

1105 Fragaria. This outer main-belt asteroid was discovered on 1929 Jan 1 by K. Reinmuth at Heidelberg observatory. We made observations from 2015 May 18-21. From our original data, we derived a synodic rotation period of 5.426 ± 0.001 h and an amplitude of 0.24 mag. On the ALCDEF site, we found data from T. A. Polakis obtained 2017 Dec 18-23 (Polakis, 2018) with a period of 5.4312 ± 0.0008 h.

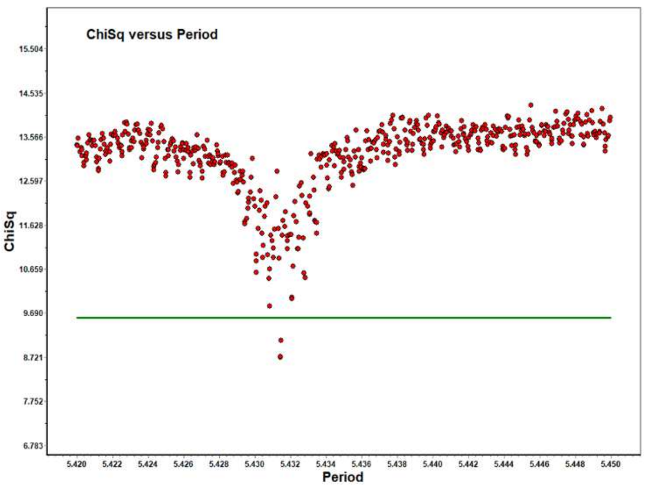
The times of the maximum lightcurve values applied in the Slivan method were:

2015 May 21: JD 2457164.4780
2017 Dic 21: JD 2458108.6573

Unfortunately, the result was ambiguous because our error interval was too wide to get a unique solution.



The “period scan” feature in *MPO LCInvert* used data weighted 0.3 from several all-sky surveys: Catalina (347 points, 2003/5/5 - 2023/4/2), Palomar (40 points, 2014/3/5 - 2021/11/22), USNO (187 points, 1998/4/4 - 2013/1/13), and ATLAS (1,173 points, 2017/11/23 - 2023/4/1). Dense data from our own observations and Polakis were given 1.0. We found a sidereal period of 5.431447 h ± 0.00005 h.



Using this more accurate solution win the Slivan method gave an unambiguous sidereal period of 5.4314465 ± 0.000002 h with an amplitude of 0.24 mag. Durech et al. (2018) found a period of 5.431437 h and Martikainen et al. (2021) found 5.431440 h.

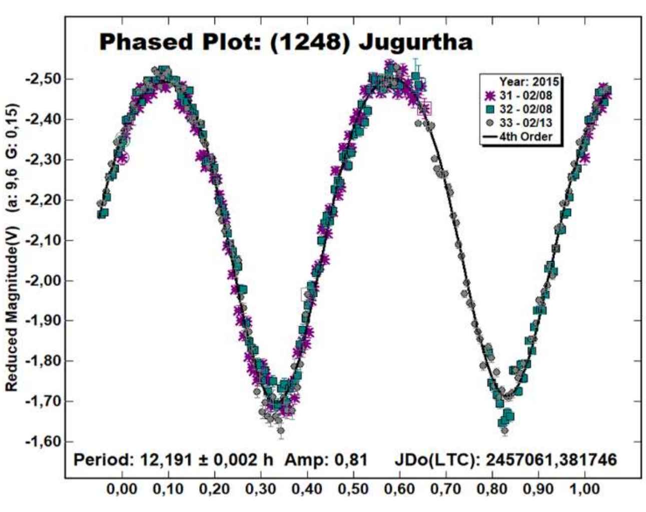
1248 Jugurtha. This middle main-belt asteroid was discovered on 1932 Sep 1 by C. Jackson at Johannesburg We made observations from 2015 Feb 8-13. From our data, we derived a rotation period of 12.191 ± 0.002 h and an amplitude of 0.81 mag. Durech et al. (2016) found 12.19047 h looking for the spin axis. Worman and Olson (2004) found 12.190 h and Koff (2002) found 12.1897 h.

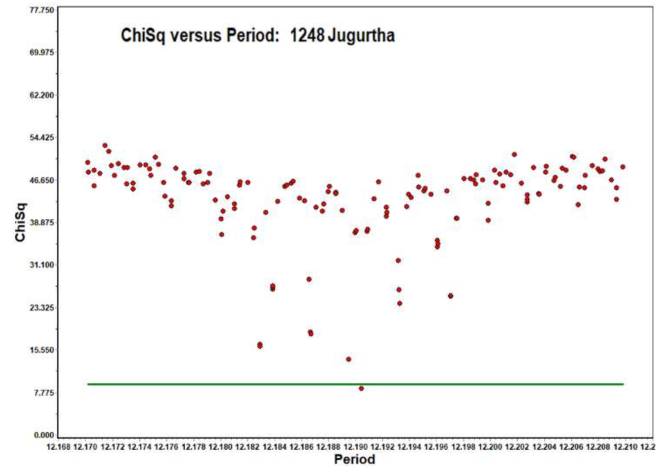
The period scan used sparse data (all weighted 0.3) from Catalina (450 points, 2005/10/2 - 2023/1/22), Palomar (123 points, 2014/12/22 - 2021/1/18), USNO (214 points, 1998/3/3 - 2012/6/2), and ATLAS (896 points, 2017/6/18 - 2023/1/24) and dense data (weight = 1.0) from our own observations and Koff. The result was a sidereal period of 12.19047 h ± 0.00005 h, which agrees with Durech et al. (2016).

The times for the maximum lightcurve values were

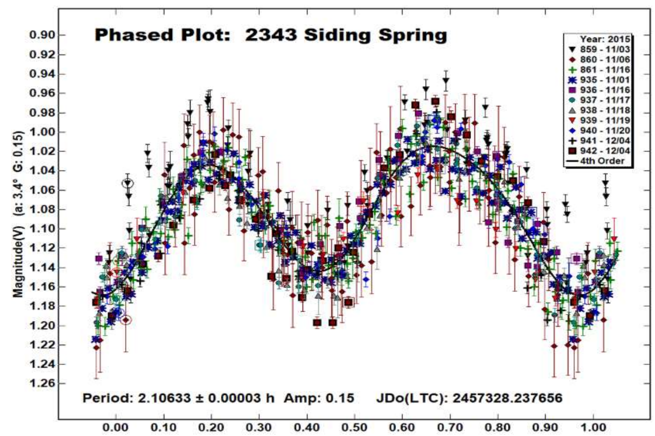
2001 Jan 03: JD 2451912.5341
2015 Feb 13: JD 2457067.2710

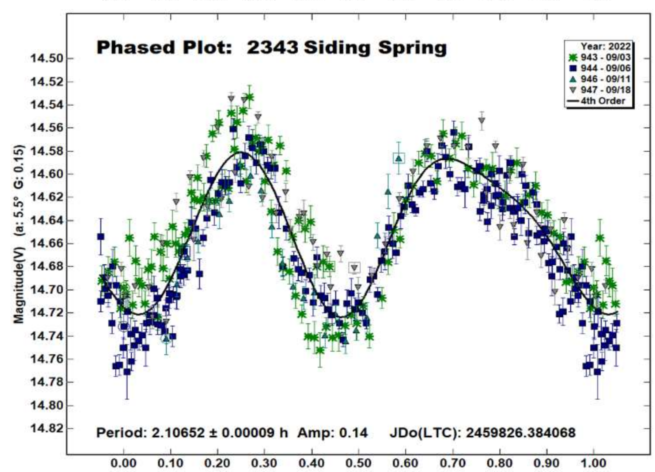
This gave a new error of 0.00005 h and an unambiguous solution with Slivan method of 12.190522 h with an amplitude of 0.24 mag.





(2343) Siding Spring. This inner main-belt asteroid was discovered on 1979 Jun 25 by E.F. Helin and S.J. Bus at Siding Spring, Australia. We made observations from 2015 Nov 03-16. On the ALCDEF site, we found data from Julian Oey (2015/11/16-12/19) and Vladimir Benishek (2015/11/01-12/04).





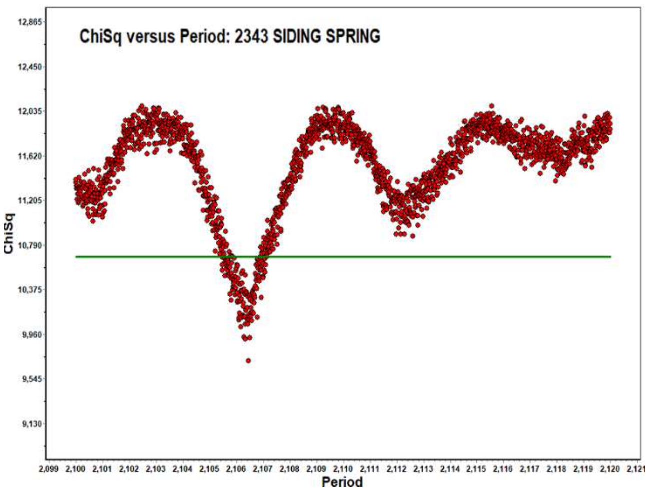
Since these data were from the same apparition, we joined them to ours to improve the quality of the result. The result was a rotation synodic period of 2.10633 ± 0.00003 h and an amplitude of 0.15 mag. In ALCDEF we also found data from 2022 by R.G. Farfan (2022/9/3), F. García (2022/9/3-18), E.F. Mananes (2022/9/6-10), and E. Fernández (2022/9/6-10). Including these data found a synodic period of 2.10652 ± 0.00009 h and an amplitude of 0.15 mag.

We use again the calculation method given by Slivan. The times of the maximum values in the lightcurves were:

2015 Nov 1: JD 2457328.4305
2022 Sep 6: JD 2459828.5125

The resulting error 0.00003 h was too large to reach a unique solution.

Sparse data from Catalina (465 points, 2003/4/22 - 2023/3/5), Palomar (43 points, 2019/8/28 - 2022/6/29), and ATLAS (566 points, 2017/6/15 - 2023/3/18) in the period scan found a sidereal period of 2.106498 ± 0.000002 h.



With this new error restriction, we applied the Slivan method, arriving at a unique sidereal period solution of 2.106505 h. Pollock et al. (2015) and Oey et al. (2017) found synodic periods of 2.10637 and 2.10639 h, respectively and Behrend (2015web) got 2.10659 h, all of which are consistent with our results. We could not confirm their discovery of a satellite for the asteroid.

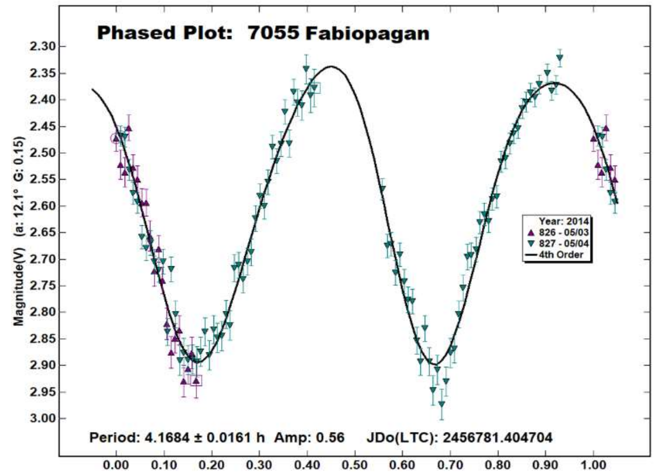
<u>(7055) Fabiopagan</u>. This inner main-belt asteroid was discovered on 1989 May31 by H.E. Holt at Palomar. We made observations from 2014 May 03-05 and found a synodic rotation period of 4.1684 ± 0.016 h and an amplitude of 0.56 mag. Pravec (2007web) and Stephens (2007) found a period of 4.16845 h. We merged the two groups of data from 2007 available in ALCDEF and obtained a synodic period of 4.16847 ± 0.00005 h and an amplitude of 0.6 mag.

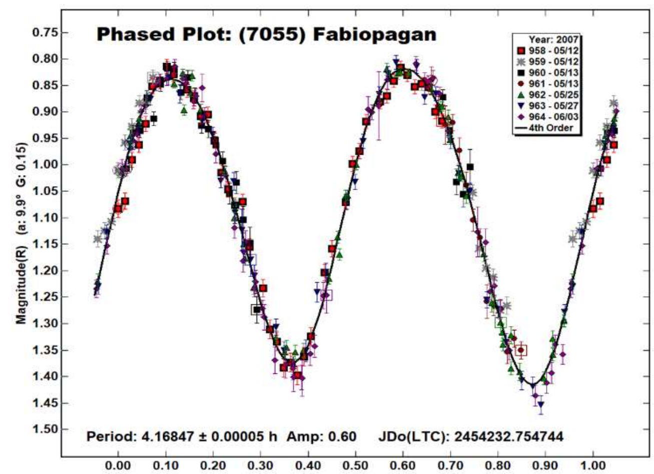
We used the period scan with sparse data (w = 0.3) from Catalina (562 points, 2005/11/4 - 2023/3/28), Palomar (180 points, 2014/12/22 - 2021/1/18), USNO (214 points, 2014/4/24 - 2021/6/12), and ATLAS (650 points, 2017/6/20 - 2023/3/18) and dense data from our own observations (2014), Pravec et al. (2007web), and Stephens (2007) with a weight of 1.0. These led to a sidereal period of 14.168782 ± 0.000005 h, which agrees with Hanus et al. (2013), who found 4.168782 h.

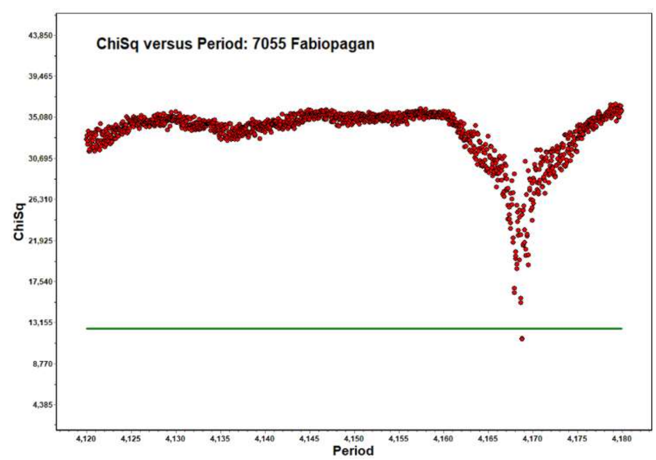
We used Slivan's method with maximum lightcurves values at

2014 May 03: JD 2456781.5647
2007 May 12: JD 2454232.77407

From this, we got an unambiguous sidereal period of 4.168785 h. This matches Hanus et al. (2013), who found 4.16878 h.







Acknowledgements

We would like to express our gratitude to Brian Warner for supporting the CALL web site and his suggestions and to Dr. Stephen Slivan for his advice.

Number	Name	yyyy mm/dd	Phase	L_{PAB}	B_{PAB}	Period(h)	P.E.	Amp	A.E	Grp
435	Ella	2015 02/18-02/23	5.8,7.9	135	2	4.62267	0.0007	0.45	0.02	MB-I
	E.V. Dose	2020 05/18-05/27	*3.2,1.4	243	-2					
1105	Fragaria	2015 05/18-05/21	5.1,5.8	247	11	5.426	0.001	0.24	0.02	MB-O
	T.A. Polakis	2017 12/18-12/23	2.6,2.9	87	-7					
248	Jugurtha	2015 02/08-02/13	9.9,11.7	117	8	12.191	0.002	0.81	0.02	MB-M
	R.A. Koff	[21]2000 11/29-01/11	22.7,20.5	160	-4					
2343	Siding Spring	2015 11/03-03/16	3.4,11.6	36	0	2.10633	0.00003	0.15	0.02	MB-I
	Julian Oey	2015 11/16-12/19	11.7,25.6	41	-1					
	V. Benishek	2015 11/01-12/04	2.1,21.0	41	0					
	R.G Farfan	2022 09/03	6.1	348	2					
	F. García	2022 09/03	6.1	348	2					
	E.F. Mananes	2022/09/06-09/10	4.2,2.2	348	2					
	E. Fernández	2022 09/06-09/10	4.2,2.2	348	2					
7055	Fabiopagan	2014/05/03-05/04	12.1-12.2	213	22	4.1684	0.016	0.56	0.02	MB-I

Table I. Synodic Periods. Observing circumstances and results. The phase angle values are for the first and last date. L_{PAB} and B_{PAB} are the approximate phase angle bisector longitude and latitude at mid-date range (see Harris et al., 1984). Grp is the asteroid family/group (Warner et al., 2009). MB-I/M/O: Main-belt inner/middle/outer.

Number	Name	yyyy mm/dd	Phase	L_{PAB}	B_{PAB}	Period(h)	P.E.	Grp
435	Ella	2015 02/18-02/23	5.8,7.9	135	2	4.6228035	0.0000005	MB-I
	E.V. Dose	2020 05/18-05/27	*3.2,1.4	243	-2			
1105	Fragaria	2015 05/18-05/21	5.1,5.8	247	11	5.4314465	0.000002	MB-O
	T.A. Polakis	2017 12/18-12/23	2.6,2.9	87	-7			
1248	Jugurtha	2015 02/08-02/13	9.9,11.7	117	8	12.190522	0.00005	MB-M
	R.A. Koff	[21]2000 11/29-01/11	22.7,20.5	160	-4			
2343	Siding Spring	2015 11/03-11/16	3.4,11.6	36	0	2.106505	0.00000	MB-I
	Julian Oey	2015 11/16-12/19	11.7,25.6	41	-1			
	V. Benishek	2015 11/01-12/04	2.1,21.0	41	0			
	R.G Farfan	2022 09/03	6.1	348	2			
	F. García	2022 09/03	6.1	348	2			
	E.F. Mananes	2022 09/06-09/10	4.2,2.2	348	2			
	E. Fernández	2022 09/06-09/10	4.2,2.2	348	2			
7055	Fabiopagan	2014 05/03-05/04	12.1-12.2	213	22	4.168785	0.000005	MB-I

Table II. Sidereal Periods. Observing circumstances and results. The phase angle values are for the first and last date. L_{PAB} and B_{PAB} are the approximate phase angle bisector longitude and latitude at mid-date range (see Harris et al., 1984). Grp is the asteroid family/group (Warner et al., 2009). MB-I/M/O: Main-belt inner/middle/outer.

References

Behrend, R. (2015web). Observatoire de Geneve web site. *http://obswww.unige.ch/~behrend/page_cou.html*

Dose, E.V. (2020). "A New Photometric Workflow and Lightcurves of Fifteen Asteroids." *Minor Planet Bull.* **47**, 324-330.

Durech, J.; Hanus, J.; Oszkiewsicz, D.; Vanco, R. (2016). "Asteroid models from the Lowell photometric database." *Astron. Astrophys.* **587**, A48.

Durech, J.; Hanus, J.; Ali-Lagoa, V. (2018). "Asteroid models reconstructed from the Lowell Photometric Database and WISE data." *Astron. Astrophys.* **617**, A57.

Hanus, J.; Marchis, F.; Durech, J. (2013). "Sizes of main-belt asteroids by combining shape models and Keck adaptive optics observations." *Icarus* **226**, 1045-1057.

Harris, A.W.; Young, J.W.; Scaltriti, F.; Zappala, V. (1984). "Lightcurves and phase relations of the asteroids 82 Alkmene and 444 Gyptis." *Icarus* **57**, 251-258.

Kaasalainen, M; Torppa, J. (2001). "Optimization Methods for Asteroid Lightcurve Inversion. I Shape Determination." *Icarus* **143**, 24-36.

Kaasalainen, M; Torppa, J.; Muinonen, K. (2001). "Optimization Methods for Asteroid Lightcurve Inversion. II The complete Inversion Problem." *Icarus* **153**, 37-51.

Koff, R.A. (2002). "Lightcurve Photometry of Asteroid (1248) Jugurtha." *Minor Planet Bull.* **29**, 75-76.

Marciniak, A.; Bartczak, P.; Santana-Ros, T.; Michalowski, T.; Antonini, P. and 33 colleagues (2012). "Photometry and models of selected main belt asteroids. IX. Introducing interactive service for asteroid models." *Astron. Astrophys.* **545**, A131.

Martikainen, J.; Muinonen, K.; Penttila, A.; Cellino, A.; Wang, X.-B. (2021). "Asteroid absolute magnitudes and phase curve parameters from Gaia photometry." *Astron. Astrophys.* **649**, A98.

Oey, J.; Williams, H.; Groom, R.; Pray, D.; Benishek, V. (2017). "Lightcurve Analysis of Binary and Potential Binary Asteroids in 2015." *Minor Planet Bull*. **44**, 193-199.

Polakis, T. (2018). "Lightcurve Analysis for Eleven Main-belt Asteroids." *Minor Planet Bull*. **45**, 199-203.

Pollock, J.; Caton, D.; Hawkins, R.; Pravec, P.; et al. (2015). *CBET* **4206**.

Pravec, P.; Wolf, M.; Sarounova, L. (2007web). *http://www.asu.cas.cz/~ppravec/neo.htm*

Slivan, S.M. (2012). "Epoch Data in Sidereal Period Determination. I. Initial Constraint from Closest Epochs." *Minor Planet Bull.* **39**, 204-206.

Slivan, S.M. (2013). "Epoch Data in Sidereal Period Determination II. combining Epochs from Different Apparitions." *Minor Planet Bull*. **40**, 45-48

Stephens, R.D. (2007). "Photometry from GMARS and Santana Observatories - April to June 2007." *Minor Planet Bull.* **34**, 102-103.

Warner, B.D.; Harris, A.W.; Pravec, P. (2009). "The Asteroid Lightcurve Database." *Icarus* **202**, 134-146. *https://minplanobs.org/alcdef/index.php*

Worman, W.E.; Olson, M.P. (2004). "CCD photometry of 1248 Jugurtha". *Minor Planet Bull.* **31**, 42.

LIGHTCURVES OF ELEVEN ASTEROIDS

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We present lightcurves and synodic rotation periods for eleven asteroids including the family parent asteroids 1911 Schubart and 2085 Henan.

We present asteroid lightcurves obtained via the workflow process described by Dose (2020) and later improved (Dose, 2021). This workflow applies to each image, which includes an ensemble of typically 25-80 nearby comparison ("comp") stars selected from the ATLAS refcat2 catalog (Tonry et al., 2018). This abundance of comp stars and our custom diagnostic plots allow for rapid identification and removal of outlier, variable, and poorly measured comp stars.

The product of this custom workflow is one night's time series of absolute Sloan r´ (SR) magnitudes for one target asteroid. These absolute magnitudes are corrected for instrument transforms, sky extinction, and image-to-image ("cirrus") fluctuations, and thus they represent absolute magnitudes at the top of earth's atmosphere. These magnitudes are imported directly into *MPO Canopus* software (Warner, 2021) where they are adjusted for distance and phase-angle dependence, then fit by Fourier analysis including identifying any aliases, and plotted.

Phase-angle corrections are made by applying an *H-G* model and finding the *G* value that minimizes best-fit RMS error across all nights' data for that apparition. When we cannot estimate such a *G* value, usually due to a narrow range of phase angles, we apply the Minor Planet Center's default value of 0.15. No nightly zero-point adjustments (Delta Comps in *MPO Canopus*) were made to any session, other than by estimating *G*.

Lightcurve Results

Eleven asteroids were observed from New Mexico Skies observatory at 2310 meters elevation in southern New Mexico. Images were acquired with: a 0.50-m PlaneWave OTA on a PlaneWave L-500 mount and equatorial wedge, and a SBIG AC4040M CMOS camera cooled to -22°C (or to -15°C after April 22) and fitted with a Schott GG495 yellow filter.

This equipment was operated remotely via *ACP* software (DC-3 Dreams), running one-night plan files generated by python scripts (Dose, 2020). Exposure times targeted 2.5-5 millimagnitudes uncertainty in asteroid instrumental magnitude, subject to a minimum exposure of 90 seconds to ensure suitable comp-star photometry, and to a maximum of 480 seconds.

FITS images were calibrated using temperature-matched, exposure-matched, median-averaged dark images and recent flat images of a flux-adjustable light panel. Calibrated images were plate-solved by *TheSkyX* (Software Bisque) and target asteroids were identified in *Astrometrica* (Herbert Raab). All photometric images were visually inspected; the author excluded images with inadequate tracking or seeing quality, excessive interference by cloud or moon, or having stars, satellite tracks, cosmic ray artifacts, residual image artifacts, or other apparent light sources within 12 arcseconds of the target asteroid's signal centroid. Images passing these screens were submitted to the workflow.