PHOTOMETRY OF MINOR PLANETS. I. ROTATION PERIODS FROM LIGHTCURVE ANALYSIS FOR SEVEN MAIN-BELT ASTEROIDS

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(Received: 9 July)

CCD photometric measurements of the main-belt asteroids 417 Suevia, 453 Tea, 904 Rockefellia, 933 Susi, 1269 Rollandia, 1318 Nerina, and 1465 Autonoma were performed during the period 2010 August to 2012 March. The brightness amplitude and synodic rotation period of the composite lightcurves are presented and commented for each asteroid.

Introduction

A large part of our knowledge on asteroids is derived from their brightness variations. Indeed, shape and periodicities of lightcurves are mainly linked to the rotation rate and to the global morphology of the objects. The collections of lightcurves, built up over several decades, are a fundamental basis to perform statistical analysis, particularly the period distribution of asteroids. For example, and despite observational selection effects, a "spin rate barrier" was highlighted in a diagram of the rotation rate *versus* size (Harris and Pravec, 2005), indicating some clues on the internal structure of asteroids. Lightcurves can help to detect tumbling asteroids as well as binary and multiple asteroid systems. From many apparitions, it's also possible to determine if the Yarkovski and YORP thermal effects induce alterations of the asteroid's rotation rate and state.

Dense and/or sparse photometric observations (e.g., Ďurech *et al.*, 2009), combined with datasets from other techniques (e.g., radar, stellar occultations, thermal radiometry, spectroscopy, polarimetry, adaptative optics, interferometry) and analysed with powerful inversion methods, allow one to model and give a good approximation of the physical properties of the minor bodies, such as their spin state, 3-D morphology and scattering characteristics of the surface.

These characterization studies are bricks which contribute to built the knowledge on the composition and internal structure of the asteroids (e.g., Binzel *et al.*, 2003; Michel, 2009; Carry, 2012), as well as on their formation, collisional and rotational evolution, thermal evolution, dynamics, and interrelations with other solar systems bodies (see reviews edited by Bottke *et al.*, 2002, and also, e.g., Asphaug, 2009, and Nesvorný *et al.*, 2011).

Dense photometry is a time consuming technique – a constraint for professional astronomers. However, as small diameter telescopes remain useful, amateur astronomers – the "Masters of time"! – can play a role by their contribution to the observational effort (e.g. Fauvaud, 2009; Warner, 2009). It is in this context that we observe asteroids since several years. We were also encouraged to study this region of our Solar System by Isaac Asimov (1954) who wrote with a humoristic tone: "Space, you'd think a guy would know something about the asteroids, living out here."

We report the results of lightcurve analysis for seven main-belt asteroids: 417 Suevia, 453 Tea, 904 Rockefellia, 933 Susi, 1269 Rollandia, 1318 Nerina, and 1465 Autonoma. Table 1 summarizes some physical characteristics of these objects, in particular their semi-major axis in astronomical unit (AU), their taxonomic class, diameter, and albedo. In the following Sections, we present successively the observations, the data reduction, the lightcurve analysis and the results.

Observations

All data reported here were collected during the period 2010 August to 2012 March from Le Bois de Bardon Observatory (longitude: 0.407° E; latitude: 45.75° N; altitude: 105 m), a station located in Charente, in the Southwest of France.

Observations were carried out with a SBIG ST-402ME CCD camera attached to a 0.28 m diameter Schmidt-Cassegrain Celestron telescope. To obtain a large enough field of view (FOV) to be sure to have a sufficient sample of stars, a 0.33x telecompressor lens system designed by Optec, Inc. was chosen, giving a FOV of 17' x 26' and an image scale of 4.1 arcsec pixel^{-1} at an effective focal ratio f/3.2. In this configuration, the full-width at half-maximum (FWHM) was of ~2.5 pixels.

The CCD detector was a 16-bit Kodak KAF-0402ME microlensed device with an array of 756 x 510 pixel^2 and a pixel size of 9 x 9 μm^2. With our flat-field and bias frames, we applied the procedure described by Howell (2006) and measured a gain of 2.1 electrons ADU^{-1}, a read noise of 21.5 electrons pixel^{-1} read^{-1} and a dark current of 0.4 electron pixel^{-1} second^{-1} at a nominal temperature of about –15 °C.

The CCD camera was operated with *CCD Soft* (version 5) of Software Bisque, Inc. Images were taken at 2 x 2 binning. The telescope was unguided and tracked at the sideral rate. Typical integration times were 60, 120 or 180 s through a Bessel V or R filter, depending on the brightness of the objects and the weather conditions.

Scientific images were corrected for bias, dark and flat-field effects. For each observing run, master bias and dark frames were produced, and more than 100 twilight and/or daybreak flat-fields were obtained to perform a master flat-field frame.

During the runs, the R-exposures (respectively V-exposures) were complemented with some V-exposures (respectively R-exposures) at low airmasses (< ~1.3). This permitted, in the data reduction, to estimate the color indices of the field stars and so select and use only non-variable comparison stars that had a color similar to that of asteroids.

Data Reduction

All images were reduced with *Iris* (version 5.55), a software developed by Christian Buil (see *http://www.astrosurf.com/buil/iris/iris.htm*). Stellar and sky fluxes were measured by aperture photometry, by integrating the counts in a circular diaphragm with an aperture radius of ~2.5·FWHM pixels. A concentric annulus, with inner and outer radius of 12 and 25 pixels, respectively, centered on the asteroid and each selected stars, was used for estimating the median value of the sky background. Only differential magnitudes were computed. The methodology to reduce the image series is described below. This is based on the reduction procedure presented in Everett and Howell (2001) and adapted for our purpose.

(i) For each observational night, a set of i = 1,…, N stars (generally, N = 2 or 3) was constituted to be compared to the asteroid. Each set of stars was selected for their brightness and color index similar to that of the asteroid, and to have any variability or trends exceeding a typical scatter of ~0.01-0.03 mag. We also carefully checked that the extinction effects were negligible, thus the lightcurves were not affected within a ~0.01 mag range by differential colors.

(ii) Using the "revised CCD equation" (Merline & Howell, 1995; Howell, 2006) for a point source, and taking also into account the contribution of the atmospheric scintillation noise (Dravins *et al.*, 1998), we computed the $(S/N)_a$ and $(S/N)_*$ signal-to-noise ratios, respectively for the asteroid and stars, and thus their expected σ_a and σ_* uncertainties (in magnitude) from the expressions (Howell, 1993, 2006):

$$\sigma_a = 1.0857\left(\frac{S}{N}\right)_a^{-1} \quad \text{and} \quad \sigma_* = 1.0857\left(\frac{S}{N}\right)_*^{-1} \qquad \text{(1 and 2)}$$

(iii) The asteroid magnitude m_a was then compared to the N star magnitudes m_*, weighted by their individual uncertainties σ_*, to obtain the asteroid differential magnitude:

$$\Delta m = m_a - \sum_{i=1}^{N}\left(\frac{m_{*i}}{\sigma_{*i}^2}\right) \qquad (3)$$

(iv) Assuming that σ_a and σ_* were uncorrelated, we computed for each data point Δm its uncertainty:

$$\sigma_{\Delta m} = \sqrt{\sigma_a^2 + \sigma_{set}^2} \qquad (4)$$

where:

$$\sigma_{set} = \left[\sum_{i=1}^{N}\left(\frac{1}{\sigma_{*i}^2}\right)\right]^{-1/2} \qquad (5)$$

(v) For each night, the comparison of the set stars each other was given a standard deviation (i.e., the root mean square rms of the deviations from the mean) smaller than 0.03 mag. This standard deviation was used to estimate the magnitude dispersion in the nightly asteroid lightcurves. Then, before searching for the period in the photometric time series, all times were corrected for the effect of the light travel-time to Earth (e.g., Francou, 1997), and nightly asteroid lightcurves were shifted to a common magnitude level.

Lightcurve analysis

The search for the periodicity in the asteroid lightcurves was carried out with *Peranso* (version 2.11; Vanmunster, 2006). Various time series analysis methods are implemented in this software, in particular the Fourier analysis procedure described by Harris *et al.* (1989) that we generally used. We were assumed that the assumption of a triaxial ellipsoid shape model (e.g., Burns & Tedesco, 1979) was consistent with our program targets. This assumption is generally true, at least (but not only) for asteroids which have an amplitude lightcurve greater than ~0.2 mag (e.g., Binzel, 1987). So, nightly asteroid lightcurves were shifted along the time axis to match similar features, and to construct a composite lightcurve with two maxima and two minima per synodic rotation. The uncertainty on the synodic rotation period was estimated by inspecting the dispersion in the composite lightcurve induced by a slight variation of the period around its most probable value. The magnitude dispersion in the composite lightcurve was measured by the residuals which remain after a polynomial least-squares fitting procedure, giving a typical scatter (rms) of ~0.02 mag or less.

The peak-to-peak brightness amplitude was evaluated by the difference between the means of the maximum and the minimum of the composite lightcurve. The brightness amplitude uncertainty was estimated from the scatter in the lightcurve and/or from the uncertainty of individual data points.

Results

Observational circumstances are given in Table 2. The UT mid-time of observations is given within 0.1 day, followed by the J2000.0 ecliptic longitude λ_{2000} and latitude β_{2000}, the solar phase angle α, the V magnitude and the filter used. Table 3 summarizes the synodic rotation period and the brightness amplitude of the composite lightcurves for the observed asteroids.

The composite lightcurves are presented in Figures 1 to 7. They show the relative (V or R) magnitude *versus* the rotational phase, calculated with the synodic rotation periods given in Table 3. The caption of figures indicates, for each night, the plot symbol used, the UT mid-time of observations, the standard deviation (rms, in magnitude) in the nightly lightcurve, and the observational station. The zero phase is corrected for the light travel-time effect. Uncertainty bars (± $\sigma_{\Delta m}$, see Eq. 4) are plotted for each individual data point.

Results for each asteroid are described and commented in the following Sections.

417 Suevia. Suevia was firstly observed in 1989 by Barucci *et al.* (1992), who founded a rotation period of 7.034 h and a lightcurve amplitude of 0.20 ± 0.01 mag. Marciniak *et al.* (2012) reported observations from six apparitions (2001, 2005, 2006, 2008, 2009, and 2010), with lightcurve amplitudes from 0.07 to 0.37 mag for a period of 7.019 h. These authors were also determined a 3-D shape model of the asteroid (Ďurech, 2013). We carried out observations of 417 Suevia during five nights in 2010 August-September. This asteroid was monitored over a large range of solar phase angles (from 15.4 to 3.7°), which explains – besides, of course, the uncertainty on measurements – the scatter in the composite lightcurve (Fig. 1). Our data yield to a small amplitude (0.06 ± 0.03 mag) and a rotation period of 7.020 ± 0.003 h, values consistent with those of Marciniak *et al*.

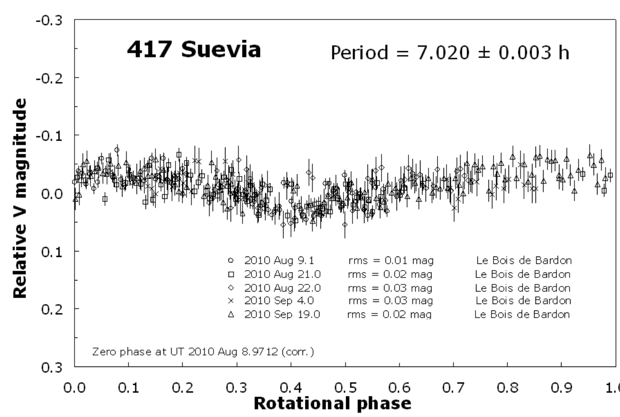

Figure 1. Composite lightcurve of 417 Suevia for 2010 August-September.

453 Tea. Wisniewski *et al.* (1997) were observed this Flora family member during one night in 1990 and reported a brightness amplitude of 0.4 mag and an indicating rotation period of ~6.4 h. Based on noisy datasets obtained by R. Roy in 2008 and M. Audejean in 2013, Behrend (2013) proposed a tentative period of 7.56 h and 7.35 h, respectively. In 2006, Licchelli (2006) found an amplitude of 0.30 ± 0.02 mag and a period of 6.812 ± 0.001 h. Observations of Kryszczyńska *et al.* (2012) were performed during five apparitions (2005, 2006, 2008, 2010, and 2011). Lightcurve amplitudes were varied from 0.45 to 0.1 mag, and the period was 6.811 ± 0.001 h, similar to the one derived by Licchelli (2006). Our observations of 453 Tea were carried out during two nights in 2011 October. The composite lightcurve (Fig. 2) is similar to the one of Kryszczyńska *et al*., with a small brightness amplitude (~0.06 mag) and a rotation period of 6.831 ± 0.021 h. Slightly higher (~0.3 %) than the ones of Licchelli and Kryszczyńska *et al*., our period is, however, in agreement with their results.

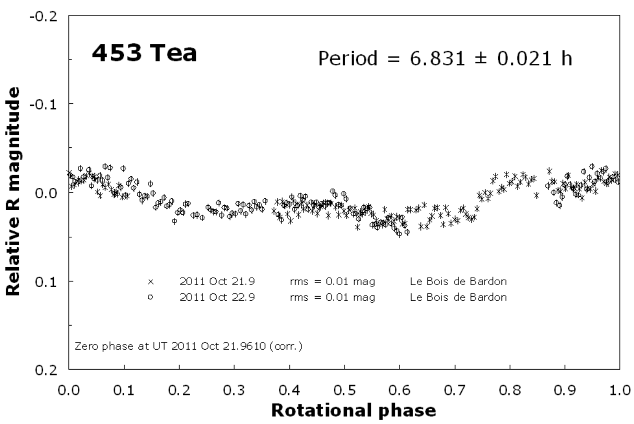

Figure 2. Composite lightcurve of 453 Tea for 2011 October.

904 Rockefellia. Ditteon and Hawkins (2007) observed 904 Rockefellia in 2006. They found a lightcurve amplitude of 0.10 ± 0.03 mag, but no period was derived from their data. A rotation period of 4.93 h and an amplitude of 0.18 mag were reported in CALL (2011; see Warner *et al*., 2009). Behrend (2013) proposed a tentative period of 12.72 h from observations carried out by P. Antonini in 2009. Based on our observations of 904 Rockefellia performed during two nights in 2011 September and October, the best fit solution for our lightcurve (Fig. 3) is a rotation period of 5.823 ± 0.011 h and a brightness amplitude of 0.10 ± 0.02 mag.

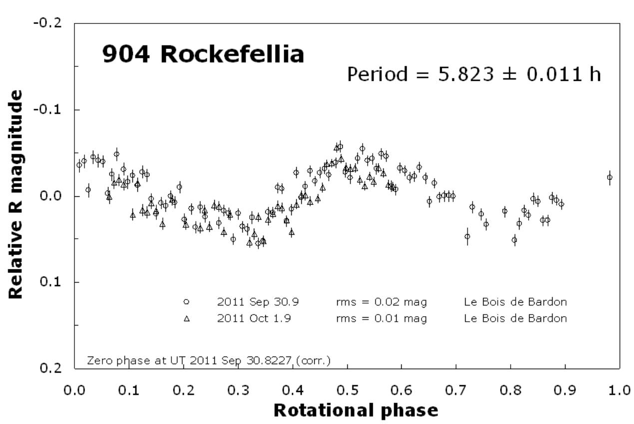

Figure 3. Composite lightcurve of 904 Rockefellia for 2011 September-October.

933 Susi. Behrend (2013) reported for this Erigone family member a period of 5.13 h from noisy data obtained by R. Roy and G. Casalnuovo in 2007 and 2011, respectively. Observed in 2011 by Bin et al. (2011), Higgins (2011), and Strabla et al. (2011), the brightness amplitude of Susi was in the range 0.30 to 0.35 mag, and the period of 4.622 h, a value also reported by Li and Zhao (2012). We performed observations of 933 Susi over ~4.9 h of a single night in 2011 April. The lightcurve amplitude is 0.32 ± 0.02 mag, and the search for the best period yields to 4.412 ± 0.034 h (Fig. 4), a value 4.5 % smaller than the previous published one.

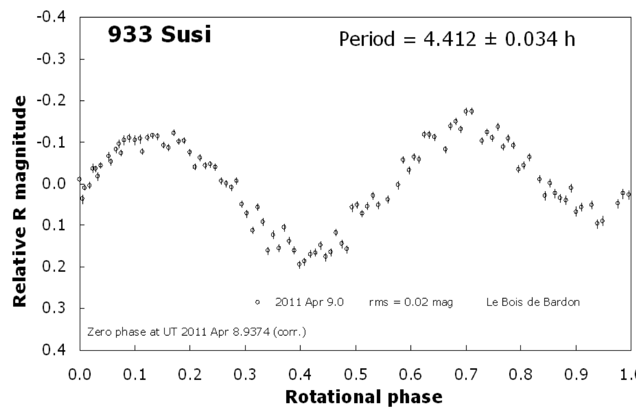

Figure 4. Composite lightcurve of 933 Susi for 2011 April.

1269 Rollandia. In 2008, Slyusarev *et al.* (2012) observed a very small lightcurve amplitude (0.02 mag) and a period of 30.98 h (see Warner *et al.*, 2009) for 1269 Rollandia. The amplitude and period from Franco's (2012) data, performed in 2012 March, were 0.08 mag and 15.4 ± 0.1 h, respectively. We also observed 1269 Rollandia in 2012 March, during three nights. Our composite lightcurve (Fig. 5) shows a lightcurve amplitude of 0.13 ± 0.02 mag, and a period of 15.315 ± 0.030 h, in agreement with Franco's results.

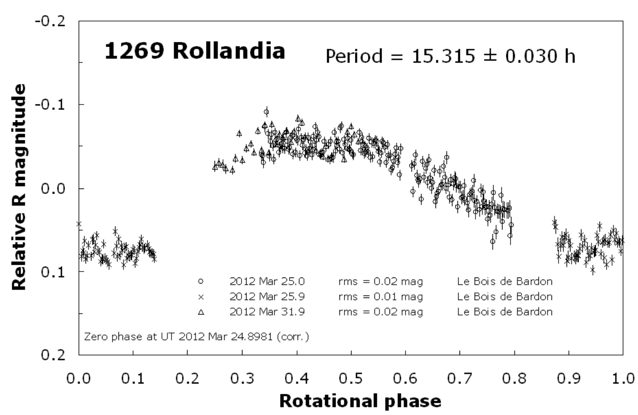

Figure 5. Composite lightcurve of 1269 Rollandia for 2012 March.

1318 Nerina. Behrend (2013) reported data obtained by R. Cripa *et al.* in 2007 and by G. Casalnuevo *et al.* in 2011, indicating a tentative period of 2.532 h for this Phocaea family member. Observed in 2004 and 2010 by Clark (2007, 2011), and in 2011 by Aymani (2011), Durkee (2011), Stephens (2011), and Strabla *et al.* (2011), the period of Nerina was found to be 2.525 h with a small lightcurve amplitude, from 0.16 mag (2004) to ~0.10 mag (2010-2011). Although noisy, our data on 1318 Nerina, obtained during two nights in 2011 April, are consistent with those of other authors, giving a rotation period of 2.529 ± 0.003 h and a lightcurve amplitude of 0.07 ± 0.02 mag (Fig. 6).

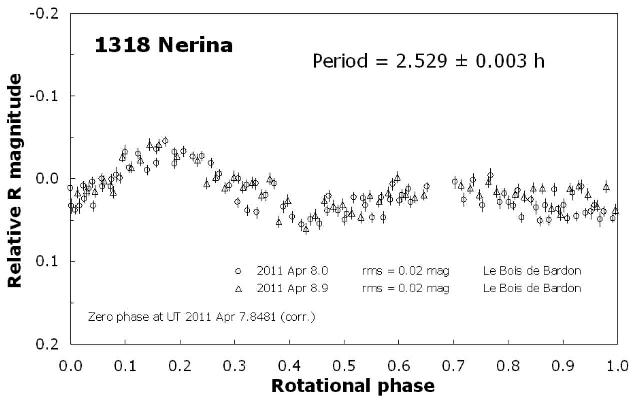

Figure 6. Composite lightcurve of 1318 Nerina for 2011 April.

1465 Autonoma. Only sparse measurements were obtained during our two runs on 1465 Autonoma in 2012 March, and any obvious common patterns were identified in the datasets. So, we used the phase dispersion minimization (PDM) method, developed by Stellingwerf (1978), to estimate the rotation period of the asteroid. Indeed, this method is well suited to search for periodicities if only a few data are available, and especially if the lightcurve is highly non-sinusoidal, which was the case for our time series. From this way, a rotation period of 4.886 ± 0.010 h and a 0.14 ± 0.02 mag lightcurve amplitude match the datasets (Fig. 7). If this period is correct, only 75 % of the rotation was covered by our data. This period is, however, similar to the one previously published by Brinsfield (2008) from observations carried out in 2007.

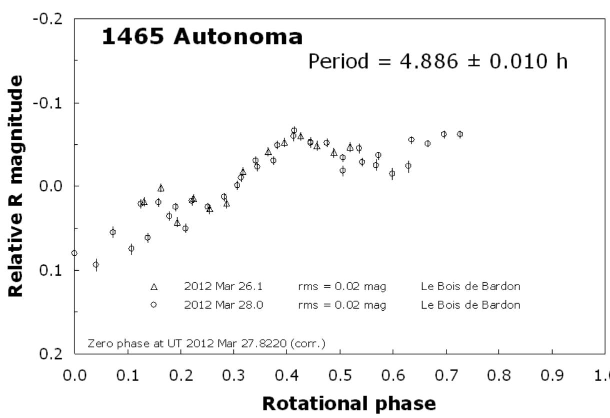

Figure 7. Composite lightcurve of 1465 Autonoma for 2012 March.

Acknowledgments

This research was made use of the Institut de mécanique céleste et de calculs des éphémérides (IMCCE) ephemeris generator, provided by the observatoire de Paris (France), and of the Astrophysics Data Systems (ADS) and Solar System Dynamics (SSD) Small-Body Database, provided by NASA and JPL (USA), respectively. We gratefully acknowledge Brian D. Warner and Alan H. Harris for the updated versions of the Lightcurve Database (LCDB).

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Table 1. Selected physical parameters of the observed asteroids (from Warner *et al.*, 2009, and JPL Small-Body Database, available at *http://ssd.jpl.nasa.gov/sbdb.cgi*).

Asteroid	a (UA)	Taxonomic class	Diameter (km)	Albedo	Commentary
417 Suevia	2.799	X	40.7	0.1960	
453 Tea	2.183	S	20.9	0.1827	Flora family
904 Rockefellia	2.992	C	58.8	0.0561	
933 Susi	2.368	C	21.8	0.0707	Erigone family
1269 Rollandia	3.905	D	105.2	0.0473	
1318 Nerina	2.307	S	13.0	0.1811	Phocaea family
1465 Autonoma	3.027	C	~20	< ~0.12	

Table 2. Observational circumstances for the observed asteroids.

Asteroid	Date (UT)	λ_{2000} (°)	β_{2000} (°)	α (°)	V (mag)	Filter
417 Suevia	2010 Aug 9.1	12.6	+ 3.2	15.4	14.7	V
	2010 Aug 21.0	11.9	+ 3.1	12.8	14.5	V
	2010 Aug 22.0	11.8	+ 3.1	12.6	14.5	V
	2010 Sep 4.0	10.2	+ 2.9	8.9	14.2	V
	2010 Sep 19.0	7.4	+ 2.6	3.7	13.9	V
453 Tea	2011 Oct 21.9	21.6	+ 2.1	2.8	13.3	R
	2011 Oct 22.9	21.3	+ 2.1	3.3	13.3	R
904 Rockefellia	2011 Sep 30.9	20.4	+ 0.9	4.5	14.4	R
	2011 Oct 1.9	20.2	+ 0.9	4.2	14.4	R
933 Susi	2011 Apr 9.0	177.7	+ 7.7	10.8	14.8	R
1269 Rollandia	2012 Mar 25.0	180.6	+ 2.8	1.4	13.8	R
	2012 Mar 25.9	180.4	+ 2.8	1.6	13.8	R
	2012 Mar 31.9	179.4	+ 2.8	3.4	14.0	R
1318 Nerina	2011 Apr 8.0	163.4	– 2.6	17.8	14.3	R
	2011 Apr 8.9	163.3	– 2.9	18.3	14.3	R
1465 Autonoma	2012 Mar 26.1	187.4	+ 5.5	2.3	14.8	R
	2012 Mar 28.0	187.0	+ 5.7	2.2	14.8	R

Table 3. Synodic rotation period and brightness amplitude results for the observed asteroids.

Asteroid	Period (hour)	Amplitude (mag)
417 Suevia	7.020 ± 0.003	0.06 ± 0.03
453 Tea	6.831 ± 0.021	~0.06
904 Rockefellia	5.823 ± 0.011	0.10 ± 0.02
933 Susi	4.412 ± 0.034	0.32 ± 0.02
1269 Rollandia	15.315 ± 0.030	0.13 ± 0.02
1318 Nerina	2.529 ± 0.003	0.07 ± 0.02
1465 Autonoma	4.886 ± 0.010	0.14 ± 0.02

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LIGHTCURVE INVERSION FOR 38 LEDA

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(Received: 15 July)

We present shape and spin axis model for main-belt asteroid 38 Leda. The model was obtained with lightcurve inversion process, using combined dense photometric data from apparitions in 1979, 1995, 2000, 2008, 2009-10, 2011, 2012 and sparse data from USNO Flagstaff. Analysis of the resulting data found a sidereal period P = 12.836164 ± 0.000016 h and two possible pole solution at (λ = 160°, β = -17°) and (λ = 343°, β = -6°), with an error of ± 10 degrees. From sparse data from the USNO Flagstaff station we find H = 8.61 ± 0.04, G = 0.09 ± 0.04.

The main-belt asteroid 38 Leda has been observed in last four consecutive apparitions by Frederick Pilcher, with a variety of phase angles and phase angle bisectors. To improve the coverage at various aspect angles, we found in the literature further observations, whose lightcurves were downloaded from the Asteroid Photometric Catalogue (APC) by Lagerkvist et al. (2001) at website: *http://asteroid.astro.helsinki.fi/apc*. The observational circumstances for the seven apparitions are reported in Table I.

The data from two of the three sessions of Wang and Shi (2002) were reconstructed by Frederick Pilcher, starting from the published lightcurves, following the failed attempt to contact via email the authors.

To improve the solution we have also used sparse data from USNO Flagstaff Station, as has been shown by Kaasalainen (2004), Ďurech et al. (2009). Sparse data were taken from the AstDys website (*http://hamilton.dm.unipi.it/astdys/index.php/*) for a total of 211 data points. Figures 1, 2 and 3 shows respectively PAB Longitude/Latitude distribution for dense/sparse data and phase curve for the sparse data.

Lightcurve inversion process ware performed using MPO LCInvert v.11.0.0.2. Software (Bdw Publishing), which implement algorithms and code provided by Mikko Kaasalainen and Josef Ďurech. For guidelines and a description of the modeling process see LCInvert Operating Instructions manual and Warner et al. (2008).

Data Analysis

All data from thirty dense lightcurves and one sparse dataset were imported in *LCInvert* for analysis, assigning them a different weighting factor, from 1.0 for best data to 0.3 for sparse data.

In the inversion process the first step is to find an accurate sidereal rotational period. We have started the period search centered on the average of the synodic periods found in the previously published works. The search process found a isolated sidereal period of 12.83611412 h with lower chi-square value (Figure 4).

For pole search we have started using the "Medium" search option (312 fixed pole position with 15° longitude-latitude steps) and the previously found sidereal period set to "float". The "dark facet" weighting factor was increased from 0.1 (default) to 0.5 to keep the dark facet area below 1% of total area. The number of iterations of processing was increased from 50 (default) to 75 for best convergence.

Data analysis shows two lower chi-square solutions differing by 180°, centered at (λ = 165°, β = -15°) and (λ = 345°, β = -15°), see Figure 5 for log(chi-square) values distribution. These values were then refined by running again the pole search using the "Fine" option with the previous period/longitude/latitude set to "float" (49 fixed pole steps with 10° longitude-latitude pairs). The two best solutions are reported in Table II with an averaged sidereal period obtained from the two values found in the pole search process. Typical errors in the pole solution are ± 10 degrees and the uncertainty in period has been evaluated as a rotational error of 10° over the total time-span of the observations.