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Original scientific paper

PHOTOMETRY AND SHAPE MODELING OF MARS CROSSER ASTEROID (1011) LAODAMIA[1]

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SUMMARY: An analysis of photometric observations of Mars crosser asteroid 1011 Laodamia conducted at Bulgarian National Astronomical Observatory Rozhen over a twelve year interval (2002, 2003, 2004, 2006, 2007, 2008, 2011, 2012 and 2013) is made. Based on the obtained lightcurves the spin vector, sense of rotation, and preliminary shape model of (1011) Laodamia have been determined using the lightcurve inversion method. The aim of this investigation is to increase the set of asteroids with known spin and shape parameters and to contribute in improving the model in combination with other techniques and sparse data produced by photometric asteroid surveys such as Pan-STARRS or GAIA.

Key words. minor planets, asteroids: individual: 1011 Laodamia – techniques: photometric

1. INTRODUCTION

The periodic variations of asteroid brightness caused by rotation depend on geometrical conditions during the observation, the shape of the asteroid, and on the morphology and microscopic scattering properties of its surface. For a long time Russell's assumption was accepted (Russel 1906) that albedo variations would prevent the determination of the shape of the asteroid. This pessimistic opinion was abandoned when photometric investigations combined with laboratory experiments (Dunlap 1971) confirmed that asteroid albedo variations are only a small fraction of the total amplitude variation while an asteroid rotates. Koshkin (1988) in his experiments concluded that triaxial ellipsoid model yields almost sinusoidal lightcurves while more complex shapes give lightcurves with broader maxima and narrower minima of brightness.

Several methods were developed to find a spin axis solution, i.e. the ecliptic longitude and latitude to where the north pole of the asteroid is pointing, along with sidereal period. Additionally, some of the methods could reconstruct the shape models of asteroids. An important new approach was the lightcurve inversion method by Kaasalainen and Torppa (2001) and Kaasalainen et al. (2001). This method allows deriving of rotational states and the convex shapes

[1]Based on data collected at Rozhen National Astronomical Observatory.

of asteroids from lightcurves obtained at different geometrical conditions of observations. The accuracy of the method was confirmed by radar measurements and flyby observations in space (Kaasalainen et al. 2001).

There are other observing techniques such as stellar occultations, adaptive optics imaging, radar echo, thermal infrared technique or space probe imaging which can yield or exploit detailed shape models. One possibility for comparison of the photometric models with those from other observing or modeling techniques is the online Interactive Service for Asteroid Models (ISAM) created by Marciniak et al. (2012). All published asteroid spin parameters are available in the database by Kryszczyńska et al. (2007)[2]. The models obtained from lightcurve inversion are collected in Database of Asteroid Models from Inversion Techniques (DAMIT) (Ďurech et al. 2010)[3], which contains 650 models for 382 asteroids (as of September 2014).

Photometric investigations of asteroids allow us to determine rotational properties and to derive shape models of asteroids. In combination with other types of observational data they could help in determining sizes and thermal properties of asteroids. A large database with these physical parameters is crucial for understanding of conditions during the creation of our planetary system, and especially the processes that take place in formation of asteroid populations.

Calculation of pole solution and deriving the shape of the asteroids using lightcurve inversion method require dense lightcurves obtained at various geometrical aspects. This can be fulfilled from at least four or five apparitions and thus several years of observations. By this approach, therefore, models for only about one hundred asteroids have been derived. The number of asteroids with shape models significantly increased when sparse photometric data were started to be used in light inversion method (Ďurech et al. 2009).

This is especially important since we expect from GAIA a wealth of sparse-in-time photometric data which will help in determination of the rotational properties and the overall shapes of large number of minor planets (Cellino and Dell'Oro 2012). In the meantime, the sparse-in-time data from astrometric surveys available on AstDyS (Asteroid Dynamic Site)[4] in combination with relative lightcurves were used to derive around 300 asteroid physical models by Hanuš et al (2013). With models of several hundred asteroids obtained by the lightcurve inversion and with numerical simulation of the evolution of collisional family Hanuš et al. (2013) constrain the age of two asteroid families.

2. OBSERVATIONS AND DATA REDUCTION

(1011) Laodamia with a perihelion below the Martian aphelion but above the perihelion of Mars belongs to the group of Mars crosser asteroids. Laodamia refers to Mars outer grazers, it enters the ring whose inner radius is the Mars planet's perihelion and its outer radius the aphelion, from outside without traversing it. Mars crossers are believed to have originated as the main-belt asteroids that fell into a 3:1 orbital resonance (at a heliocentric distance of 2.5 AU) with Jupiter. They are investigated dynamically in order to reveal their origin and their subsequent evolution to Earth crossing orbits. The group of Mars crossers is about 35 times more numerous than the group of Earth crossers (at least down to 5 km in diameter) (Michel et al. 2000). According to NASA/JPL "Absolute Magnitude (H)" (retrieved 2014-06-28) (1011) Laodamia is about 7-17 km in diameter.

For photometric observations of (1011) Laodamia since 2002 until 2013 the 2m RCC, 50/70 Schmidt and 60cm Cassegrain telescopes of the NAO Rozhen were used. During 2003 observations, the 2m RCC telescope was equipped with Photometrics CE200A CCD camera (1024x1024 pixels, pixel size 24 μm), and since 2007 observations, the VersArray:1300B CCD camera (1340 x 1300 pixels, pixel size 20 μm) was in use. Since 2002 until 2006 observations, Schmidt telescope was equipped with the SBIG ST8 CCD camera (1536x1024 pixels, pixel size 9 μm), and for 2013 observations, the CCD FLI PL 16803 (4096 x 4096 pixels, pixel size 9 μm) was in use. For 2012 and 2013 observations on 60 cm telescope the CCD FLI PL09000 (3056 x 3056 pixels, pixel size 12 μm) was available.

The aspect data of the asteroid, and telescopes and filters used for observations are shown in Table 1. The first column is the date of the observation referring to the midtime of the lightcurve observed, and the following columns are: the asteroid distance from the Sun (r), the distance from the Earth (Δ), the Sun-asteroid-observer angle (phase angle), and the J2000.0 ecliptic longitude (λ) and latitude (β) of the asteroid referred to the time given in the first column.

Observations in 2002 were taken through the V filter, and all others were taken through the R filter. In the preliminary reduction, CCD images of asteroid were dark and/or bias subtracted and normalized using the flat-field images. Aperture photometry of the asteroid and the comparison stars was performed using the software program CCDPHOT (Buie 1996)[5] and for the lightcurve analysis we used software package MPO (Warner 2014). The photometry of this asteroid was determined relative to a few (usually 3 to 5) comparison stars in every frame.

[2]http://www.astro.amu.edu.pl/Science/Asteroids/

[3]http://astro.troja.mff.cuni.cz/projects/asteroids3D/web.php

[4]http://hamilton.dm.unipi.it/astdys

[5]Most recent version of this package could be found at: http://www.boulder.swri.edu/∼buie/idl/ccdphot.html

Table 1. Aspect data for (1011) Laodamia.

Date (UT)	r (AU)	Δ (AU)	Phase Angle (°)	λ (°)	β (°)	Telescope	Filter
2002 02 10.08	1.612	0.709	21.42	177.49	5.00	Schmidt	V
2002 02 12.08	1.617	0.704	20.30	177.41	5.27	Schmidt	V
2003 06 26.98	3.157	2.187	6.68	295.89	3.15	2m RCC	R
2004 09 20.98	2.692	1.692	2.39	356.43	-6.13	Schmidt	R
2006 05 26.92	2.408	1.418	6.74	231.98	9.03	Schmidt	R
2006 05 28.94	2.416	1.432	7.55	231.50	8.95	Schmidt	R
2006 05 29.95	2.420	1.439	7.94	231.28	8.91	Schmidt	R
2007 08 09.94	3.226	2.222	3.00	307.35	0.33	2m RCC	R
2007 08 10.88	3.226	2.224	3.35	307.13	0.31	2m RCC	R
2008 10 03.96	2.237	1.302	11.94	37.23	-9.06	2m RCC	R
2008 10 05.98	2.229	1.284	11.09	36.87	-9.18	2m RCC	R
2011 09 23.85	3.058	2.224	12.27	320.15	-2.55	2m RCC	R
2012 12 14.08	1.591	0.740	26.33	127.94	-6.11	60cm	R
2013 03 19.87	1.616	0.792	28.81	128.20	4.61	60cm	R
2013 04 29.91	1.727	1.185	34.51	143.44	5.70	Schmidt	R
2013 04 30.87	1.731	1.196	34.52	143.90	5.71	Schmidt	R

3. POLE AND SHAPE RESULTS

For calculating the pole solution and deriving the shape model of the asteroid by means of the lightcurve inversion method, lightcurves of sufficiently different geometries are required. This means that observations should cover a range of phase angles, including some at phase angles $> 10°$ and, for an even better solution, $> 20°$. Aspect data of our observations are given in Table 1 and we could see that six lightcurves (during 2002 and 2012/13 apparitions) are taken at solar phase angles greater than 20°, three lightcurves (during 2008 and 2011 apparitions) are at about 12°, and seven lightcurves are between 2° and 8°.

Using all lightcurves from Table 1 we calculated the sidereal period to be 5.172794 h. The error of sidereal rotational period varies in accordance with the lengths of the period and the length of the observation span (Kaasalainen et al. 2001). It is usually between 0.1–0.01 times the basic resolution interval $0.5P^2/2T$ (where P is the rotation period and T is the full epoch range of the observation data set (Torppa et al. 2003). We quote the period with accuracy which corresponds to the last decimal place of value of the period.

All solutions for pole with minimum values for χ^2 gave retrograde rotation with pole latitude near $-90°$. It determined the error of pole latitude of only 3 degrees of arc. Few pairs (with roughly same spin vector ecliptic latitudes and longitudes nearly 180° apart) of solutions had very small values of χ^2. Pairs of solutions in this method are inevitable if only disk-integrated data are used and the corresponding shapes are mirror images of each other (Torppa 2003). In the process of searching of solutions, priority was given to the solution with small value of χ^2 and which, according to us, gave the best fit of observed lightcurves with those generated by the model (Fig. 1). The error of longitude pole determinations is 10 degrees of arc to pole, which is twice the standard error of 5 degrees of arc to pole estimates from lightcurve inversion (Torppa et al. 2003). Two solutions for the pole are given in Table 2 and the shape model is presented in Fig. 2.

The derived pole is almost perpendicular to the ecliptic plane which corresponds to the finding by Hanuš (2013b) that smaller asteroids ($D \leq 30$ km) have strongly anisotropic spin vector distribution and poles are clustered towards ecliptic poles. Possible explanation is that this is the result of non-gravitational torques (the YORP effect) acting on these objects.

The Table 2 gives the sidereal rotational period P, sense of rotation, ecliptic coordinates λ_1 and β_1 of the pole solution, the corresponding mirror solution λ_2 and β_2, and rough relative shape dimensions. The last column gives a rms deviation between the observed lightcurves and synthetic lightcurves in magnitudes.

Table 2. Parameters of the model

Sideral period	Sense of rotation	Pole1		Pole2		a/b	b/c	Δ rms
(h)		λ_1(°)	β_1(°)	λ_2(°)	β_2(°)			(mag)
5.172794±0.000001	R	95±10	-88.5±3	272±10	-88±3	0.83	1.3	0.019

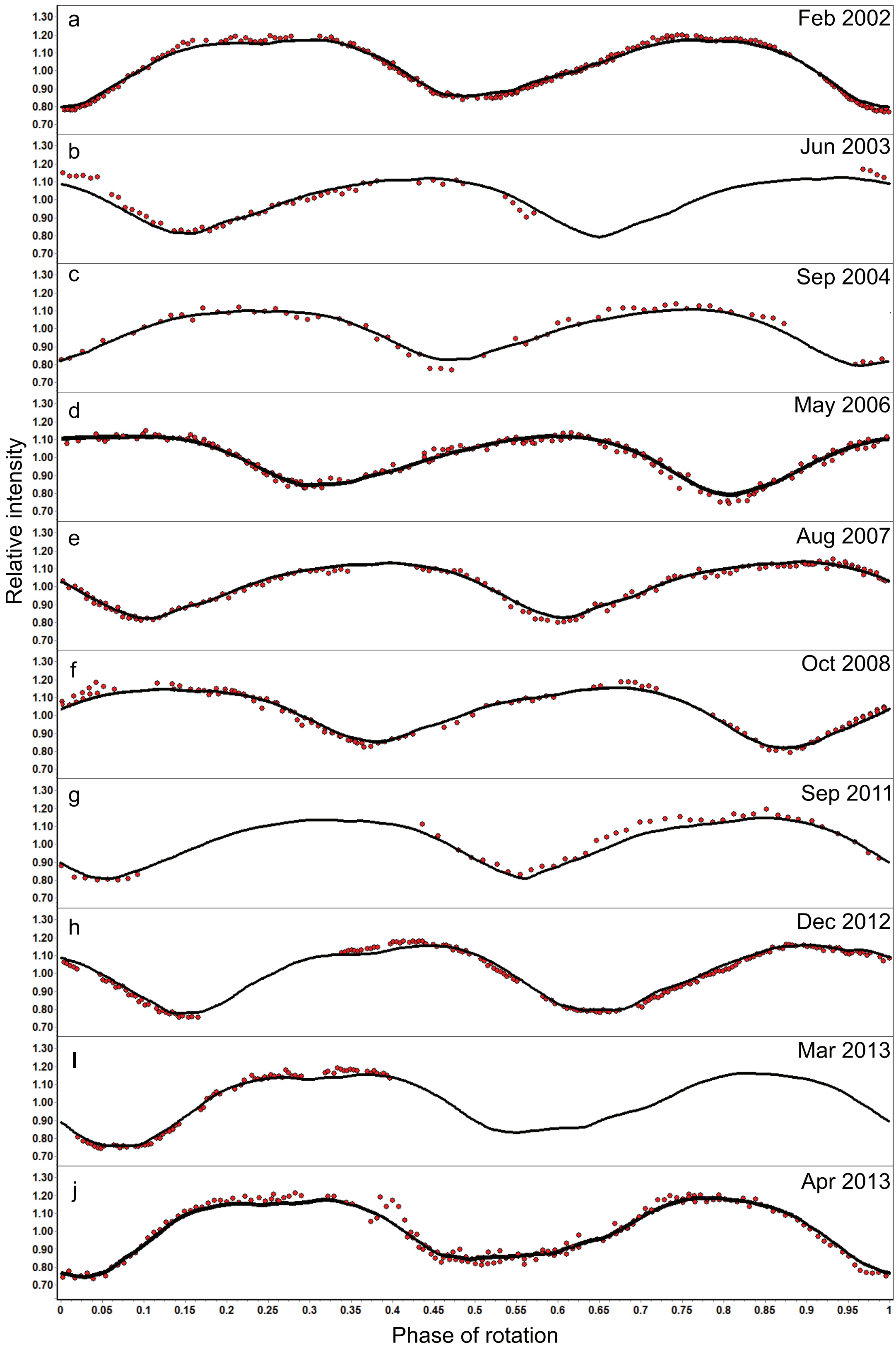

Fig. 1. *Lightcurves (points) obtained from observations in Table 1, superimposed on the lightcurves created by a model (solid line).*

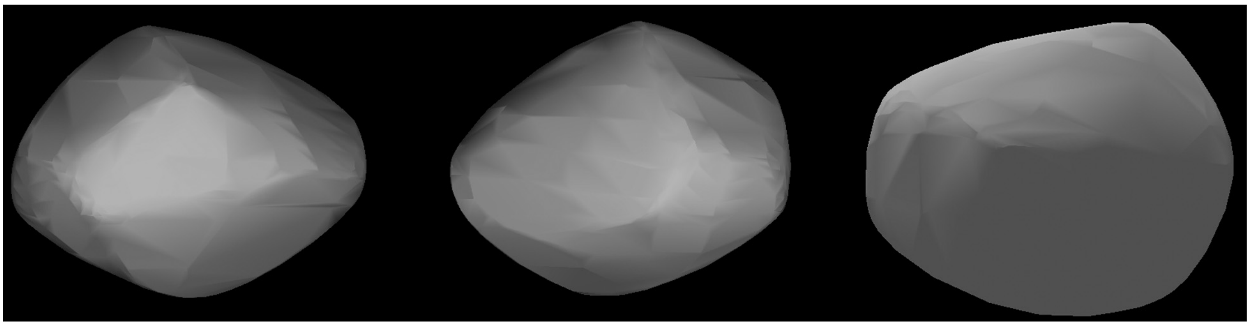

Fig. 2. *Shape model of (1011) Laodamia, shown at equatorial viewing illumination geometry, with rotational phases 90 apart (two pictures on the left) and the pole-on view on the right.*

4. PHASE CURVE AND H-G PARAMETERS

The apparent brightness of an asteroid which changes with the solar phase angle can be presented with phase curve. This curve is related to the H-G system of absolute magnitude and phase slope parameter developed by Bowell et al. (1989).

The IAU has officially adopted the H-G system to describe the variation of the apparent magnitude of an object observed at different phase angles during a given apparition. The parameter H defines the absolute magnitude of the asteroid in V filter when it is 1 AU from both the Sun and the Earth, and at zero phase angle. The slope parameter G describes the change of magnitude as a function of phase angle.

The shape of the phase curve is characterized by presence of an opposition brightness surge that takes place at phase angles of a few degrees (usually less than 7°). Although the main purpose of the H-G system and phase curve were to predict the magnitude of an asteroid as a function of solar phase angle, nowadays they are very important for theoretical modeling of the surface light scattering properties of asteroids. The number of asteroids with a good quality phase curve is less than 100 (Belskaya and Shevcenko 2014).

For the main purpose of this article, i.e. modeling of the asteroid shape, we needed lightcurves taken at different phase angles, preferably greater than 10°. Due to non perfect weather conditions and limited number of assigned (2 or 3) observing nights per month for achievement of our goals, we have performed relative photometry without observing standard star fields for photometric calibration. On the other side, for getting a good phase curve one should have dense and broad coverage from the near-zero phase to phases greater than 20°, and absolute photometry with very precise accuracy. Regardless of this discrepancy we tried to obtain the phase curve from our observations taking into consideration observing methodology for performing "quasi-absolute" photometry (Miles 2005).

Stars that were used as comparisons were relatively faint and do not have accurate catalog magnitudes (mean catalog error is $< \pm 0.25$ mag, because its main purpose is astrometric position of the objects). Selected images from all observing sessions in the R filter (Table 1.) were calibrated using the USNO-B1.0 Catalog (Monet D.G. et al. 2003).

The slow change in brightness of the asteroid caused by the changing solar phase angle is superimposed on a much more speedy periodic variation in brightness due to the rotational lightcurve. Due to the fact that there is no single answer to the question should the phase curve use the average, maximum or minimum of the lightcurve (Buchheim 2010) we chose the approach of Harris (1989) who first reported examples of phase curves based on maximum.

In order to obtain the phase curve, we first determined the maximal brightness data point of each night's lightcurve and noted the time of observation, and then the relative maximum magnitude was transformed into the absolute magnitude R using the field stars matched with the USNO-B1.0 catalog. The lightcurves of (1011) Laodamia showed symmetrical shape with maxima of equal heights which allow us to use the data even in nights with only one maximum. The brightness variance due to changing orbital geometry was removed by calculating the magnitude R_r reduced to unit distances from the Sun and Earth.

Fig. 3 shows the reduced magnitude versus solar phase angle found at the time of maximal brightness for (1011) Laodamia. The phase curve was constructed using the H-G calculator feature within MPO Canopus in which the values for H_R and G were found using the algorithm described by Bowell and implemented in the FAZ program written by Alan Harris (Bowell 1989).

According to Tholen taxonomic classification (1011) Laodamia is the S spectral type, and according to the SMASSII spectral taxonomic classification it is the Sr spectral type. Harris (1989) and Lagerkvist and Magnusson (1990) determined the slope parameters G for many asteroids and correlated them to the asteroid taxonomy type. They found $G = 0.23 \pm 0.02$ for Tholen taxonomic type S. Our calculated slope parameter G for (1011) Laodamia is $G = 0.195 \pm 0.170$. Having in mind that in V filter the absolute magnitude of (1011) Laodamia is $H = 12.74$ (according to NASA Planetary Data

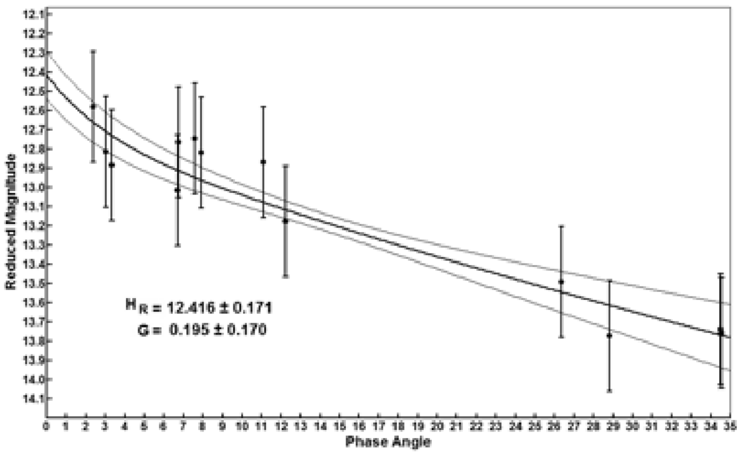

Fig. 3. *The phase curve for 1011 Laodamia based on observations in the R filter at different apparitions fitted by the HG function.*

System[6]), and our calculated absolute magnitude in R filter is $H_R = 12.416 \pm 0.171$, we could calculate for the $V - R$ color index value of 0.324 ± 0.171.

The main reason for deviation of points from the fitted HG function in Fig. 3 is due to photometry which uses catalog with large errors. Another reason for this deviation could be found in generalization of the analysis to multiple apparitions by Harris et al. (1989) and Harris and Young (1989) who found that the poor results are often obtained if all apparitions are clumped together and fitted to a single phase curve. According to Lagerkvist and Magnuson (1990), the main discrepancy between apparitions probably lies in the magnitude H, which is a function of the aspect angle, while the slope parameter G value will be roughly the same if the surface properties are homogenous.

5. CONCLUSIONS

For Mars crosser asteroid (1011) Laodamia, using convex lightcurve inversion method, we obtain the retrograde rotation, pole solutions and preliminary shape of the asteroid. Prior to the present paper there were no published solutions for the pole and the shape of this asteroid. The calculated pole latitude close to $-90°$ is in agreement with expectations based on the YORP effect analysis published in Hanuš (2013b).

Additionally to the obtained shape and pole using observations in R filter from all apparitions we constructed the phase curve for (1011) Laodamia. We calculated the slope parameter of the phase curve, the absolute magnitude in R filter and color index V-R.

A wealth of new data for better understanding of the opposition effect and of surface properties of (1011) Laodamia could be obtained with photometric observations at phase angle less than 10°. In accordance with the highlighting of the importance of polarimetry for better physical characterization of asteroids in the years to come (Cellino and Bagnulo 2014), we intend to carry out such observations with the 2m Rozhen telescope.

Next opportunities for observing Laodamia at higher phase angles ($> 10°$) using Schmidt telescope at Bulgarian National Astronomical Observatory will be in February and in March 2017 and in November 2019. Getting more data at different geometries could improve the shape model and give better accuracy for the determined poles position of Laodamia. Also we expect that calculated solutions and especially few of our dense lightcurves obtained during one decade of observation will be very helpful when sparse data from GAIA, LSST, ATLAS and other future sources of asteroid photometry will be available.

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ФОТОМЕТРИЈА И ОДРЕЂИВАЊЕ ОБЛИКА АСТЕРОИДА (1011) LAODAMIA КОЈИ ПРЕСЕЦА МАРСОВУ ОРБИТУ[7]

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УДК 523.44 1011LAODAMIA
Оригинални научни рад

У раду је дата анализа фотометријских посматрања астероида 1011 Laodamia, који пресеца Марсову путању, извршених током периода од дванаест година (2002, 2003, 2004, 2006, 2007, 2008, 2011, 2012 и 2013). На основу добијених кривих сјаја, методом инверзије одређени су вектор угаоне брзине, смер ротације и прелиминарни облик астероида 1011 Laodamia. Циљ овог истраживања је да се повећа број астероида са познатим параметрима који карактеришу облик и ротацију, и да се, у комбинацији са другим техникама и спорадичним подацима добијеним фотометријским прегледима астероида у пројектима попут Pan-STARRS или GAIA, допринесе побољшању постојећег модела.

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