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New CCD photometry of asteroid (1028) Lydina *

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Abstract New CCD photometric observations for asteroid (1028) Lydina, carried out with the 1-m and 2.4-m telescopes at Yunnan Observatory from 2011 December 19 to 2012 February 3, are presented. Using the new light curves, the rotation period of 11.680±0.001 hours is derived with the Phase Dispersion Minimization (PDM) method. In addition, using the Amplitude-Aspect method, the elementary results of the pole orientation of asteroid (1028) Lydina are obtained: $\lambda_{\rm p} = 111^{\circ}{}^{+4^{\circ}}_{-4^{\circ}}$, $\beta_{\rm p} = 31^{\circ}{}^{+4^{\circ}}_{-5^{\circ}}$. Meanwhile, the axial ratios of the tri-axial ellipsoid are estimated: $a/b = 1.77^{+0.10}_{-0.08}$ and $b/c = 1.17^{+0.07}_{-0.09}$.

Key words: asteroids: photometric — observation: rotation period — pole orientation: tri-axial ellipsoid

1 INTRODUCTION

Ground-based photometric observation is one of the most important methods to obtain light curves, from which the rotation parameters and shape of an asteroid can be inferred. These parameters may provide a clue for understanding the scenarios in planetary formation and collision evolution of asteroids.

The C-type main-belt asteroids, having a low density, might be associated with the phenomenon of angular momentum drain and the examples of binary asteroids (Wang & Gu 2003). Thus, more samples of C-type asteroids are needed, especially those slow rotators. In fact, samples of slow rotators are scarce due to observational restrictions. C-type asteroids are generally considered to have a rubble-pile structure. Hence, the shape that gives them structural equilibrium is a tri-axial ellipsoid. Meanwhile, the shape of the equilibrium figure of an asteroid is associated with its density and its spin rate. Therefore, the shape estimation with a tri-axial ellipsoid is reasonable for C-type asteroids. Several approaches (Zappala 1981; Magnusson 1986) can be applied to estimate the axial ratios of a tri-axial ellipsoid and the pole orientation of an asteroid. The advantage of the Amplitude-Aspect method (Pospieszalska-Surdej & Surdej 1985; Hainaut et al. 1990; Tancredi & Gallardo 1991; Licandro et al. 1994) is that it can take full advantage of all the photometric data to estimate the amplitude of the light curve.

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In Sections 2 and 3, the photometric observations and the data reduction are shown. The analysis for the rotation period of (1028) Lydina is shown in Section 4. The pole orientation and axial ratios of asteroid (1028) Lydina are estimated by the Amplitude-Aspect method, and are presented in Section 5.

2 OBSERVATIONS

Asteroid (1028) Lydina, discovered by V. Albitskij on 1923 November 6 at Simeis, is a C-type main-belt asteroid. Lydina was observed by Almeida et al. (2004) on 1998 November 15 and 16, and by Stephens (2012) from 2011 November 22 to December 8. The new photometric observations for asteroid (1028) Lydina were carried out with the 1-m telescope in Kunming (Observatory Code 286) and the 2.4-m telescope in Gaomeigu (Latitude $26°42'32''$, Longitude $100°01'51''$, and Altitude 3193 m) from 2011 December 19 to 2012 February 3 at Yunnan Observatory. The aspect data of these observations are listed in Table 1. The first column is the date of the observations in UT. Δ is the geocentric distance and r is the heliocentric distance in astronomical units. α is the solar phase angle. λ and β are the geocentric ecliptic coordinates in the J2000.0 frame. The following two columns are the observation duration and the telescope used. In the observations with the 1-m telescope, a 2k×2k pixel Andor DW436 CCD with a field of view (FOV) of $7.3' \times 7.3'$ is used, and with the 2.4-m telescope a 2k×4k pixel E2V 42–90 BI-DD CCD with a FOV of $10' \times 10'$ is used.

Table 1 The Aspect Data of (1028) Lydina

Date (UT)	Δ (AU)	r (AU)	$\lambda(°)$ (J2000.0)	$\beta(°)$ (J2000.0)	$\alpha(°)$	Duration (h)	Telescope
2011/12/19.46	2.106	3.046	66.327	02.391	06.8	8	a
2011/12/20.47	2.111	3.046	66.160	02.431	07.0	7	a
2012/01/23.46	2.416	3.039	63.474	03.446	16.2	5.5	a
2012/02/01.53	2.530	3.038	63.872	03.621	17.5	3.5	b
2012/02/03.48	2.555	3.038	64.022	03.655	17.7	4.5	a

a: Using the 1-m telescope of Yunnan Observatory in Kunming; b: Using the 2.4-m telescope of Yunnan Observatory in Gaomeigu.

Because of the faint magnitude of asteroid (1028) Lydina, the clear filter is used for five nights of observations. The bias frames are obtained at the beginning and end of the observations, and the twilight flat frames are obtained.

For the observations with the 1-m telescope on 2011 December 19 and 20, the weather was clear, and the seeing changed from $1.9''$ to $3.1''$. On 2012 January 23, the weather was clear and the seeing varied from $1.7''$ to $2.6''$. The observation on 2012 February 3 was done under full moon conditions, so a longer exposure time was set in order to get a better signal-to-noise ratio. Only the observation on 2012 February 1 was carried out with the 2.4-m telescope in Gaomeigu, and during that night the seeing varied from $1.1''$ to $3.1''$.

3 DATA REDUCTION

The observed scientific images are reduced using the Image Reduction and Analysis Facility (IRAF) package. Following the standard IRAF process, for these images, the bias is subtracted and the flat field is corrected using the combined twilight flats. The cosmic rays hits in the images are removed by a criterion of four times the variation of the sky background. Utilizing the APPHOT task, the magnitudes of all the selected targets in all frames are measured by the aperture photometric method. According to the seeing and the brightness of the selected targets, the optimum aperture size is chosen for each night's observation.

In order to obtain the brightness variation of the asteroid, several constant reference stars are used by a weighted mean approach. Meanwhile, light time has been corrected for each point in the photometric data.

4 PERIOD ANALYSIS

Several groups have made photometric observations for asteroid (1028) Lydina, but the measurements of the spin period from different data show a small divergence. Almeida et al. (2004) first reported a period of 15.69 hours according to their two nights' observational data on 1998 November 15 and 16, and there is only one minima in their composite light curve folded over 15.69 hours (see Almeida et al. 2004). They suggested the period with a low reliability, and called for more data to improve it. Behrend's website[1] presented the three nights' observations obtained by A. Pierre and B. Jean-Gabriel, which had large errors (about 0.1 mag) for individual data and showed a very low amplitude (about 0.07 mag) each night. The composite light curve that was folded over 48 hours covered only one maximum (see Behrend's website). We think that this period of 48 hours may be an alias frequency. Recently, Stephens (2012) suggested a period of 11.680±0.005 hours.

Using five new nights of photometric data from asteroid (1028) Lydina, the rotation period is analyzed by the PDM method (the Phase Dispersion Minimization method, Stellingwerf 1978). This is a statistical approach for period analysis and useful for data sets with gaps, non-sinusoidal variation, and poor time coverage. The statistical quantity Θ is calculated for a selected period value. From examining Figure 1, two period values of 11.680 hours and 5.838 hours are significant. If 5.838 hours is taken as the rotation period, the composite light curve will have one minimum and one maximum. If 11.680 hours is taken as the spin period, the light curve will have two maxima and two minima (see Fig. 2), which reflects a tri-axial ellipsoid shape. Considering the equilibrium figure of a C-type asteroid, we think the period of 11.680 hours is more reasonable. According to Warner (2006), the uncertainty of the period is estimated: 0.001 hours. Our result of a spin period of 11.680 hours is consistent with the one suggested by Stephens (2012). Therefore the period of 11.680 hours is confirmed by our data.

5 THE SHAPE AND ORIENTATION OF SPIN

The study of pole orientation in asteroids could provide a large amount of information on the process of formation and evolution of small bodies in the solar system. Thus, enlarging the sample of data about pole orientation is an important task.

5.1 The Amplitude-Aspect Method

The Amplitude-Aspect method assumes that the shape of an asteroid is a tri-axial ellipsoid ($a \geq b \geq c$) and the material on the surface of asteroid is uniform, so the brightness of the asteroid at about zero solar phase is proportional to its illuminated cross sectional area $S(\phi, \theta)$,

$$S(\phi, \theta) = \pi abc \sqrt{\sin^2\theta \times \left(\frac{\sin^2\phi}{a^2} + \frac{\cos^2\phi}{b^2}\right) + \frac{\cos^2\theta}{c^2}}\,, \tag{1}$$

where ϕ donates the rotation phase angle, and the aspect angle θ is an angle between the pole of the asteroid and the direction of the observers' sight. There is a relation of the aspect angle written as

$$\cos\theta = -\sin\beta\sin\beta_{\rm p} - \cos\beta\cos\beta_{\rm p}\cos(\lambda - \lambda_{\rm p})\,. \tag{2}$$

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[1] *http://obswww.unige.ch/ behrend/page3cou.html#001028*

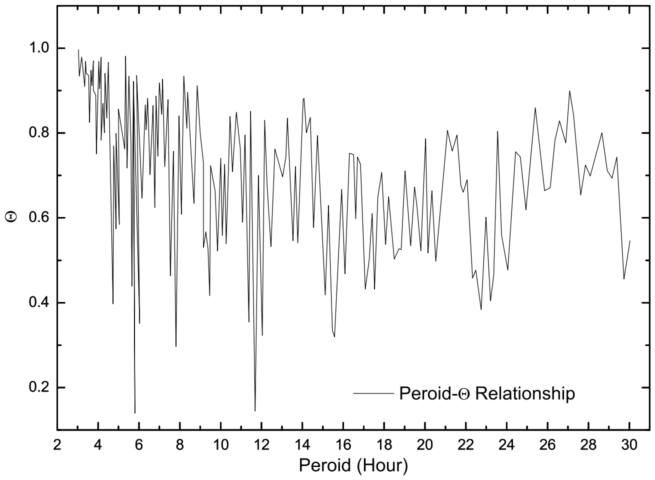

Fig. 1 Statistical quantity Θ vs. period. Two minimum values of the quantity Θ correspond to the periods of 5.838 hours and 11.680 hours.

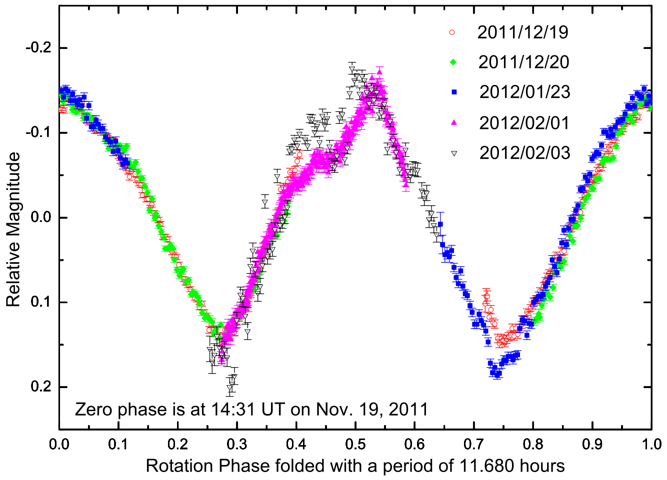

Fig. 2 The composite light curve of asteroid (1028) Lydina.

In Equation (2), (λ,β) is the geocentric ecliptic coordinates of the asteroid and ($\lambda_{\rm p}$,$\beta_{\rm p}$) is the ecliptic coordinates of the pole of the asteroid.

For a rotating asteroid, the maxima and minima cross sectional areas are obtained when $\phi = 0$ and $\phi = \frac{\pi}{2}$, respectively. The magnitude $V(\phi, \theta)$ of each data point in the light curve with respect to the maximum brightness is written as

$$V(\phi, \theta) = -2.5 \log_{10} \frac{S(\phi, \theta)}{S_{\rm max}(\theta)} \, . \tag{3}$$

Equation (3) can be written into a linear form

$$y = Bx + C\,. \tag{4}$$

Here, $x = \cos^2\phi$ and $y = 10^{\frac{-V(\phi,\theta)}{1.25}}$. B and C are a function of both the aspect angle and the axial ratios of a tri-axial ellipsoid, and they can be fitted linearly with the photometric data in a small interval period.

$$B = \frac{[(\frac{c}{b})^2 - (\frac{c}{a})^2]\sin^2\theta}{(\frac{c}{b})^2\sin^2\theta + \cos^2\theta}, \qquad C = \frac{(\frac{c}{a})^2\sin^2\theta + \cos^2\theta}{(\frac{c}{b})^2\sin^2\theta + \cos^2\theta}\,. \tag{5}$$

According to the definition of the amplitude $A(\theta)$ of the light curve, the relationship between the amplitude and the fitted intercept C can be derived.

$$A(\theta) = 2.5\log_{10}\frac{S_{\max}}{S_{\min}} = 1.25\log_{10}\frac{\cos^2\theta + (\frac{c}{b})^2\sin^2\theta}{\cos^2\theta + (\frac{c}{a})^2\sin^2\theta} = 1.25\log\frac{1}{C}\,. \tag{6}$$

From Equation (5), it is noted that $B + C = 1$ due to the assumption of a tri-axial ellipsoid, which means that the shape of an asteroid with $B + C$ close to 1 may be close to the tri-axial ellipsoid. Otherwise, this shape has more divergence from that of a tri-axial ellipsoid.

Pospieszalska-Surdej & Surdej (1985) demonstrate that the effect of solar phase angle can be neglected for $\alpha \leq 15°$, when estimating the shape of an ellipsoidal asteroid with the Amplitude-Aspect method. As for the photometric data at the larger phase, the Amplitude-Phase relationship (Zappala et al. 1990) is used to correct the influence of the solar phase angle on the amplitude.

$$A(\theta, 0) = \frac{A(\theta,\alpha)}{1 + m\alpha}\,. \tag{7}$$

For C-type asteroids, the coefficient m of 0.015 is applied.

In a short time interval, the variation of the aspect angle can be ignored and the shapes of light curves are approximately the same. Because the observations span a large time interval, light curves vary significantly due to the change of the aspect angle. Therefore, using the light curves obtained at the different aspect angles, the orientation of spin and axial ratios of an asteroid can be estimated.

5.2 The Shape and Spin Orientation of Asteroid (1028) Lydina

Our observations span more than one month, and the amplitudes of these light curves in the two apparitions (2011 December 19 and 2012 February 1) changed significantly, as can be seen in Figure 2. Therefore, the observational data are divided into two groups. Group 1 involves the observational data on 2011 December 19 and 20; and Group 2 involves the observational data on 2012 January 23, February 1 and February 3. The data from the two groups are fitted using Equation (4) according to the period of 11.680 hours. The linear regression parameters are listed in Table 2, from which the quantity of $B + C$ close to 1 implies that the shape of (1028) Lydina is very close to a tri-axial ellipsoid.

Table 2 The Linear Regression Parameters of the Two Groups of Data

Group	Date	B	C	R	A
Group 1	2011 Dec. 19 and Dec. 20	0.37	0.61	0.99	0.27
Group 2	2012 Jan. 23, Feb. 1 and Feb. 3	0.36	0.55	0.96	0.32

From Figure 3, it is noted that the observational data are fitted well at most phases, except for a small scale deviation in panel (b). This small deviation could be caused by the irregular shape of the asteroid or by a non-uniform distribution of the mineralogical composition.

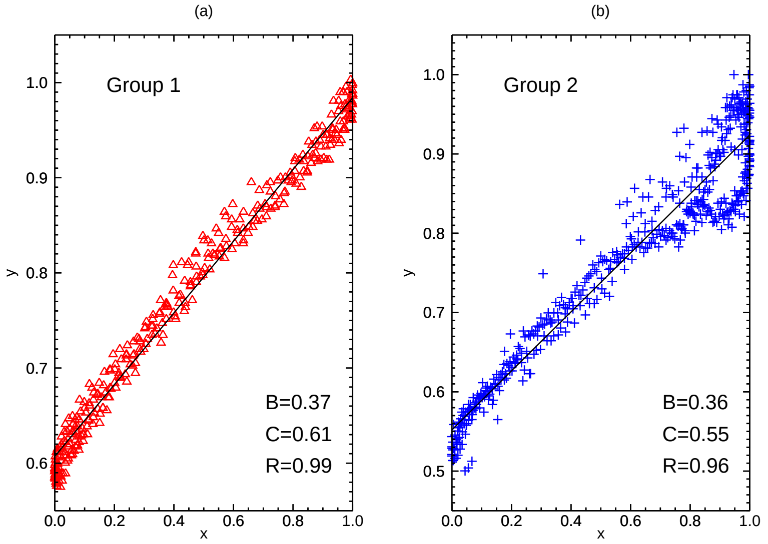

Fig. 3 The linear regression for the photometric observational data following Eq. (4).

Table 3 The Data are Used to Estimate the Pole Orientation and the Axial Ratio of (1028) Lydina

Date	Ecliptic Coordinates (J2000.0)	Amplitude (mag)	α (°)	Author
1998/11/15	$(25.0°, -6.6°)$	0.70	8.9	Almeida et al. (2004)
2011/11/30	$(70.0°, 1.6°)$	0.22	1.0	Stephens (2012)
2011/12/19	$(66.2°, 2.4°)$	0.27	6.9	Present work
2012/02/01	$(63.9°, 3.6°)$	0.32	17.5	Present work

Additionally, the amplitudes of Almeida et al. (2004) on 1998 November 15 and Stephens (2012) on 2011 November 30 are applied in the estimation of a tri-axial ellipsoid according to the good quality of their light curves (Light Curve Quality $U \geq 2$ in LCDB[2]) and the duration of photometric observation. Due to the poor quality of the light curves, Behrend's amplitude data have been abandoned. All data used by us have been listed in Table 3. Meanwhile, all the amplitudes have been corrected to account for the effect of solar phase angle. The amplitude of 0.7 mag obtained by Almeida et al. (2004) is the largest one among all the available data. So, we assume that this amplitude is obtained when the aspect angle is close to 90°, then the axial ratio $a/b = 1.77$ is derived.

In order to find the optimal resolution for the other parameters, we scanned the parameter spaces of pole orientation $(\lambda_\mathrm{p}, \beta_\mathrm{p})$ at a 5° step at the beginning, and estimated the other parameter with the least-squares method for each step.

Figure 4 shows the chi-square for (1028) Lydina obtained by scanning the celestial sphere with trial pole values in steps of 5° along the ecliptic longitude and latitude. In Figure 4, the red cross and the green cross mark the minima of chi-square. Because it is not possible to determine the direction of rotation with the Amplitude-Aspect method, the derived solutions have the same spin axis, but opposite directions of rotation. Then a small step (1°) is set to scan the marked regions

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[2] Collaborative Asteroid Lightcurve Link *http://www.minorplanet.info/lightcurvedatabase.html*

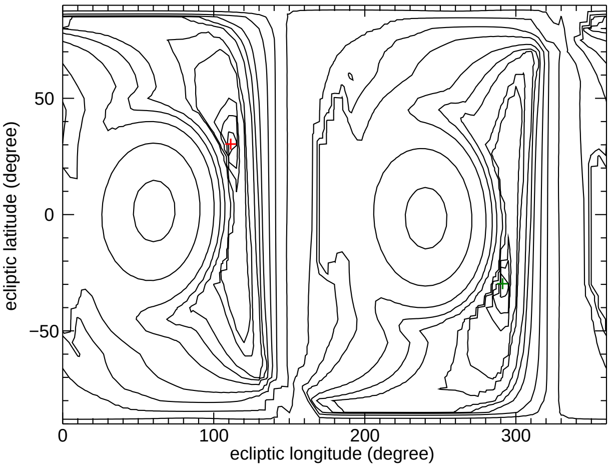

Fig. 4 $(\lambda_{\rm p},\beta_{\rm p})$-$\chi^2$ map corresponding with trial pole values in steps of 5° in the ecliptic longitude and ecliptic latitude.

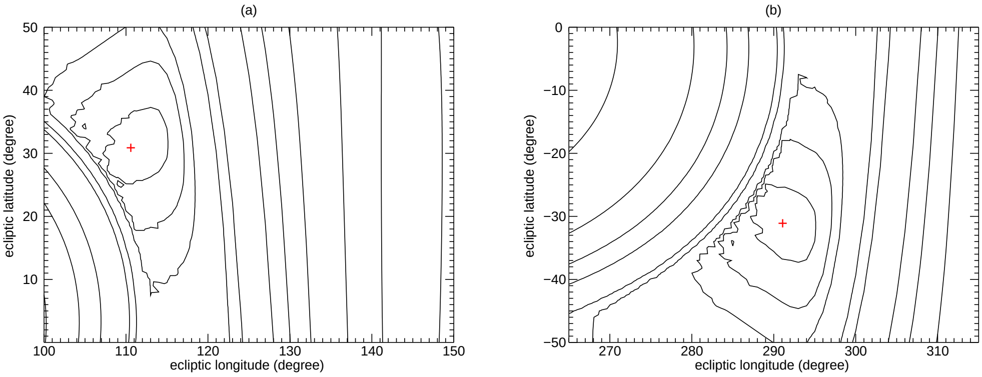

Fig. 5 $(\lambda_{\rm p},\beta_{\rm p})$-$\chi^2$ map corresponding with trial pole values in steps of 1° in the ecliptic longitude and ecliptic latitude. Panel (a) corresponds to the case $\lambda_{\rm p}=111^\circ{}^{+4^\circ}_{-4^\circ}$, $\beta_{\rm p}=31^\circ{}^{+4^\circ}_{-5^\circ}$; Panel (b) corresponds to the case $\lambda_{\rm p}=291^\circ{}^{+4^\circ}_{-4^\circ}$, $\beta_{\rm p}=-31^\circ{}^{+5^\circ}_{-4^\circ}$.

in Figure 4. More precise pole solutions of $(111^\circ, 31^\circ)$ and $(291^\circ, -31^\circ)$ are derived (see Fig. 5). The corresponding solutions for the axial ratio b/c are both 1.17. Figure 6 shows the relationship between the model values and corrected observed data.

The uncertainty in the parameters is analyzed with statistical methods. That is, when one of these parameters is checked, the rest of the parameters are fixed. The estimated parameter varies randomly, and the chi-square value is calculated for each jump. After a quantity for a jump is calculated, the $\log_{10}(\chi^2)$-plot on this parameter is obtained (see Figs. 7 and 8), in which the minimum of the chi-square value is the most likely estimation of the parameter. According to the principle of Pearson's chi-square test, the uncertainty ranges for the parameters are derived by setting

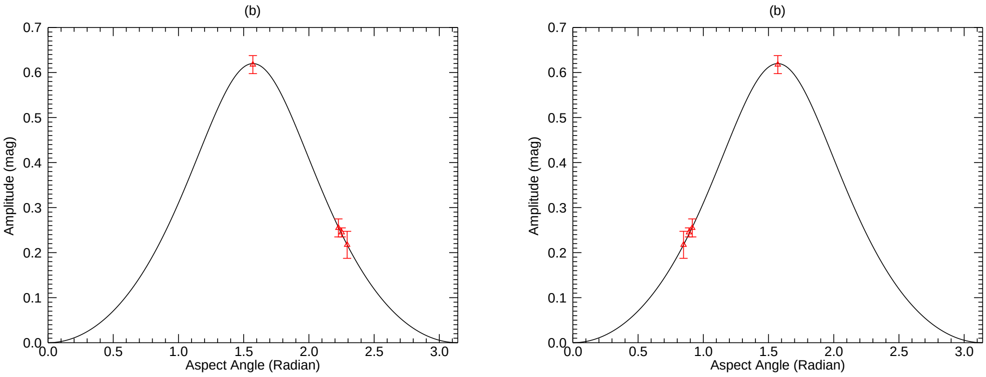

Fig. 6 The model of the Aspect-Amplitude and the observed amplitudes of asteroid (1028) Lydina. The red triangles represent the corrected observed amplitude, and the line is the theoretical model. Panel (a) corresponds to the case $\lambda_{\rm p} = 111^{\circ}{}^{+4^{\circ}}_{-4^{\circ}}$, $\beta_{\rm p} = 31^{\circ}{}^{+4^{\circ}}_{-5^{\circ}}$; Panel (b) corresponds to the case $\lambda_{\rm p} = 291^{\circ}{}^{+4^{\circ}}_{-4^{\circ}}$, $\beta_{\rm p} = -31^{\circ}{}^{+5^{\circ}}_{-4^{\circ}}$.

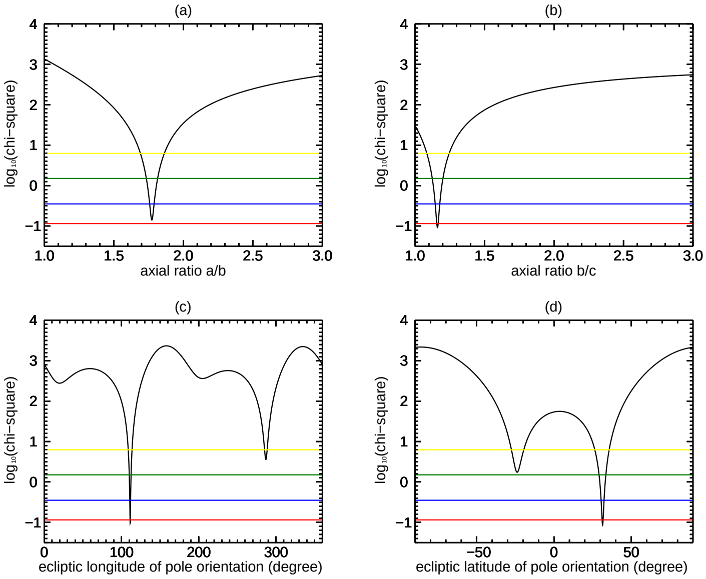

Fig. 7 The $\log_{10}(\chi^2)$-plot corresponds to the case $\lambda_{\rm p} = 111^{\circ}{}^{+4^{\circ}}_{-4^{\circ}}$, $\beta_{\rm p} = 31^{\circ}{}^{+4^{\circ}}_{-5^{\circ}}$. The red lines correspond to the significance level of 0.99, the blue lines correspond to the significance level of 0.95, the green lines correspond to the significance level of 0.32 and the yellow lines correspond to the significance level of 0.10.

a significance level of 0.10. In detail, the estimations of the pole orientation are: $\lambda_{\rm p} = 111^{\circ}{}^{+4^{\circ}}_{-4^{\circ}}$, $\beta_{\rm p} = 31^{\circ}{}^{+4^{\circ}}_{-5^{\circ}}$ and $\lambda_{\rm p} = 291^{\circ}{}^{+4^{\circ}}_{-4^{\circ}}$, $\beta_{\rm p} = -31^{\circ}{}^{+5^{\circ}}_{-4^{\circ}}$. Similarly, the axial ratios of the tri-axial ellipsoid are: $a/b = 1.77^{+0.10}_{-0.08}$ and $b/c = 1.17^{+0.07}_{-0.09}$. From the axial ratio a/b, it seems that asteroid (1028)

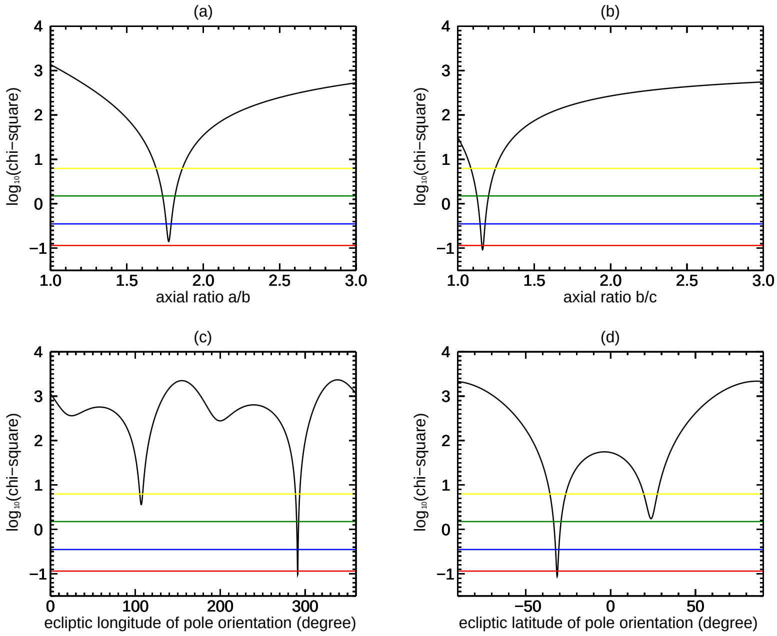

Fig. 8 The $\log_{10}(\chi^2)$-plot corresponds to the case $\lambda_{\rm P} = 291^{\circ}{}^{+4^{\circ}}_{-4^{\circ}}$, $\beta_{\rm P} = -31^{\circ}{}^{+5^{\circ}}_{-4^{\circ}}$. The red lines correspond to the significance level of 0.99, the blue lines correspond to the significance level of 0.95, the green lines correspond to the significance level of 0.32 and the yellow lines correspond to the significance level of 0.10.

Lydina has an extremely elongated shape. Is this true? We need more observational data to confirm this conclusion.

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