

## Variability Study of the SX Phoenicis Star BL Camelopardalis \*

Jian-Ning Fu<sup>1</sup>, Chao Zhang<sup>1</sup>, Kanokwan Marak<sup>2</sup>, Chayan Boonyarak<sup>2</sup>, Pongsak Khokhuntut<sup>2</sup> and Shi-Yang Jiang<sup>3</sup>

<sup>1</sup> Department of Astronomy, Beijing Normal University, Beijing 100875; [jnifu@bnu.edu.cn](mailto:jnifu@bnu.edu.cn)

<sup>2</sup> Faculty of Science, Naresuan University, Phitsanulok 65000, Thailand

<sup>3</sup> National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012

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**Abstract** New time-series photometric observations of BL Cam in the  $V$  band and white light were made during 2005 to 2007 at the Xinglong Station of China. The frequency analysis confirms two closely separated frequencies,  $25.181 \text{ d}^{-1}$  and  $25.571 \text{ d}^{-1}$ , but the frequency of  $31\text{--}32 \text{ d}^{-1}$  reported in the literature was not detected in the new data. New times of maximum light were determined from both our light curves and those available on Internet, allowing a more comprehensive study of the  $O - C$  diagram, together with the times of maximum light in the literature. A new interpretation, including the period increasing before 1988 and decreasing since 1992 of BL Cam and the light-time effect in a binary system, looks plausible.

**Key words:** techniques: photometric — stars: variables: delta Scuti — stars: individual: BL Cam

### 1 INTRODUCTION

SX Phe variables are  $\delta$  Scuti stars of Population II and old disk population, discovered both in the general field (Rodríguez & Breger 2001) and globular clusters (Rodríguez & López-González 2000). The field SX Phe variables show low metallicities and high spatial motions. The majority of these stars display very simple frequency spectra with short periods ( $\leq 0^{\text{d}}08$ ) and large visual peak-to-peak amplitudes ( $\geq 0^{\text{m}}1$ ). The origin of these stars is not yet known but two hypotheses have been put forward: Population II blue-stragglers and post-horizontal-branch evolution.

Since the times of maximum light of these stars can be determined with very good precision, their possible period changes, which should reflect the evolutionary changes in radius hence provide an observational handle on the stellar evolution theory, provide a good tool for deducing their evolutionary status and the evolutionary tracks across the  $H - R$  diagram. The period changes predicted by the evolution models within the boundaries of the  $\delta$  Scuti instability strip should always be in the positive sense, except in the zone of the overall contraction phase when the evolutionary periods decrease (Rodríguez 2004). However, these predictions are not always borne out by the observations (Breger & Pamyatnykh 1998). On the other hand, Khokhuntut et al. (2007) supported the predictions when they found the change in the period of AD CMi to be  $2.1 \times 10^{-8} \text{ yr}^{-1}$  after eliminating the light-travel time (LTT) effect in the binary system.

BL Cam is one of the 13 known field SX Phe stars (table 9 of Rodríguez & Breger 2001). It has been observed extensively since the discovery of its variability by Berg & Duthie (1977). McNamara & Feltz (1978) and Rodríguez et al. (1990) respectively reported 13 and 5 times of maximum light in the Strömgren  $y$  filter. The CCD photometry of Hintz et al. (1997) showed the multiperiodicity with two pulsation modes. Breger & Pamyatnykh (1998) found  $dP/Pdt = 2.9 \times 10^{-7} \text{ yr}^{-1}$ . Zhou et al. (1999) found six harmonics and combination frequencies, and reported  $dP/Pdt = 3.4 \times 10^{-7} \text{ yr}^{-1}$ . Kim et al. (2003) reported a primary

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**Table 1** Journal of observations. Filter symbols:  $V$  = Johnson  $V$ ,  $W$  = white light

Date	Observatory	Telescope	Filter	Nights	Hours
2005 Feb.	Naresuan	40 cm	$W$	1	2.0
2005 Oct.	Xinglong	80 cm	$V,W$	2	9.4
2005 Dec.	Xinglong	50 cm	$V$	3	15.8
2006 Sep.	Xinglong	85 cm	$V$	6	9.9
2007 Jan.	Xinglong	100 cm	$V,W$	4	14.5
2007 Jan.-Feb.	Xinglong	50 cm	$W$	5	21.6

frequency of  $25.5769 \text{ d}^{-1}$  and its harmonic and a secondary frequency of  $32.3182 \text{ d}^{-1}$ , and pointed out a reversed trend in the  $O - C$  diagram since 1999, suggesting that BL Cam might be a component of a binary system. Fauvaud et al. (2006) reported a number of secondary modes close to the main frequency and confirmed the existence of a secondary frequency at  $31.6$  or  $32.6 \text{ d}^{-1}$ . They determined more than 100 new times of maximum light and gave  $dP/Pdt = 1.17(\pm 0.03) \times 10^{-7} \text{ yr}^{-1}$ , showing that the star has a companion in a rather eccentric orbit ( $e = 0.7 \pm 0.2$ ) with a period of  $10.5(\pm 0.2) \text{ yr}$ .

We carried out time-series CCD photometry of BL Cam from 2005 to 2007. The present paper reports the observations of the new data and an analysis of its pulsation in Sections 2 and 3. The newly-determined times of maximum light are tabulated. Together with those listed in the literature and determined from the light curves available on the Internet, we constructed the  $O - C$  diagram given in Section 4, together with an analysis. Our conclusions are given in Section 5.

## 2 NEW OBSERVATIONS AND DATA REDUCTION

New CCD photometric observations of BL Cam were made at the Xinglong Station of National Astronomical Observatories, CAS, from 2005 October 1 to 2007 February 5 on four telescopes, and at the campus of Naresuan University, Thailand on 2005 February 7 with a 40 cm telescope. Table 1 lists the journal of observations. In total, over 73 hours of useful data were collected on 21 nights. Figure 1 shows an image of BL Cam taken with the 50 cm telescope at the Xinglong Station. The variable, the comparison and the check stars are marked on the image.

The frames were reduced with standard procedure, then the magnitude values of the variable, comparison, and check stars were extracted with either a fitted point-spread function plus the aperture photometry following the MOMF code (Kjeldson & Frandsen 1992) or the aperture photometry alone, using the Maxim DL software<sup>1</sup>, according as the star images show a point-spread-function profile or not. The light curves of BL Cam and the check star relative to the comparison star were obtained. Figure 2 shows the light curves of BL Cam (top part) and those of the check star (bottom part) observed with the 50 cm telescope on three nights in December, 2005.

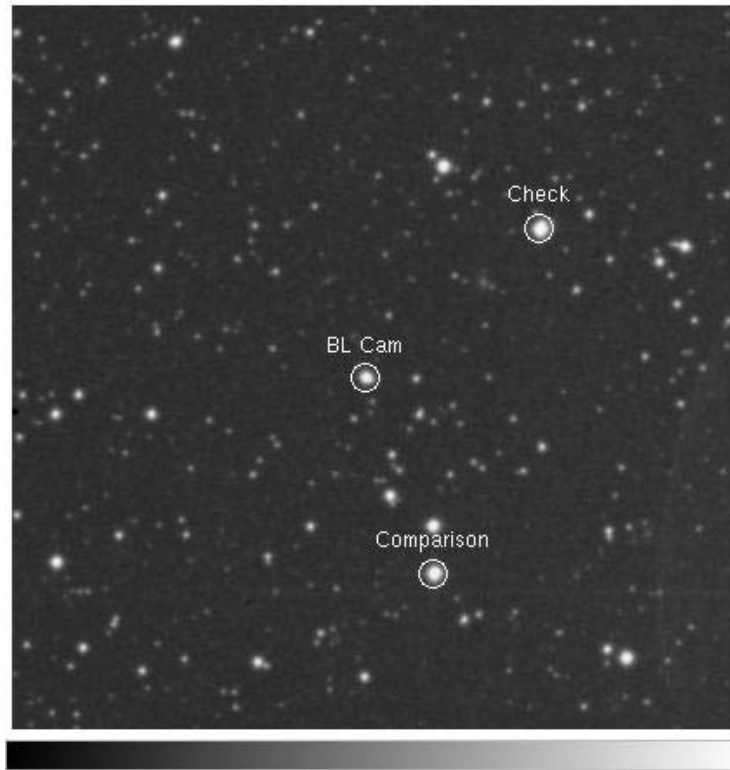
## 3 PULSATION ANALYSIS

Since the data were collected with different observation systems at different seasons, rather than using two sets of data which may have different zero-point shifts, we analyzed only the data observed in December of 2005 with the 50 cm telescope through the Johnson  $V$  filter. The software PERIOD04 (Lenz & Breger 2005) was applied to calculate the amplitude spectra to search for significant frequency peaks. Six peaks with signal-over-noise (S/N) ratios higher than 4.0 (following the criterion of Breger et al. 1993 and Kuschnig et al. 1997) were extracted and listed in Table 2. Figure 2 shows the fitting curves with the six-frequency solution (solid curves). Figure 3 shows the window function, the amplitude spectra of BL Cam, and the check star.

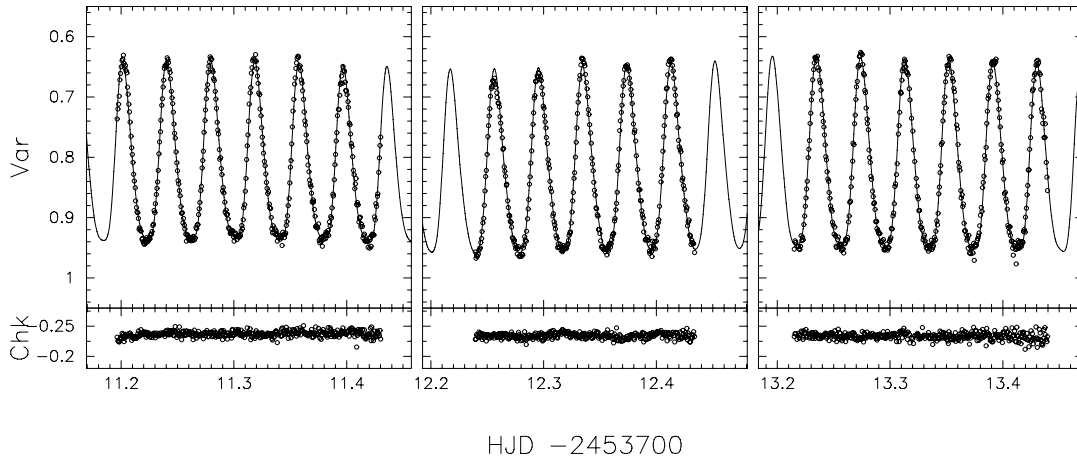
As seen from Figure 2, the multi-frequency solution listed in Table 2 fits the observed light curves very well for the data collected in December of 2005 (on the contrary, systematic deviations between the fitting and observed light curves are visible in figure 6 of Zhou et al. 1999).

Table 2 lists the frequencies  $f_0$  and  $f_1$  and their harmonics and a linear combination, and an unusual frequency of  $1.553 \text{ d}^{-1}$ , which is not linked in any way with  $f_0$  and  $f_1$  and whose value is out of the general frequency range for SX Phe stars. Note, in the FT of the check star (the bottom panel of Fig. 3), there is

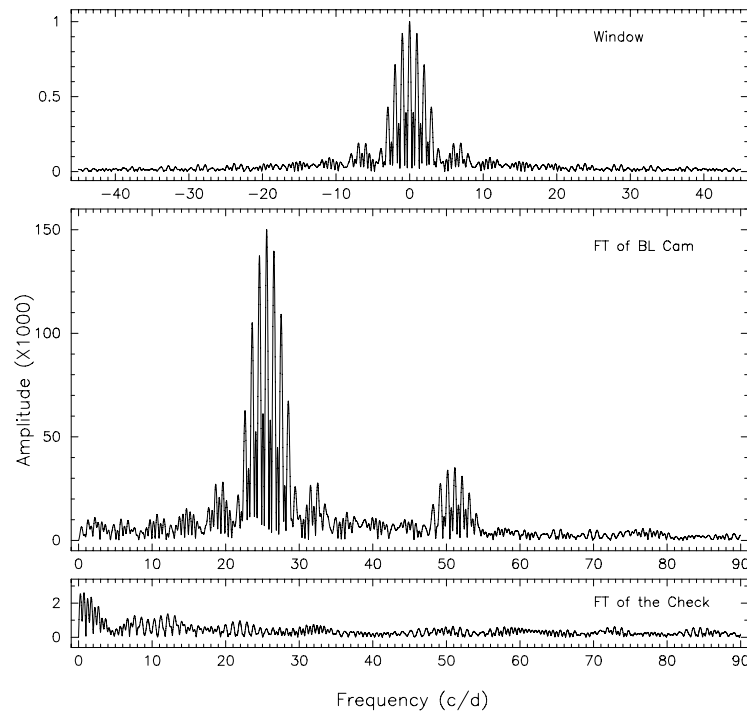
<sup>1</sup> [http://www.cyanogen.com/products/maxim\\_main.htm](http://www.cyanogen.com/products/maxim_main.htm)



**Fig. 1** A CCD image ( $7' \times 7'$ ) of BL Cam ( $\alpha = 03^{\text{h}}47^{\text{m}}19^{\text{s}}$ ,  $\delta = 63^{\circ}22'48''$ , 2000.0) taken with the 50 cm telescope of the Xinglong Station. North is up and East is to the left. BL Cam, the comparison and check stars are marked.



**Fig. 2** V-band Light curves of BL Cam and the check star relative to the comparison in mag in December 2005, plotted as open circles in the top and bottom panels, respectively. The solid curves are the fitting with the six frequencies listed in Table 2.



**Fig. 3** From top to bottom: the window function, the Fourier amplitude spectra of the light curves of BL Cam, and the check star. Note the different scales of ordinates in the middle and bottom panels.

**Table 2** Multi-frequency Solution of the Light Curves in *V* Band in December 2005 for BL Cam

	Frequency ( $d^{-1}$ )	Amplitude (mmag)	S/N
$f_0$	25.571	149.2	235.4
$2f_0$	51.143	31.8	41.8
$f_1$	25.181	8.5	14.3
?	1.553	7.6	6.7
$3f_0$	76.725	5.9	5.6
$3f_0 - f_1$	51.613	5.9	7.0

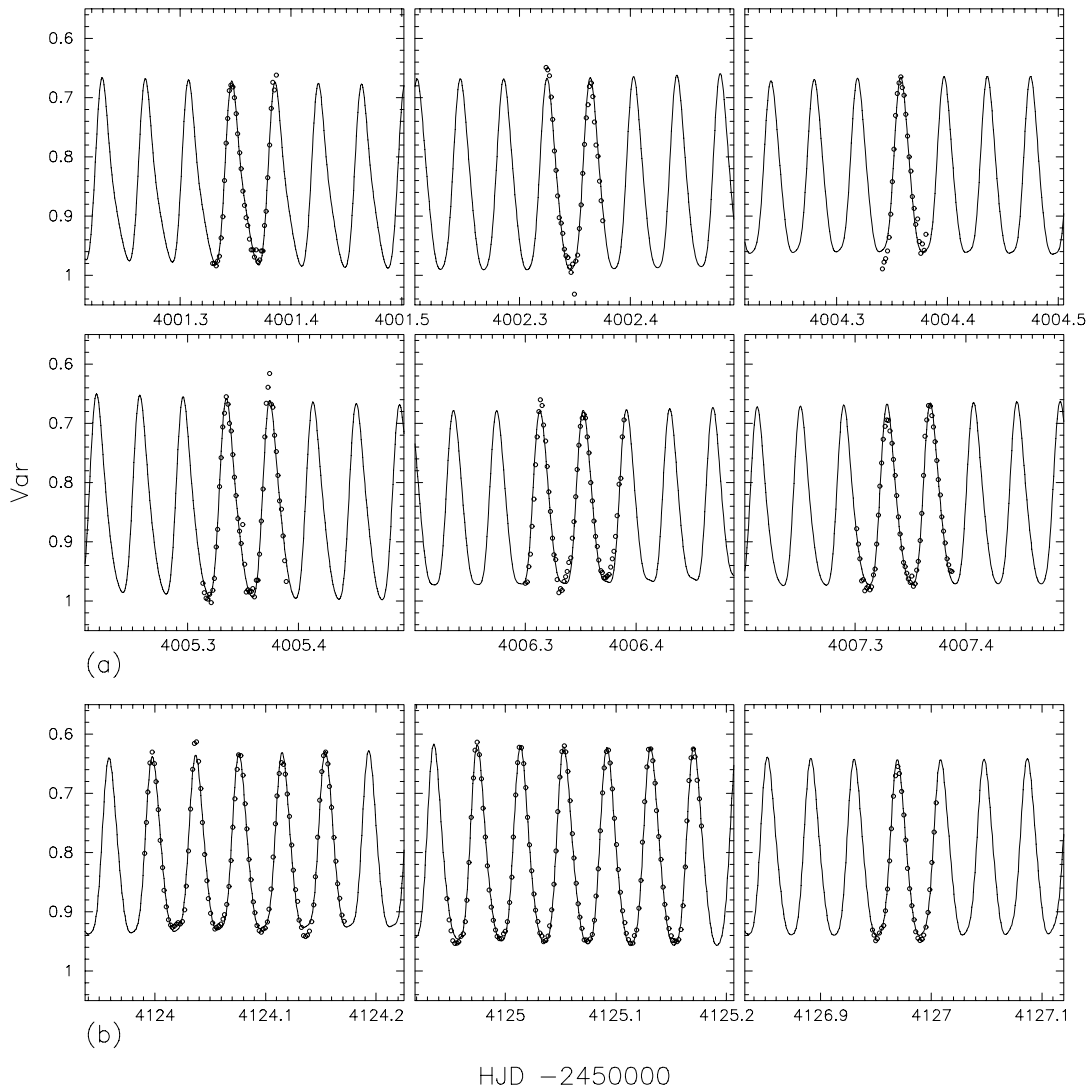
**Table 3** Parameters of the Fit to the Light Curves in *V* Band in Sept. of 2006 and Janu. of 2007 for BL Cam

	Frequency ( $d^{-1}$ )		Amplitude (mmag)	
	2006	2007	2006	2007
$f_0$	25.577	25.574	150.2	156.2
$2f_0$	51.146	51.136	33.5	35.9
$f_1$	25.226	25.239	9.4	10.5
?	1.255	1.620	6.1	3.7
$3f_0$	76.735	76.721	6.7	6.3
$3f_0 - f_1$	51.666	51.736	7.8	6.8

power excess in the range  $0 - 4 d^{-1}$ . Hence, the frequency of  $1.553 d^{-1}$  might not be an intrinsic mode of BL Cam, but rather, is caused by some observational factor.

It is surprising that, in the FT of the new data, no peaks of high enough amplitude (above 0.004) are detected within the frequency range  $31-32 d^{-1}$ , which were reported by Zhou et al. (1999), Kim et al. (2003) and Fauvaud et al. (2006). This might be due to variability in the amplitude of the mode, which made the present level to fall below the photometric limit.

The six frequencies resolved from the data of December 2005 (Table 2) were used to fit the data in *V* band collected in September, 2006, with a 85 cm telescope and in January, 2007 with a 100 cm telescope, both in the Xinglong Station. Table 3 lists the fitting parameters. Figure 4 shows the light curves with open circles and the fitting with the solid curves, respectively. It can be seen from Figure 4 that the six frequencies resolved from the data of December 2005 can fit the data collected both in 2006 and 2007.



**Fig. 4** Light curves of BL Cam in  $V$  in mag (a) in September, 2006 and (b) in January, 2007. The solid curves show the fitting with the six frequencies listed in Table 3.

## 4 THE $O - C$ DIAGRAM

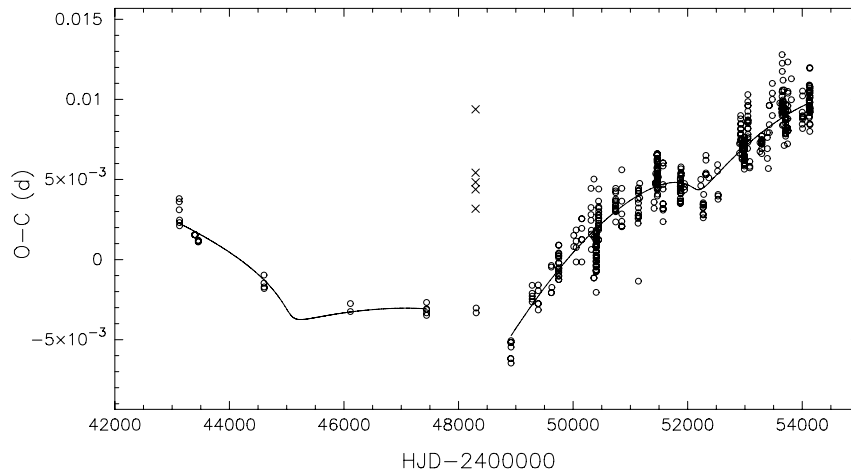
### 4.1 New Times of Maximum Light

With the new observations from 2005 to 2007, 43 times of maximum light in the  $V$  band and 30 times in white light were determined by fitting a third or fourth degree polynomial on each peak of the observed light curves. Typical uncertainties were estimated to be  $0^d.0003$ . Table 4 lists the 73 new times of light maxima. In addition, a series of light curves were downloaded from three Internet websites <sup>2</sup>. We made the heliocentric corrections to the Julian dates of these light curves and then a third or fourth degree polynomial fitting to the peaks. Thus, 49 times of light maxima were determined. Combining with the 398 times of

<sup>2</sup> [http://chris.kingsu.ab.ca/~brian/astro/cba\\_alta/data\\_archive/blcam.html](http://chris.kingsu.ab.ca/~brian/astro/cba_alta/data_archive/blcam.html)  
<http://ostrava.astronomy.cz/onl.php>  
<http://asp.jm-data.no/geke.150obs>

**Table 4** Newly-determined times of maximum light of BL Cam.  $T_{\max}$  is in HJD-2450000. Filter symbols are the same as in Table 1.

$T_{\max}$	Filter	$T_{\max}$	Filter	$T_{\max}$	Filter	$T_{\max}$	Filter	$T_{\max}$	Filter	$T_{\max}$	Filter
3409.1282	W	3711.2792	V	3713.3912	V	4124.0767	V	4131.0337	W	4135.1006	W
3645.2436	W	3711.3179	V	3713.4299	V	4124.1148	V	4131.9741	W	4135.1406	W
3645.2830	W	3711.3566	V	4001.3461	V	4124.1538	V	4132.0122	W	4136.9785	W
3647.0813	W	3711.3967	V	4002.3634	V	4124.9746	V	4132.0513	W	4137.0166	W
3647.1209	W	3712.2560	V	4004.3571	V	4125.0137	V	4132.0928	W	4137.0547	W
3647.1600	W	3712.2952	V	4005.3344	V	4125.0532	V	4132.1294	W	4137.0947	W
3647.1995	V	3712.3346	V	4005.3736	V	4125.0923	V	4133.0298	W	4137.1343	W
3647.2381	V	3712.3733	V	4006.3136	V	4125.1304	V	4133.0703	W	4137.1738	W
3647.2780	V	3712.4124	V	4006.3524	V	4125.1694	V	4133.1079	W		
3647.3160	V	3713.2344	V	4007.3286	V	4126.9699	V	4133.1445	W		
3647.3547	V	3713.2734	V	4007.3669	V	4129.0015	W	4134.9849	W		
3711.2018	V	3713.3132	V	4123.9980	V	4129.0405	W	4135.0239	W		
3711.2405	V	3713.3526	V	4124.0371	V	4130.9956	W	4135.0615	W		



**Fig. 5**  $O - C$  diagram of BL Cam using the ephemeris of Zhou et al. (1999, eq. (2)). The crosses show the five “unusual” points which were not taken into account in the  $O - C$  diagram analysis of Fauvaud et al. (2006). The two solid curves show the fit of combining a positive and a negative period change rate with a binary solution, respectively.

light maxima available in the literature (see Berg & Duthie 1977; McNamara & Feltz 1978; Rodríguez et al. 1990; Hintz et al. 1997; Zhou et al. 1999, 2001; Blake et al. 2000; Van Cauteren & Wils 2000; Wolf et al. 2002; Kim et al. 2003; Fauvaud et al. 2006; Klingenberg et al. 2006), a total of 520 times of maximum light were used to calculate the  $O - C$  values using the linear ephemeris given by Zhou et al. (1999, eq. (2)):  $\text{HJD}_{\max} = 2443125.8015 + 0.03909785 \times E$ , ( $E$  the cycle number). The resulting  $O - C$  diagram is shown in Figure 5 with open circles and crosses.

#### 4.2 $O - C$ Analysis

The straight-line fit to the 520 times of light maxima yields the ephemeris formula,

$$C = \text{HJD } 2443125.7961(\pm 4) + 0.039097898(\pm 2) \times E. \quad (1)$$

There are five points between HJD 2448297 and 2448299 which show very large discrepancies with the rest of the data. They are marked with crosses in Figure 5. Fauvaud et al. (2006) did not take these

**Table 5** Orbital Elements of the Possible BL Cam Binary System

LTT semi-amplitude (s)	106 ( $\pm 10$ )
Eccentricity	0.7 ( $\pm 0.2$ )
Argument of periastron (deg)	234 ( $\pm 7$ )
Orbital period (yr)	9.7 ( $\pm 1.6$ )
Periastron passage	HJD 2448617 ( $\pm 596$ )

into account in their analysis of the  $O - C$  diagram, and made a fit with a parabolic curve combined with the light-time effect in a binary system. However, they found that the solutions with free eccentricity were unstable. From figure 4 of Fauvaud et al. (2006), one finds that the fit is inconclusive.

In order to interpret the new  $O - C$  diagram, we first carried out a binary analysis to all available  $O - C$  data points except the five “unusual” points, as Fauvaud et al. (2006) did. We found that solutions with free eccentricity were unstable. Then, fits were run by fixing the eccentricity to values between 0.5 and 0.9 at regular steps. The parameters provided in table 9 of Fauvaud et al. (2006) were used as initial values to carry out the fit. However, no converged fit can lead to an acceptable result: there were always systematic trends in the residuals.

In fact, this is not surprising. By comparing Figure 5 of the present paper with figure 4 of Fauvaud et al. (2006), one finds that trend of the predicted fitting curve since HJD 2453500 in figure 4 of Fauvaud et al. (2006) is not supported by the newly-determined points based on new observational data.

In the meantime, we note that the points before HJD 2448297.3617 ( $E = 132272$ ) and after HJD 2448308.1403 ( $E = 132548$ ) show two reversed trends. Combining with the existence of the five “unusual” points between the two trends, we made fitting of the first 30 points (the first group) and the last 483 points (the second group) separately.

Since the second group of points is large and show clear cyclic variations, we fit these points with a quadratic plus a sinusoid of the form,

$$C = \text{HJD}_0 + P \times E + \frac{1}{2}\beta E^2 + A \sin \phi + B \cos \phi, \quad (2)$$

where  $\phi$  is the solution of Kepler’s equation,

$$\phi - e \sin \phi = \frac{2\pi}{P_{\text{orb}}}(P \times E - t_0). \quad (3)$$

Equation (2) is equivalent to equation (2) of Irwin (1952) and equation (1) of Ribas et al. (2002), and describes the light time effect (where  $P_{\text{orb}}$  is the orbital period,  $P$  the pulsation period of the variable star,  $t_0$  the time of periastron passage). The solid curve after HJD 2448912 in Figure 5 shows the fitting. The period variation rate is obtained as  $dP/Pdt = -0.81(\pm 0.31) \times 10^{-7} \text{ yr}^{-1}$ . Table 5 lists the orbital elements of the possible binary system resolved from the second group of  $O - C$  points. Since the fit is very reasonable and the residuals do not show any systematic trends, we like to believe that BL Cam is a binary system. From the LTT semi-amplitude value, the projection of the orbit radius is estimated as:  $a_1 \sin i = 0.21(\pm 0.02) \text{ AU}$ . The mass function is:  $f(m) = (a_1 \sin i)^3 / P_{\text{orb}}^2 = 0.98(\pm 0.04) \times 10^{-4}$ .

Since there are too few data points in the first group of points to make an independent fit, we simply imposed on it the binary solution obtained from the fit of the second group, leading to a period variation rate of  $1.04(\pm 0.30) \times 10^{-7} \text{ yr}^{-1}$ . The solid curve before HJD 2447443 in Figure 5 shows the fit by combining a positive period change rate and the binarity solution.

### 4.3 Discussion

Equation (1) gives the up-to-date value of the pulsation period of BL Cam. The second group of points in the  $O - C$  diagram (Fig. 5) shows cyclic variation, leading to a solution comprising a quadratic function plus the light-time effect. Interestingly, according to the result shown in Figure 5, the primary period should be increasing and then decreasing while the “unusual”  $O - C$  points correspond to the time when the star was switching from a phase of overall expansion to one of contraction.

Since the second group of data span approximately one and a half the orbital period, its solution should not be considered as providing accurate orbital parameters, even though the light-time effect is shown

clearly in the  $O - C$  diagram. The newly-determined orbital parameters of BL Cam binary system agree with those given by Fauvaud et al. (2006) within the uncertainties, except the LTT semi-amplitude values. The absolute values of period change rates for the two groups of points are consistent with what Fauvaud et al. (2006) derived in concerning the binarity model within the uncertainties, although a reversed direction is present in our interpretation of the points before 1988.

As the two groups of points in Figure 5 show opposite directions of variation, another possible reason of period change is LTT effect of a third body. However, since the span of the  $O - C$  points (Fig. 5) is limited, we did not make any further investigation about this possibility.

## 5 CONCLUSIONS

The analysis of the pulsation of BL Cam resolved six frequencies, including two known frequencies,  $25.571 \text{ d}^{-1}$  and  $25.181 \text{ d}^{-1}$ , with their harmonics and a linear combination, and a low-value one of  $1.553 \text{ d}^{-1}$ , which might not be an intrinsic mode of BL Cam. However, the frequency of  $31\text{--}32 \text{ d}^{-1}$  reported in the literature is not detected in the new data set.

The newly-observed data, combining with the data collected from the literature, gave an updated value of pulsation period of  $0.039097898(\pm 2) \text{ d}$ . The representation of the  $O - C$  diagram by a combination of a continuously increasing and then decreasing period change and the light time effect in a binary configuration, looks acceptable. Then, BL Cam might be the first SX Phe star caught with a reversal in the period change. However, the binary model presented in this paper should not be considered as an accurate and unique solution of the  $O - C$  diagram of BL Cam. Future observations are needed to study the mode of frequency  $31\text{--}32 \text{ d}^{-1}$ , to verify the binary model and provide more accurate solution for the binary system, and to reveal the real interpretation of the long-timescale period changes in BL Cam.

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