

The Rotational Periods of Three C-Type Asteroids 431, 521 and 524

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Abstract The determination for asteroids' spin parameters is very important for the physical study of asteroids and their evolution. Sometimes, the low amplitude of light curves and kinds of systematic errors in photometric data prevent the determination of the asteroids' spin period. To solve such a problem, we introduced the de-correlation methods developed in searching for exoplanetary transit signal into the asteroid's data reduction in this paper. By applying the principle of Collier Cameron (MNRAS 373:799–810, 2006) and Tamuz et al. (MNRAS 356:1466–1470, 2005)'s, we simulated the systematic effects in photometric data of asteroid, and removed those simulated errors from photometric data. Therefore the S/N of intrinsic signals of three selected asteroids are enhanced significantly. As results, we derived the new spin periods of 18.821 ± 0.011 h, 28.202 ± 0.071 h for (431) and (521) respectively, and refined the spin period of (524) as 14.172 ± 0.016 h.

Keywords Asteroids · De-correlation methods · Rotation periods

1 Introduction

The C-type asteroid is a major component of the asteroid population. Relatively, more information on planetary formation may be remained on them due to their far distance from the Sun. So the study of physical parameters (e.g. the spin parameters and shape of asteroid.) of C-type asteroids may provide the important clue to understand the characteristic of asteroid, and its collision evolution as well. Since 2000, we started to do photometric observation for some selected main belt C-type asteroids with moderate size (around 100 km in diameter). The aim of our project is to determine the spin period and their shape if possible and find new binary asteroids. As follow paper, photometric data of three of them are reduced and analyzed here.

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As we known, the shape (or the features) of light curve of asteroid is a key in determining the spin parameters and reversing the shape of an asteroid. However, sometimes these features of low-amplitude light curves are blurred by kinds of errors (e.g. systematic errors or 'red noise' called in Pont et al. (2006) and white noise). Therefore the determination of spin period may become amphibolous, and the inverse of the shape of asteroid is impossible using such light curves. Under this circumstance, we introduced new techniques (developed by Tamuz et al. (2005) and Collier Cameron et al. (2006) for searching the faint transit signal of extra-solar planet.) into the photometric data reduction of asteroids'. Simply, by applying the principle of Tamuz et al. (2005)'s method, we modeled the relative systematic errors in asteroid's photometric data, and then removed them out. The detail form of systematic errors simulated and the effect after these correction of systematic errors are presented in Sect. 3. The Sect. 2 lists observation condition of 3 selected C-type asteroids. And last section presents the light curves after the correction of the systematic errors and their spin period estimated with the light curves.

2 Observation

Three selected C-type asteroids of moderate size were observed with the 1-m RC telescope at Yunnan Observatory. Photometric data of selected asteroids were obtained with a 1024×1024 back CCD. Table 1 lists the aspect data of three selected C-type asteroids, Δ and r are the geocentric and heliocentric distance of asteroid, respectively, 'Phase' is the phase angle of asteroid. The last two columns are the filter adopted and the range of airmass of asteroid in each night. The center wavelength for V-band and I-band filters are 539 and 832 nm respectively, and the symbol N represents no filter was used.

3 Data Reduction

With standard IRAF process, the effects of the bias and flat on CCD images are corrected. The cosmic rays hitting accidentally on the CCD detector, are identified and removed by a threshold of four times of standard deviation of background. Then the magnitude of objects in each image are measured with APPHOT task of IRAF by a optimum aperture.

Table 1 The aspect data of three observed asteroids

Obj.	Date in UT	(α, δ) (J2000.0) Hour, Degree	Δ (AU)	r (AU)	Phase ($^\circ$)	$V_{mag.}$	Filter	Airmass range
(431)	2004/01/19.0	08.536, +19.137	2.630	3.609	1.9	13.8	I	1.00–1.42
	2004/02/11.0	08.222, +20.329	2.693	3.626	5.9	14.1	I	2.06–1.35
	2004/02/13.0	08.210, +20.369	2.700	3.627	5.9	14.2	I	1.56–1.85
(521)	2004/02/14.0	06.271, +29.635	1.550	1.506	19.8	12.4	V	1.16–2.35
	2004/02/15.0	06.274, +29.666	1.563	2.299	20.1	12.4	V	1.17–2.24
(524)	2005/11/24.0	04.725, +36.202	1.356	2.315	7.6	12.9	N	1.09–1.28
	2005/11/25.0	04.707, +36.176	1.355	2.316	7.3	12.9	N	1.02–1.18
	2005/11/26.0	04.689, +36.147	1.353	2.316	7.0	12.8	N	1.03–1.74
	2005/11/27.0	04.670, +36.114	1.352	2.317	6.8	12.8	N	1.03–1.98

In fact, as ground-based observation, some remnant errors, like errors related to changing airmass, atmospheric conditions, telescope tracking, flat-field, still exist in the measured magnitudes of objects. And those errors are correlated on millimagnitude photometry (Pont et al. 2006). Those correlated errors, also called the systematic effects hereafter in this paper may blur the faint features of light curves, and prevent us from searching for periodic signals in low-amplitude light curves.

Recently, several techniques (Tamuz et al. 2005; Pont et al. 2006; and Collier Cameron et al. 2006) had been developed to simulate and remove the remnant systematic effects existed in photometric data. These methods had been applied successfully in identifying the faint exoplanetary transit signal from stellar photometric survey. Here, we applied both of Collier Cameron et al. (2006) (or called the coarse de-correlation method) and Tamuz et al. (2005)'s methods to the photometric data of asteroids for their low-amplitude light variation.

Before modeling the systematic effects existed in measured magnitudes, the coarse de-correlation algorithm is performed to remove the small night-to-night and frame-to-frame differences in the zero-point from the magnitudes. Simply, we have the original residual magnitudes r_{ij} of individual measured magnitude with Eq. (1).

$$r_{ij} = m_{ij} - \hat{m}_i - \hat{z}_j \tag{1}$$

$$\begin{aligned} \hat{m}_i &= \frac{\sum_j m_{ij} \omega_{ij}}{\sum_j \omega_{ij}}, & \omega_{ij} &= \frac{1}{\sigma_{ij}^2 + \sigma_{t(j)}^2} \\ \hat{z}_j &= \frac{\sum_i (m_{ij} - \hat{m}_i) u_{ij}}{\sum_i u_{ij}}, & u_{ij} &= \frac{1}{\sigma_{ij}^2 + \sigma_{s(i)}^2} \end{aligned} \tag{2}$$

In Eq. (1), m_{ij} is the measured magnitude of the i -th star in the j -th frame, \hat{m}_i , the mean of magnitude of the i -th star in one night, and \hat{z}_j , the zero-point of the j -th frame. The quantity σ_{ij} is the magnitude error of a data point calculated by the appphot task in IRAF. $\sigma_{t(j)}$ is introduced in individual frames by passing wisps of cloud and $\sigma_{s(i)}$ is introduced by the intrinsic stellar variability. Initially, we calculated \hat{m}_i and \hat{z}_j considering $\sigma_{s(i)} = 0$ and $\sigma_{t(j)} = 0$. Then, with the estimated values of \hat{m}_i and \hat{z}_j , $\sigma_{s(i)}$ and $\sigma_{t(j)}$ are estimated with maximum likelihood algorithm (described in detail by Collier Cameron et al. 2006). By an iterative algorithm, the convergence value of each of unknown quantities can be derived. Two additional variance components $\sigma_{s(i)}$ and $\sigma_{t(j)}$ are used as part of weight in further simulation and correction for systematic effects in photometric data (or say reduced residual magnitude) of asteroid.

Based on the situation of our observation of asteroid, the systematic effects associated with the atmospheric extinction are considered here. Thus,

$$r_{ij} = c_i a_j + d_i a_j^2 \tag{3}$$

In practice, the different systematic effects are modeled independently by applying Tamuz et al.'s method. For example, we firstly performed the simulation of the linear extinction effect $c_i a_j$ under the condition of minimizing the quantity S^2 in Eq. (4).

$$S^2 = \sum_{ij} \frac{(r_{ij} - c_i a_j)^2}{\sigma_{ij}^2} \tag{4}$$

Here, in σ_{ij}^2 , the calculated formal variance of the magnitude m_{ij} and two additional variance components $\sigma_{s(i)}^2$ and $\sigma_{t(j)}^2$ are included. c_i and a_j are the linear extinction

coefficient of the i -th star and the airmass of the j -th frame in one night. Using the algorithm of Tamuz et al. (2005), the best-fitting values of c_i and a_j are derived.

To generalize, c_i and a_j may represent any other systematic effect, e.g. associated with the time, temperature or position of stars on the CCD. What kinds of systematic error are included in original residual magnitude depends on the situation of observation. For our observation of asteroid, the conic extinction effect $d_i a_j^2$ was also modeled based on the new residual magnitudes $r_{i,j}^{(1)}$ assuming the airmass a_j has been confirmed by the previous simulation.

$$r_{i,j}^{(1)} = r_{i,j} - c_i a_j \tag{5}$$

After removing the all simulated systematic errors from original residual magnitudes, we derived the reduced residual magnitude $r_{i,j}^{(2)}$ for example in this paper.

$$r_{i,j}^{(2)} = r_{i,j} - c_i a_j - d_i a_j^2 \tag{6}$$

As a comparison, we plot the original residual magnitude r_{ij} and the reduced residual magnitudes $r_{i,j}^{(2)}$ of comparison stars of (431) Nephela's observations on February 13 2004 in two panels of Fig. 1. The abscissa of two panels are the uncertainties of magnitude, and the Y-axis of panel A is the original residual magnitudes derived with Eq. (1), and one of panel B is the reduced residual magnitudes derived with Eq. (6) (Fig. 1).

For an asteroid, its linear and conic extinction coefficients $c_{ast.}$ and $d_{ast.}$ are estimated by weighted average of all simulated values of comparison stars. Then the systematic errors $c_{ast.} a_j$ and $d_{ast.} a_j^2$ are removed from the photometric data of asteroid with Eq. (7).

$$r_{ast,j}^{(2)} = r_{ast,j} - c_{ast.} a_j - d_{ast.} a_j^2 \tag{7}$$

$$c_{ast.} = \frac{\sum_{i=1}^n c_i \omega_i}{\sum_{i=1}^n \omega_i} \quad d_{ast.} = \frac{\sum_{i=1}^n d_i \omega_i}{\sum_{i=1}^n \omega_i} \tag{8}$$

In Eq. (7), $r_{ast,j}$ is the original residual magnitude of asteroid after removed its mean magnitude in each night and the zero-point of j -th frame. The weight ω_i is the reciprocal of

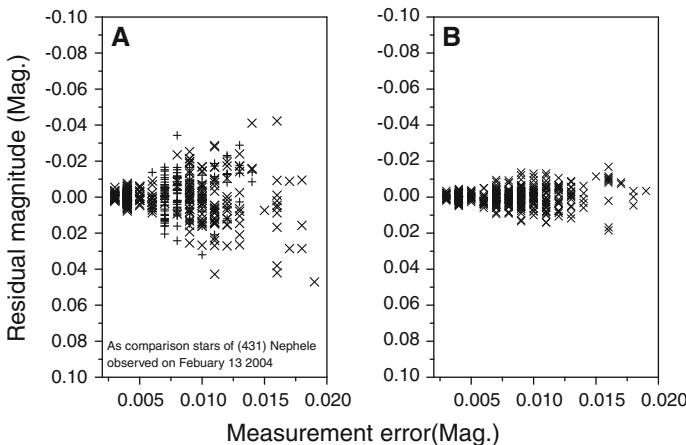


Fig. 1 Panel A, the original residual magnitudes of comparison stars; Panel B, their reduced residual magnitudes after the Tamuz et al.'s correction

the variance $\sigma_{s(i)}^2$ of stellar intrinsic variability, which is estimated during the process of coarse de-correlation by the maximum-likelihood approach.

4 Periodic Analysis and Results

Using the reduced residual magnitudes of asteroids, we estimated the rotational period of (431), (524) and (521) with the PDM method (Stellingwerf 1978) and the ANOVA method (Schwarzenberg-Czerny 1989). For the uncertainty of period, the Bayesian inference is used. Namely, we obtained the posterior distribution of parameter–period by the Markov Chain Monte Carlo method (Ford 2005), and took a half of confidence interval (with a confidence level of 68%) of the posterior distribution as the uncertainty of period. When the posterior distribution of parameter has a narrow widths shape, the uncertainty of the parameter will be small. The significance in the last column of Table 2, is the ratio between period signal and noise in amplitude.

4.1 (431) Nephela

(431) Nephela, a C-type asteroid with a diameter of 95 km, have been observed by some people. Carlsson and Lagerkvist (1981)'s observation for (431) Nephela didn't give any period value. So did Di Martino et al. (1995)'s observation on July 21, 22, 24 and 25, 1990. RenRoy et al. suggested a dubious period of 21.432 h and suspected it probably is a binary asteroid system in Behrend (2006)'s web site.

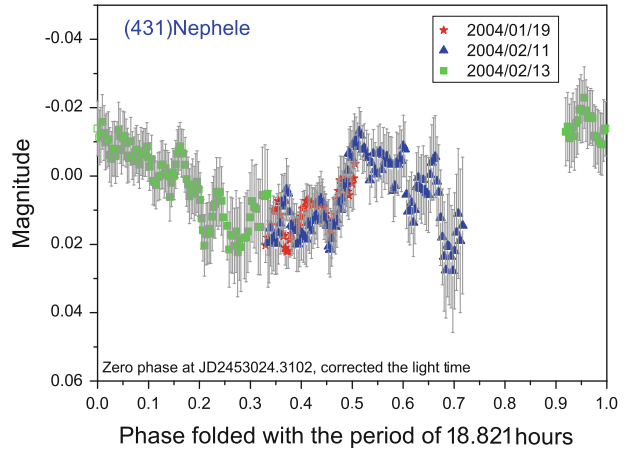
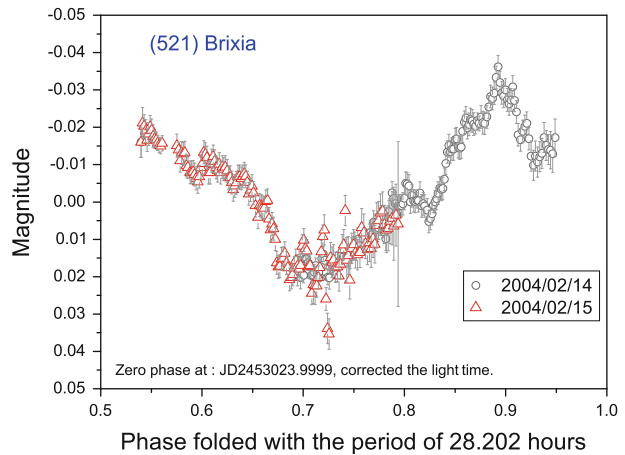
We observed the (431) Nephela on three nights (January 19, February 11 and 13, 2004). The photometric data of three nights' bear low amplitude. With the photometric data after coarse de-correlation correction and Tamuz et al.'s correction, the spin period of 18.821 h with an amplitude of 0.06 mag. is derived. Figure 2 shows the phase plot of (431) Nephela. The interest in phase plot is the flat feature between phase 0.2 and 0.5, which probably is an evidence of a binary system. Anyway, the further observations for (431) Nephela are needed to determine full spin parameters, its shape and to repeat the feature of a binary system. [htb]

4.2 (521) Brixia

The C-type asteroid (521) Brixia has a diameter of 115 km. Surdej et al. (1983)'s observation for (521) Brixia couldn't give any clear periods due to the low variation amplitude. We observed the (521) Brixia on February 14 and 15, 2004 with the 1-m telescope. Based on the photometric data after coarse de-correlation and Tamuz et al.'s corrections, a spin period of 28.202 h is inferred by ANOVA method for small samples. Figure 3 is phase plot of (521) Brixia folded with 28.202 h. Indeed, the absence of phase before 0.5 prevents us to conclude that it is an unambiguous period value. So we just

Table 2 The analysis results for selected C-type steroids

Name	Period, uncertainty (Hour)	Amp. (Mag.)	Significance
(431)	18.821 ± 0.011	0.06	9.8
(521)	28.202 ± 0.071	0.07	49.0
(524)	14.172 ± 0.016	0.19	16.5

Fig. 2 The light curves of (431)**Fig. 3** The light curves of (521)

suggest that the value of 28.202 h may be its spin period, and the magnitude difference between the light maximum and minimum in this apparition is about 0.07 mag. Additionally, we noticed that there is a 'V' shape with a flat bottom around phase 0.7. Is it a feature of an asteroid with a component? Further observation for (521) Brixia are called for to confirm it.

4.3 (524) Fidelio

The C-type asteroid (524) Fidelio, is another moderated size target. Koff (2006) made five nights' observations for (524) from 25 October to 2 November 2005, and gave a rotational period of 14.19 h with an amplitude of 0.22 mag.

We made four nights' observations for (524) one month after Koff's observations, and derived a slightly different period of 14.172 h with an amplitude of 0.19 mag. Figure 4 shows the phase plot of our observation data. Combined with Koff's data, we derived the same period. Figure 5 shows the phase plot of our's and Koff's data.

Fig. 4 The light curves of (524)

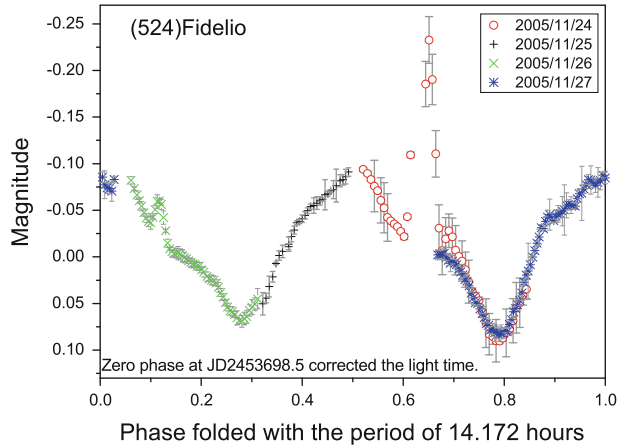
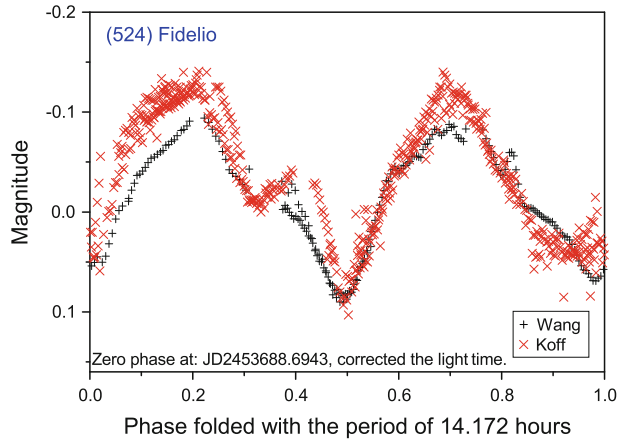


Fig. 5 The phase plot of (524)



The brighter features at phases 0.15 and 0.60 in Fig. 4 are caused by the asteroid’s appulse to two un-resolved faint stars USNO-A2 1200-02459983 (17.8mag in B-band) and USNO-A2 1200-02434816 (18.6mag in B-band) on November 24 and 26, 2005, respectively. For the flux of the un-resolved faint stars is involved in the aperture of magnitude measurement of asteroid, the magnitudes of asteroid are overestimated. So, some over-estimated data point around phase of 0.15 are removed. Nearly equivalent two maxima and minima of light curve imply that the shape of (524) is symmetry as whole.

With the application of coarse de-correlation and the Tamuz et al.’s method, the study on the spin parameters and the shape of asteroids can be expedited in future because of the application of the good quality of low amplitude light curves. And it can help us in searching for new binary asteroids from the light curves with eclipse shape or multiple periodic variation.

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