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The Distinct Light Curve Shape of the Asteroid (469)

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Abstract. The observation light curves of the main belt asteroid (469) Argentina, obtained on March 9–11 2002 and August 10–11 2004, are presented in this paper. The complex light curve of the (469) suggests that it may be in NPA rotation. Using the Fourier analysis method, some prominent spectrum values are derived individually for two subset data. Among these period values, periods of 13.00 and 8.74 h are regarded as basic components. Other derived period values can be combined linearly with these two basic period values. If the (469) is in a free-force precession mode, the motion mode will be LAM (largest-axis mode) according the ratio of precession and rotation periods. And the minimum of I_1/I_3 (ratio of the largest and smallest principal momentum of inertial) is 3.05. Assuming an external torque releasing by a satellite forces the (469) to precess, the mass of satellite roughly is the same order as the primary's on condition that the precession and rotation periods are two basic values. At present, we cannot draw an unambiguous conclusion on (469)'s motion for sparse data, So the further observations are necessary for understanding the (469)'s tumbling motion farther.

Keywords: Asteroids, precession, satellite

1. Introduction

The number of suspected binary asteroids in main belt is scarce for difficult to identify. Only some of them can be confirmed as the binary systems (Margot et al., 2002). Most suspected objects were deduced from their complex light curves. Celliino et al. (1985) gave such criteria for identifying the synchronized binary asteroid: the light curves (1) with flat minima; (2) bearing the strong amplitude-phase dependence; (3) bearing the changes of slope in the descending and ascending parts of the light curves, will be related to the eclipse.

For the binary systems, if the rotation of components does not synchronize completely with orbital revolution, or the satellite forces the spin axis of primary unaligned with its maximum moment of inertia, the shape of light curve will be different from the case mentioned above, which is more complicated. For an asteroid, if two or more than two periods appear in its light curve, it suggests that the asteroid is in NPA rotation. It may be in free procession or forcing procession mode. Or even the objects is a non-synchronous binary system.

The (469) Argentina's light curves that we obtained in 2002 and 2004, show such characteristic. In this paper, the frequency analysis for those light curves we obtained was done. For its distinct light curves in our observational apparition, we analysed again the data observed by Szekely (2005), which was 39 days before ours observation. The detail frequency analysis for the lightcurves are presented in Section 3. The multiple frequencies variation in the lightcurves suggests that the spin axis of (469) may precess except the rotation. In Section 4, we make preliminary estimation on the asteroid's shape based on the free force precession mode, and the mass of satellite based on the force precession mode.

2. Observation

The C-type asteroid (469) Argentina with the diameter of 129 km, was discovered by Carnera in Heidelberg on February 2 1901. Szekely (2005) published their three night observations (January 28, 29 and February 1 2002) for the (469), and presented a rotation period of 13.2 h. We made the CCD photometric observation for (469) on March 9, 10 and 11, 2002 with 1-m telescope at Yunnan Observatory, China.

The CCD chip (TEK 1024×1024, Back-illuminated, 24 μm $\times$ 24 μm/pixel) made by Princeton Instruments, is used in our observation. The deepest operating temperature is -50°C. The gain of CCD is $3.9e^{-}$/ADU; the read noise is $4e^{-}$; the dark current is $0.1e^{-}$/pixel/s; and dynamic range is 16 bit.

For the photometric data of (469) in 2002 show the complex light curve shape, the extensive observations were made on August 10 to 11, 2004. The aspect data of observations are listed in Table I. Column R.A. and Decl. are the right ascension and declination of the asteroid in the J2000.0 frame; Δ is the geocentric distance of the asteroid; r, the heliocentric distance; El, the solar elongation; α, the phase angle of the asteroid; V, the predicted magnitude in V band. The last column is the photometric dispersion of each night.

3. Frequency Analysis for Light Curves

Three nights' observations in 2002 show significantly diversity in periodic characteristic. In the first night, magnitude of the (469) (Figure 1) vary with a small amplitude and short period. Using the frequency analysis software, a period of 3.00 h with an amplitude of 0.06 mag can be derived from the first night's data.

TABLE I
The aspect data of (469) Argentina

Date UT	R.A., Decl. (J2000)	Δ (AU)	r (AU)	El (°)	α (°)	V (mag)	Dispersion (mag)
2002/03/09.5	07 20 35.9, +29 29 08	2.190	2.804	118.6	18.1	13.5	0.007
2002/03/10.5	07 20 41.3, +29 23 38	2.200	2.803	117.7	18.3	13.5	0.01
2002/03/11.5	07 20 48.3, +29 18 06	2.210	2.802	116.7	18.5	13.5	0.008
2004/08/10.5	20 50 06.9, − 24 33 14	2.456	3.455	168.1	3.5	13.6	0.01
2004/08/11.5	20 49 16.1, − 24 33 35	2.460	3.456	167.2	3.7	13.6	0.009

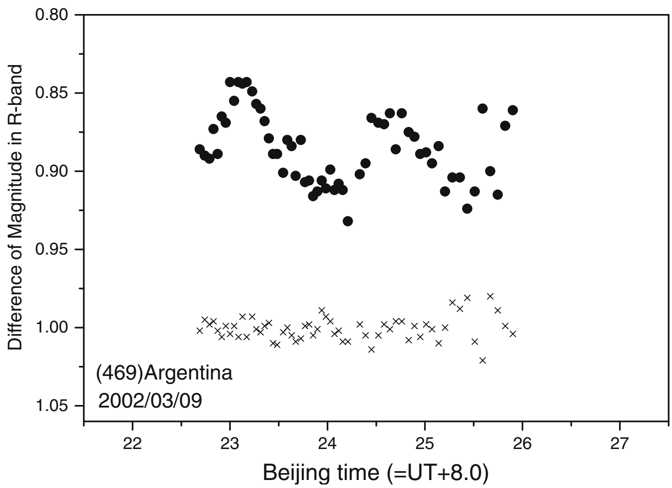

Figure 1. The solid dot represents the light variation of (469) on March 9 2002, the cross represents the photometric dispersion.

The dispersion of difference magnitude of two comparison stars in this night is 0.007 mag, which is smaller than the amplitude of 0.06 mag. For the motion of asteroid among the stars, the irregular background due to unseen faint background stars, may effect determination of asteroid's magnitude. For the purpose of investigation for the sky background, we fit the Histogram of density across whole a image with gaussian distribution. The maximum of standard deviation of the gaussian fit among first night's observational images is less than 24 ADU, three times of which is less than the ADU number of 0.06 magnitude difference of (469)'s in that night. So we don't think the short period variation in the first night is the result of irregular background. Maybe, there are other unconscious factors to rise such fluctuation. Anyway, we can regard the trend of the light curve as flat if ignore the fluctuation.

The shape of light curve (Figure 2) in the second night, is obviously different from the first night's one. The period of 10.19 h (providing two maximum and two minimum in one rotational period) derived individually from second night's data is longer than that of first night's, and the amplitude of 0.15 mag is also larger than that of first night's.

The most complex light variation (Figure 3) occurred in the third night, in which two different characteristic fluctuation can be noted. Because the irregular background or other observational error can give rise to a small amplitude fluctuation, we would rather regard the former part of data with small amplitude fluctuation as a flat trend. The later part of light curve show a long-period variation with large amplitude. The individual frequency analysis for the third night's data suggests a periods of 8.78 h providing two maximum in one rotational period.

Obviously, such complex light curves means a complex rotation, if not to consider the factors of the extremal shape of the asteroid or the diversity of albedo across asteroid's surface. The diversity of light curves of different night can be explained as the modulated results of procession and rotation.

The extensive observation for this object was done on August 10 and 11, 2004. Figures 4 and 5 show the observed light curves in 2004. The dispersion of August 10 and 11 are 0.01 and 0.009 mag, respectively. The amplitude from maximum to minimum in two nights reach 0.07 and 0.03 mag, respectively, we estimate roughly, the period of light variation on August 10 is longer than 5 h. The data of next night show a smaller fluctuation.

Because the change of the geometric condition may effect the shape of light curves, the fourier analysis was done individually for two different

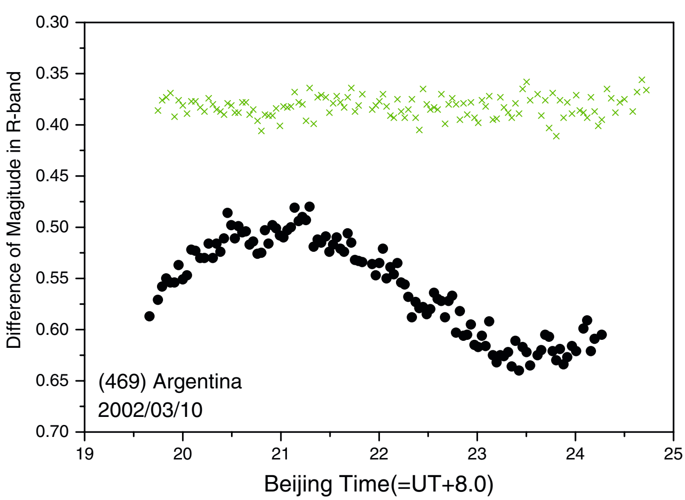

Figure 2. The solid dot represents the light variation of (469) on March 10 2002, the cross represents the photometric dispersion.

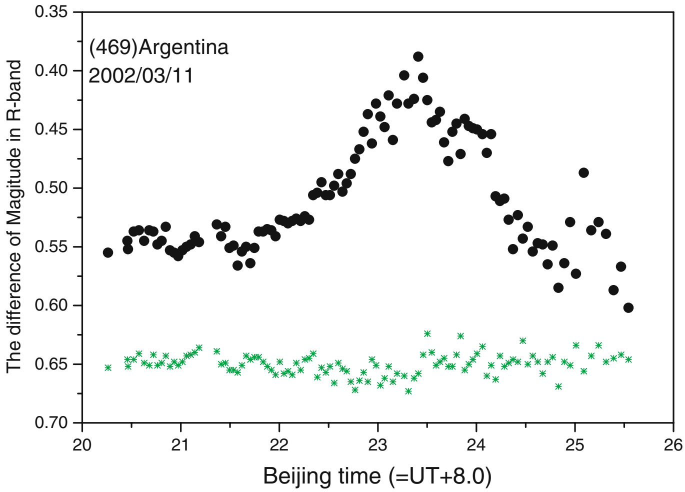

Figure 3. The solid dot represents the light variation of (469) on March 11 2002, the cross represents the photometric dispersion.

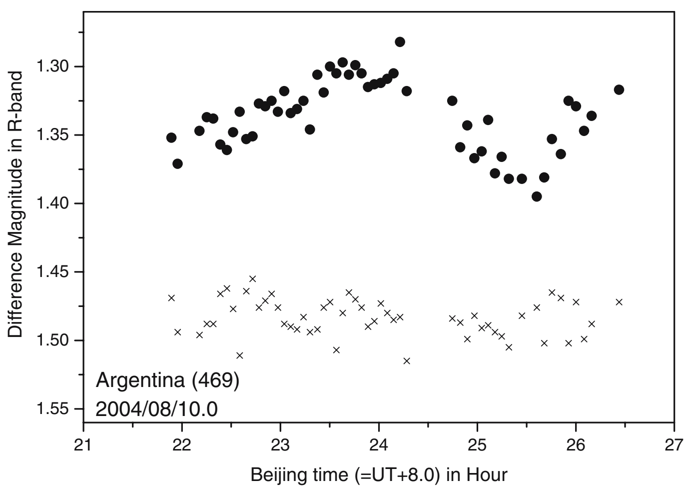

Figure 4. The solid dot represents the light variation of (469) on August 10, 2004, the cross represents the photometric dispersion.

apparition data. For the 2002s data, the four strongest period values (listed in Table II) were derived. The period of 6.514 h can be regard as a half of period of 13.004 h. It seems the period of 13.004 and 4.378 h are the independent basic period components for 2002s data. Figure 6 presents the folder phase with the period of 8.74 h. The fit line in Figure 6 is created with the four most prominent period values.

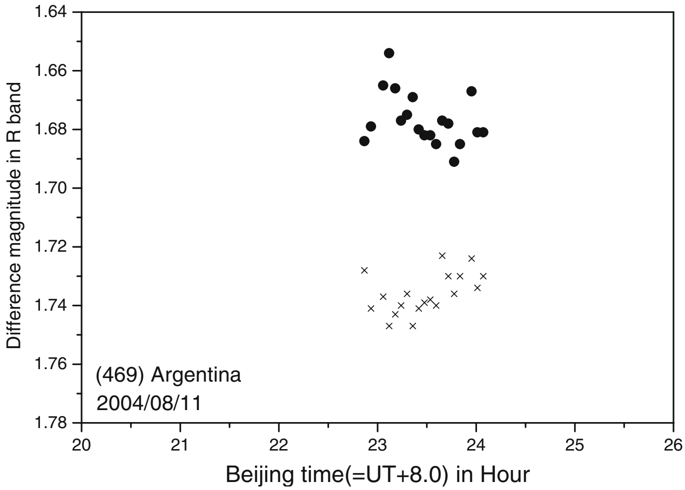

Figure 5. The solid dot represents the light variation of (469) on August 11, 2004, the cross represents the photometric dispersion.

TABLE II
The Fourier frequencies involved in 2002s data

Frequency (rev/h)	Peroid (h)	Amplitude (mag.)	Strongest f
0.0769	13.004	0.043	f_1
0.1535	6.514	0.040	$2f_1$
0.2284	4.378	0.042	$2f_2$
0.4491	2.226	0.011	

We denote the period of 13.004 and 4.385 h as $p_1(p = \frac{1}{f})$ and $\frac{1}{2}p_2$(the factor of 2 is due to the two maximum in one rotational period). The period of 6.514 h can regards as $\frac{1}{2}p_1$.

Three most prominent period values derived from the 2004s data with Fourier analysis method is listed in Table III. The period of 6.570 and 4.380 h are close to the values of $\frac{1}{2}p_1$ and $\frac{1}{2}p_2$. The slight difference may be due to the different geometric conditions when the data were obtained (As we have known, the synodic period changes slightly in different geometric conditions.) and the dispersion of observational data. Figure 7 shows the folder phase with period of 8.74 h.

We also do frequency analysis for Szekely's data. Three most prominent period values are 8.627, 4.370 and 12.837 h (see Table IV). It seems that the period of 8.627 h is close to p_2 which corresponds to the rotation frequency, and the period of 4.370 and 12.837 h are close to $\frac{1}{2}p_2$ and p_1. The large

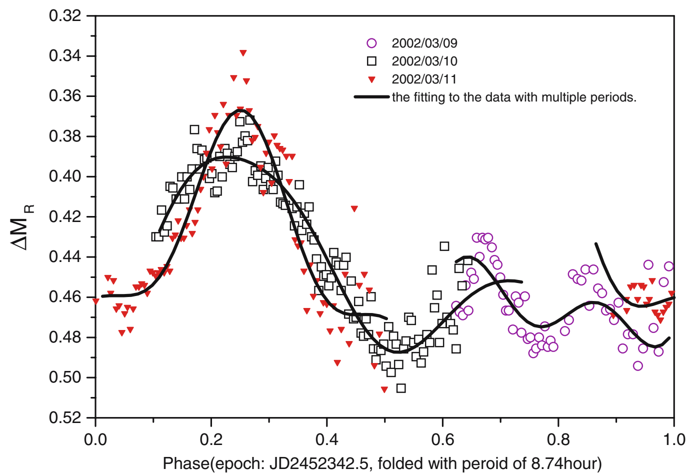

Figure 6. The phase light curves of (469) folded with period of 8.74 h.

TABLE III
The Fourier frequencies involved in 2004s data

Frequency (rev/h)	Peroid (h)	Amplitude (mag)	Strongest f
0.2281	4.380	0.062	$2f_2$
0.1530	6.570	0.051	$2f_1$
0.4538	2.203	0.018	$4f_2$

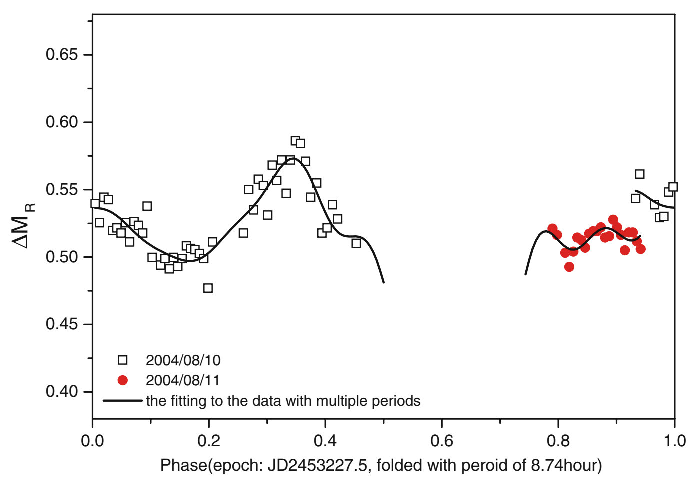

Figure 7. The phase light curves of (469) folded with period of 8.74 h.

TABLE IV
The Fourier frequencies involved in Szekely's data

Frequency (rev/h)	Peroid (h)	Amplitude (mag)	Strongest f
0.1159	8.627	0.063	f_2
0.0779	12.837	0.045	f_1
0.2288	4.370	0.039	$2f_2$

scatter in data will effect the analysis results. So, we attribute the slight difference of Szekely's period values from ours to the large scatter in Szekely's data. Figures 8 and 9 show the fitting lines with multiple periods and actual observed data.

From the analysis above, we can see, two basic period components from different apparition are around 13.00 and 8.627 h. Difference in two basic period values from different subset data can be explained with geometric change and the observational error in data. Hereby, we infer, the Argentina(469) probably is in non-principal axis rotational state (it also is called as tumbling motion). Two basic periods correspond to the precession period and the rotation period.

As we have known, the precession of the spin axis is due to the unalign of the spin axis and the angular momentum vector. A collision or external torque by satellites can rise such an unalign. In the following section, the preliminary analysis for this precession sample is made under some assumption.

4. The Precession of (469)

4.1. Free-force precession

If the (469) is in free-force precession, the damping time of (469)'s calculated with the equation providing by pravec (2005) and Harris (1994) is about 2.68×10^4 year. It is far short comparing with the life time of asteroids. so, if it is in free-force procession, the collision giving rise to the unalign should happen in recent.

Let $P_1 = 13.004$ and $P_2 = 8.627$ h are the period of precession and rotation, respectively, the ratio P_1/P_2 ($=1.507$) is less than 2, which implies that the rotation of the asteroid is in largest-axis mode (LAM) according to the definition given by Kaasalainen (2001). The LAM mode means that the (469) rotates around its the longest axis, meanwhile its spin axis precess around the angular momentum vector with a period of 13.00 h.

Let three principal momentum of inertial of a elongate triaxial ellipsoid be $I_1 \geq I_2 > I_3 = 1$(corresponding to semi-axis: $a \leq b \leq c = 1$). The

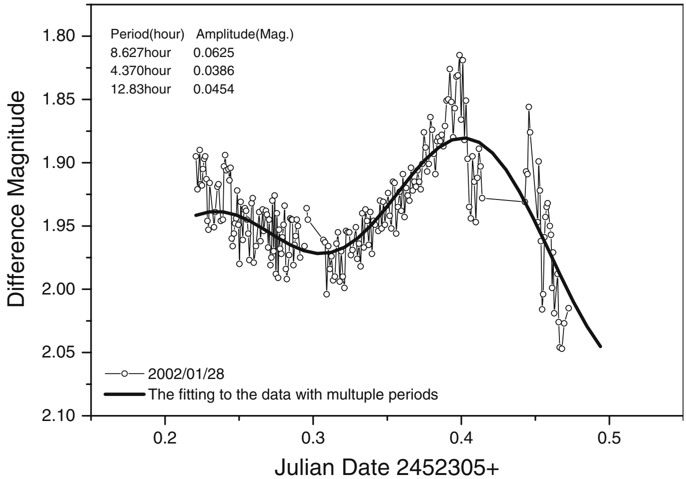

Figure 8. The light curve of (469) on January 28 2002.

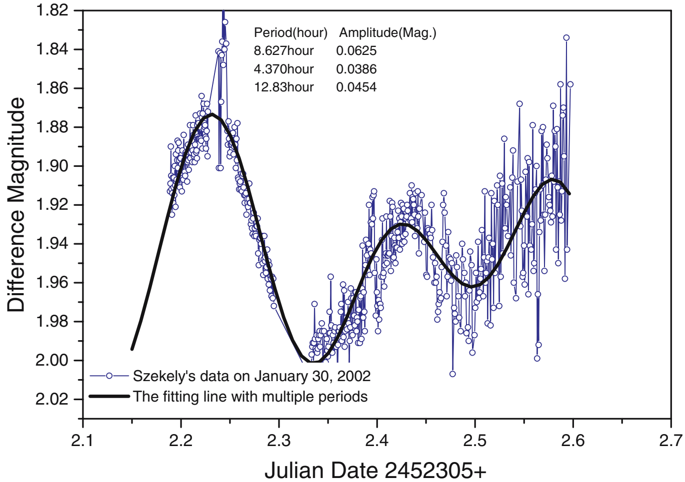

Figure 9. The light curve of (469) on January 30 2002.

elongate body rotating initially about C-axis, was disturbed slightly. Consequently, angular velocity of precession Ω can be determined with equation (1) (given by Efroimsky, 2000):

$$\Omega = \left(\frac{(I_2 - I_3)(I_1 - I_3)}{I_1 I_2}\right)^{1/2} \omega_r \tag{1}$$

Here, Ω and ω_r are the angular velocity of precession and rotation, respectively. With Eq. (1), we can compute the ratio between the largest and smallest principal moment of inertial as $\frac{I_1}{I_3} = 3.05$ on condition that $I_1 = I_2$;

$\frac{I_1}{I_3} = 3.22$, for $I_2 = 0.9I_1$; and $\frac{I_1}{I_3} = 4.69$, for $I_2 = 0.5I_1$. Although the explicit shape of (469) cannot be estimated, we can limit the minimum of $\frac{I_1}{I_3}$ is 3.05.

4.2. Force precession

Considering this precession sample is the force precession mode with a precession period of 13.004 h and a rotation period of 8.627 h, the mass ratio of two components can be estimated with the equation given by Harris and Binzel (1985).

$$\frac{m}{M} = \frac{\Omega \cdot \omega_r}{\omega_{orb}^2} \frac{1}{1 - \frac{1}{2}(I_1 + I_2)} \tag{2}$$

Here, Ω represents the precession angular velocity of primary's spin axis; ω_r, the rotation angular velocity of primary; ω_{orb}, the orbit angular velocity of secondary.

Due to the tide torque, the orbit motion of satellite will be synchronous with the rotation of the primary, or less than the rotation of primary. If the situation is former, the mass ratio will be:

$$\frac{m}{M} \simeq \frac{\Omega}{\omega_r} \frac{1}{1 - \frac{1}{2}(I_1 + I_2)} \tag{3}$$

The quantity of Ω and ω_r are the same order. The minimum value of $\frac{1}{1-\frac{1}{2}(I_1+I_2)}$ will be 2.0 if it is a very oblate shape. So, the mass ratio of two components will be same magnitude as the primary. If this is true, the characteristic of eclipse should occur in the light curves. The light curve on March 9 and the former part on March 11 seem show such characteristic, but it cannot be imagination for the flat part occur nearby the minimum. So, the assumption of a satellite may be impossible.

5. Conclusion

Those complex light curves of (469) suggest it is in NPA rotation state (tumbling motion).

From the analysis for our observation and Szekely's observational data, two basic periods of 13.004 and 8.627 h are found out.

Considering the free precession mode, the (469) is in LAM model with a precession of 13.004 h and a rotation period of 8.627 h. The ratio between the largest principal momentum and the smallest one $\frac{I_1}{I_3}$ will larger than 3.05.

If it is in force precession, the mass of secondary would be large, even the same order as the primary's mass when let the 13.004 h as the precession and 8.627 h as the rotation period. Is is true? the more evidence will be needed to prove it.

Up to now, it is difficult to draw an unambiguous result on (469)'s motion without further evidence, So the continuous observation are call for.

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