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Differential Time-Series CCD Photometry of BL Camelopardalis Revisited

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ABSTRACT. New differential time-series observations of BL Camelopardalis were secured using *B* and *V* filters. It was confirmed that BL Cam is an optical double star. Differential magnitudes were obtained through a photometric profile reduction procedure to eliminate the influence of a faint adjacent star. Variations in $O - C$ values for light maxima were investigated. We found that the parabolic period variation was recently reversed. The periods of BL Cam were investigated, and five frequencies were determined using Fourier analysis. We also investigated the relationship between metallicities and period ratios, and we compared the theoretical and observational relationships. It was found that the theoretical relationship is better than the observational one for BL Cam.

1. INTRODUCTION

BL Camelopardalis ($\alpha = 03^h47^m19^s$, $\delta = +63°22'7''$ [J2000.0], $V = 13.10$, $\Delta V = 0.33$ mag) was classified as an SX Phoenicis variable in the General Catalogue of Variable Stars. The characteristics of SX Phe variables are that they have short periods (0.03–0.08 days), are metal poor, and have typical amplitudes of 0.3–0.7 mag. They are found in the field as well as in globular clusters and nearby dwarf galaxies (Rodríguez & López-González 2000). Large-amplitude δ Scuti variables exhibiting similar light variations are metal rich. The term "dwarf Cepheid" has also been used to describe both SX Phe variables and large-amplitude δ Scuti variables.

Nemec & Mateo (1990) reported that the characteristics of SX Phe variables are not entirely different from those of the so-called pulsating blue stragglers (PBSs), which are found in a few globular clusters (Nemec & Mateo 1990; Mateo 1993). Therefore, the investigation of SX Phe variables may provide valuable information on the origin and evolution of blue stragglers (BSs). BSs have been found in both open clusters and globular clusters, and they are located above the turnoff point along the main sequence in the H-R diagram. However, their origin has been controversial because the standard evolution theory cannot explain their characteristics. Hence, a few different scenarios such as mass exchange in a binary system or the merging of two stars have been proposed to explain their origin (see Mateo 1993; A. Sills et al. 1995, unpublished).

The number of known SX Phe variables in globular clusters and nearby dwarf galaxies has been increasing (see Jiang, Hyung, & Kim 2000; Rodríguez & López-González 2000, and references therein); however, only 12 SX Phe field stars have been discovered. Interestingly, three of the 12 are double-mode pulsators (McNamara 1997; Martin & Rodríguez 1995).

BL Cam was first discovered by Giclas, Burnham, & Thomas (1970) as a possible white dwarf candidate. Since then, BL Cam has been frequently observed by other investigators. Berg & Duthie (1977) discovered that BL Cam is a variable star, and McNamara & Feltz (1978) observed it with a *uvbyβ* color system and estimated its physical and atmospheric parameters. Hintz et al. (1997, hereafter H97) discovered that BL Cam is a double-mode pulsating star with a primary period of 0.0391 days, a secondary period of 0.0306 days, and a period ratio (π_1/π_0) of 0.783. They also found that the fundamental period has increased by 0.009 s over the past 20 years. They derived a linear relationship between the period ratios and the metallicities of these stars.

Kim & Sim (1999, hereafter KS99) determined π_1/π_0 of 0.81, which is the highest value among all double-mode stars, and argued that BL Cam does not follow the relationship between π_1/π_0 and [Fe/H]. They suggested the possibility that BL Cam could be an optical double star on the basis of CCD images taken in good seeing. Zhou et al. (1999, hereafter Z99) analyzed their new high-speed photometric data and found six frequencies together with two harmonics and three combination frequencies. They also argued that five frequencies among these correspond to nonradial modes and reported that the fundamental frequencies are increasing at a rate of 7.1457×10^{-13} days cycle^{-1}.

We have undertaken differential CCD photometric observations of BL Cam to investigate its multiperiodicity and pulsational characteristics. In order to confirm that it is an optical double star, we observed BL Cam with a 1.8 m class telescope to obtain higher resolution. The potential importance of BL Cam, aside from being a double-mode variable, is that it is an extreme case among all double-mode variables; i.e., it has the shortest period, largest period ratio (π_1/π_0), highest space motion, and lowest metallicity. Hence, in many respects, BL Cam is a very interesting object to study.

2. OBSERVATIONS

Photometric time-series observations of BL Cam were secured on nine nights between 2000 November 22 and December 6 and on 2001 December 29 with the 1.8 m reflector at the Bohyun Astronomy Observatory using *V* filters. On both 2001 December 5 and 6, BL Cam was observed using both *B* and *V* filters. The telescope was equipped with the back-illuminated thinned SITe chip. The field of view for a CCD image is 11′.6 × 11′.6 at the f/8 Cassegrain focus of the telescope. The readout noise and gain of the CCD are 7.0 e^- and 1.8 e^- ADU^{-1}, respectively. We used a 2 × 2 binning mode, resulting in a pixel scale of 0″.6876 pixel^{-1}. The CCD chip has an area of 2048 × 2048 pixels with a scale factor of 0″.34 pixel^{-1}. The exposure times were 20–30 and 70 s for the *V* and *B* filters, respectively.

3. DATA REDUCTION

A total of 712 *V* and 70 *B* frames were reduced by preprocessing, which includes biasing, flat fielding, and cosmic-ray elimination. Then we used the IRAF/DAOPHOT[1] package to determine the instrumental magnitude of each star. Figure 1 shows a CCD image of BL Cam. We can see that BL Cam is not a single star but rather an optical double star. A faint adjacent star ($V = 17.2$, $B-V = +1.1$, separation = 3″.3, and position angle = 107°) is evident. We applied the point-spread function (PSF) photometric reduction procedure instead of aperture photometry in order to eliminate the effect of the faint adjacent star. As far as we know, this is the first observation of BL Cam with a 1.8 m telescope and is also the first application of the profile reduction technique to it. The duplicity of BL Cam was not known previously because the small separation of 3″.3 would be difficult to resolve under poor seeing conditions with a 24 inch telescope.

The instrumental magnitudes of BL Cam were transformed to the standard system using photometry of Landolt (1992) standard stars in the fields Ru 149, Ru 152, SA 94, SA 95, SA 97, and SA 98, all obtained on the same nights as BL Cam. The time-series *BV* data were then calibrated using these standards.

We applied the ensemble normalization technique (Gilliland & Brown 1988; KS99) to the instrumental magnitudes between the time-series CCD frames. We used about a hundred normalizing stars ranging from $V = 13.2$ to 20.0 and $B = 14.0$ to 19.0. The normalization equation is

$$B \text{ or } V = m + c_1 + c_2(B-V) + c_3P_x + c_4P_y, \qquad (1)$$

where *B*, *V*, and *m* are the standard and instrumental magnitudes of the normalizing stars. The zero point is c_1 and the color coefficient is c_2. Position-dependent terms c_3 and c_4 correct for atmospheric differential extinction and variable PSF. The typical error of the *V* magnitudes is 0.002 mag. Figure 2 shows the light curves for both *B* and *V* observations.

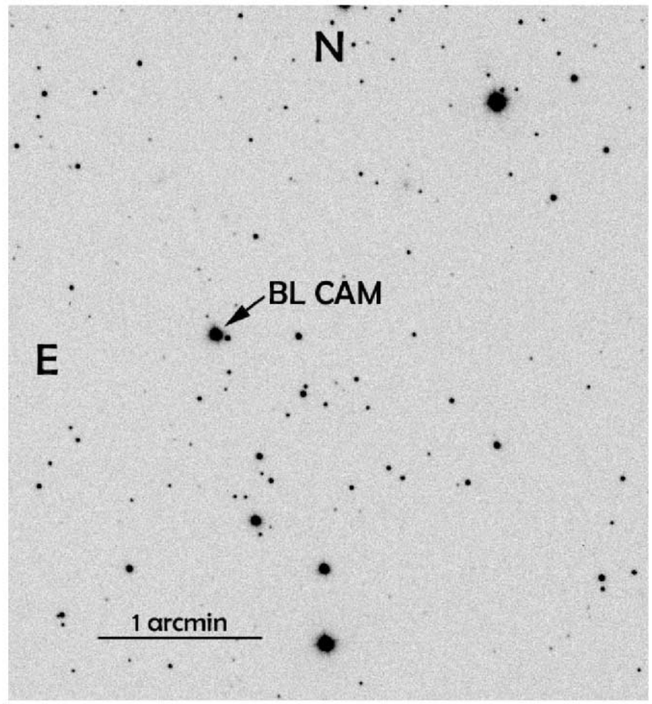

FIG. 1.—Enlarged CCD image of BL Cam. An adjacent faint star is evident.

4. DISCUSSION

We obtained 104 new times of maximum light, which are presented in Table 1. Some of them are from data by Zhou (2001) and KS99. We began our analysis by plotting the $O - C$ diagram with the times of light maxima in Table 1. We calculated the expected times of maximum light by applying the following equation from Z99:

$$\mathrm{HJD}_{\max} = 2{,}443{,}125.8015(\pm 0.0628) + 0.03909785(\pm 0.000000345)E, \qquad (2)$$

where uncertainties are in parentheses.

Figure 3 shows a plot of the differences between the ob-

[1] IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

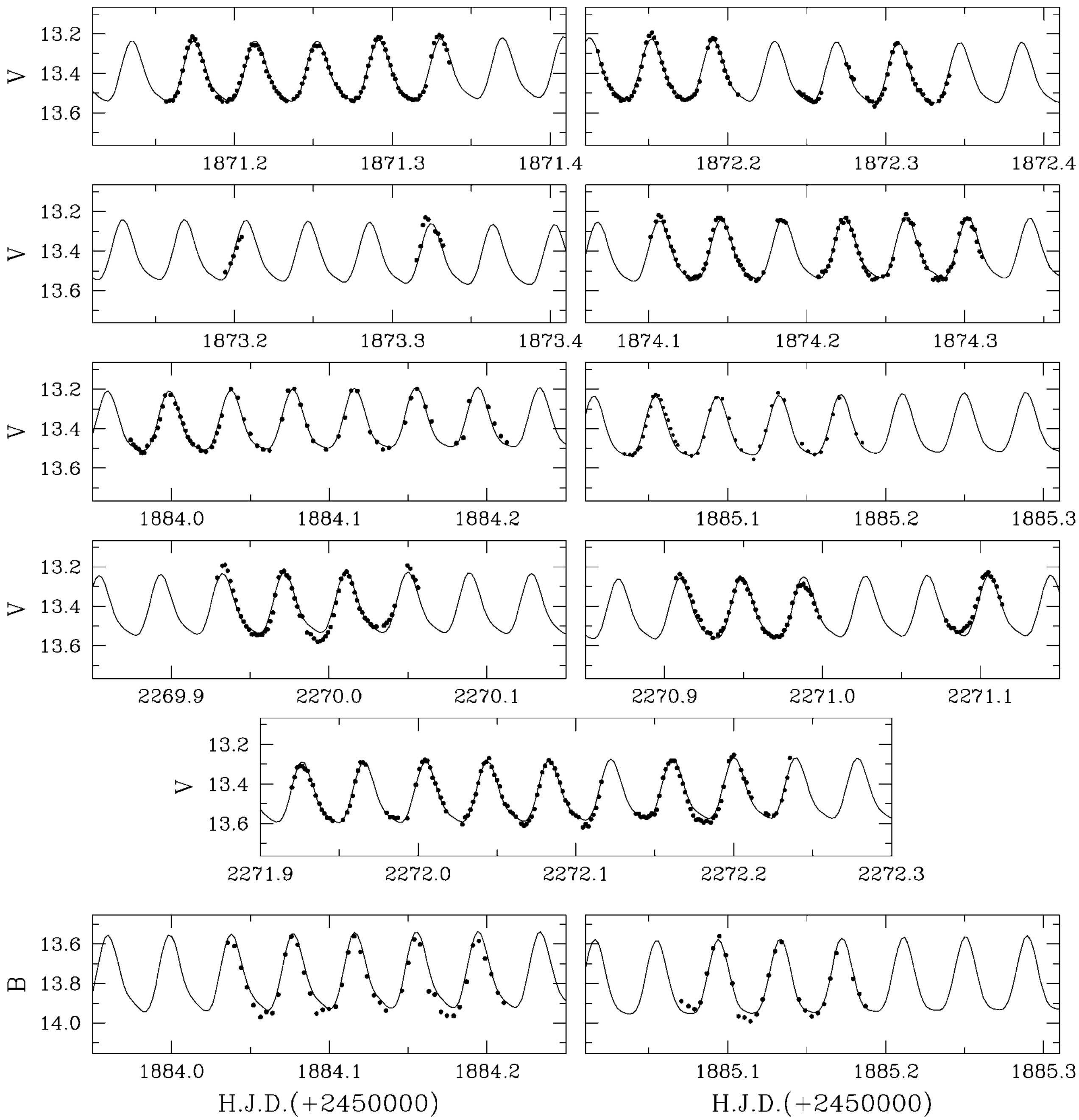

FIG. 2.—Light curves of BL Cam. Dots and solid lines correspond to the observed and synthetic light curves fitted with the coefficients in Table 2.

served and calculated times of maximum light ($O - C$) versus the calculated cycle for the total number of 249 maxima. This figure shows that a parabolic shape, as noted by Z99, appears to match all data points better than a linear fit, except for five bad data points around HJD 2,450,151 and our data points since HJD 2,451,871. This means that the period of BL Cam has been slowly increasing over time, as reported by both Z99 and H97.

However, we can see that the parabolic period variation reversed after 2001 November. Following the maximum increase in 1999, the $O - C$ values started to decrease. This reminds us of a similar pattern found in KZ Hya, another SX Phe variable. Jiang (1986) suggested that KZ Hya is a binary system, and Liu, Jiang, & Cao (1991) supported a binary hypothesis by investigating the $O - C$ diagram for a total of 113 light maxima. They found that the $O - C$ values exhibit regular variations with

TABLE 1
Times of Maximum Light of BL Cam Observed in 1999 and 2000

HJD	*E*	HJD	*E*	HJD	*E*	HJD	*E*	HJD	*E*	HJD	*E*
50,743.0044	194,824	51,441.2549	212,683	51,469.2880	213,400	51,473.3148	213,503	51,871.2122	223,680	51,884.1934	224,012
50,743.0443	194,825	51,441.2934	212,684	51,469.3272	213,401	51,473.3537	213,504	51,871.2525	223,681	51,885.0549	224,034
50,743.0823	194,825	51,441.3324	212,685	51,469.3675	213,402	51,473.3926	213,505	51,871.2912	223,682	51,885.0937	224,035
50,743.1220	194,827	51,466.2388	213,322	51,470.2262	213,424	51,474.2131	213,526	51,871.3294	223,683	51,885.1327	224,036
50,743.1612	194,828	51,466.2784	213,323	51,470.2645	213,425	51,474.2538	213,527	51,872.1515	223,704	51,885.1723	224,037
50,743.2008	194,829	51,466.3178	213,324	51,470.3032	213,426	51,474.3319	213,529	51,872.1902	223,705	52,269.9704	233,878
50,743.2386	194,829	51,466.3569	213,325	51,470.3439	213,427	51,479.1405	213,652	51,872.3079	223,708	52,270.0099	233,879
50,743.2779	194,830	51,467.2170	213,347	51,470.3830	213,428	51,479.1803	213,653	51,873.3234	223,734	52,270.9484	233,904
50,746.0147	194,900	51,467.2557	213,348	51,471.2035	213,449	51,479.2197	213,654	51,874.1069	223,754	52,270.9869	233,904
50,746.0542	194,902	51,467.2936	213,349	51,471.2421	213,450	51,479.2573	213,655	51,874.1446	223,755	52,271.1040	233,907
50,746.0942	194,903	51,467.3331	213,350	51,472.1820	213,474	51,479.2973	213,656	51,874.2234	223,757	52,272.0433	233,932
50,746.1322	194,904	51,467.3726	213,351	51,472.2212	213,475	51,479.3365	213,657	51,874.2632	223,758	52,272.0823	233,933
50,746.1716	194,905	51,468.2324	213,373	51,472.2593	213,476	51,479.3756	213,658	51,874.3021	223,759	52,272.1605	233,935
50,746.2094	194,905	51,468.2706	213,374	51,472.2985	213,477	51,480.1571	213,678	51,883.9988	224,007	52,272.1994	233,935
50,746.2492	194,906	51,468.3100	213,375	51,472.3389	213,478	51,480.1961	213,679	51,884.0374	224,008		
51,416.3083	212,044	51,468.3497	213,376	51,473.1975	213,500	51,480.2346	213,680	51,884.0759	224,009		
51,416.3478	212,046	51,469.2111	213,398	51,473.2379	213,501	51,483.1669	213,755	51,884.1155	224,010		
51,436.3280	212,557	51,469.2499	213,399	51,473.2760	213,502	51,871.1733	223,679	51,884.1554	224,011		

a long period of approximately 9 yr. In Figure 3, if the $O - C$ values on the far left side closely correspond to the maximum, then the variation shows a pattern similar to that in KZ Hya. The $O - C$ results for BL Cam suggest that it might be another binary system, although interpretation of a periodic variation is premature. To discover more binary SX Phe variables, long-term observations are required.

In order to investigate the pulsating properties of BL Cam, we determined five frequencies by applying the traditional Fourier transformation method and the generalized least-squares method developed by Vanicek (1971; see also Antonello et al. 1986 and Andreasen 1987). Table 2 presents the synthetic light curve coefficients for all BL Cam data points except those around HJD 2,452,270 with poor seeing. The solid line in Figure 2 shows the curves produced using these coefficients.

We see that the frequencies in Table 2 are different from the

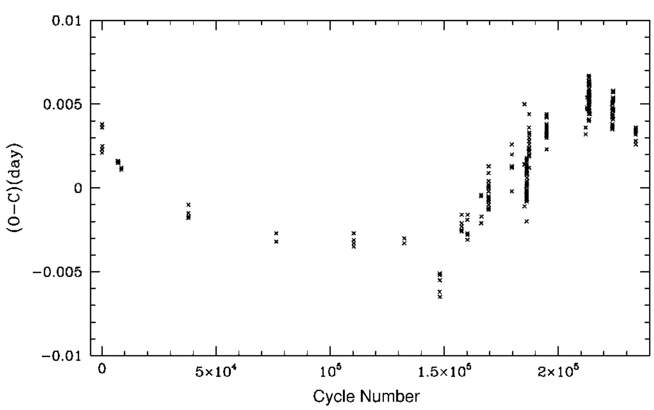

Fig. 3.—Difference between observed times of maximum light and times of maximum light calculated from eq. (1).

results obtained by Z99. We found a fundamental frequency of 25.5769 cycles day^{-1}, which is the well-known fundamental frequency (f_0) of BL Cam, identified in previous investigations. Harmonic terms of $2f_0$ can be easily identified. However, identification of the frequency features for 0.2508 and 1.8066 cycles day^{-1} is not so easy; 32.3182 cycles day^{-1} should correspond to a second frequency (f_1). In order to identify the frequency features, we calculated the pulsational constants (Q) using the formula derived by Breger & Bregman (1975):

$$\log Q = -6.454 + \log P + 0.5 \log g + 0.1 M_{\rm bol} + \log T_{\rm eff}, \quad (3)$$

where P is the period, $\log g$ is the surface gravity, $M_{\rm bol}$ is the bolometric magnitude, and $T_{\rm eff}$ is the effective temperature. We use the atmospheric and physical parameters of BL Cam determined by McNamara (1997): $\log g = 4.26$, $M_{\rm bol} = 3.02$, $T_{\rm eff} = 7970$ K, and $Q = 0.0244$.

Fitch (1981) developed a pulsational model at the instability strip for δ Scuti stars and determined the pulsation constants that depend on mass and the degree of evolution for $l = 1, 2, 3$.

TABLE 2
Coefficients of the Synthetic Light Curves of BL Cam

Frequency	Frequency (cycles day^{-1})	Amplitude (mag)	Phase (rad)
f_0	25.5769	0.1487 ± 0.0009	4.0579 ± 0.0061
$2f_0$	51.1513	0.0347 ± 0.0009	3.4389 ± 0.0262
?	0.2508	0.0185 ± 0.0011	0.7076 ± 0.0638
?	1.8066	0.0121 ± 0.0010	2.9766 ± 0.1009
f_1	32.3182	0.0076 ± 0.0009	4.0278 ± 0.1196
	Standard deviation:	0.0132	

He argued that the pulsation constant is not sensitive to a change of mass or the degree of evolution, but rather to the pulsation mode (n, l) (i.e., $Q_0 = 0.032$–0.036, $Q_1 = 0.024$–0.028, $Q_2 = 0.0195$–0.0225, and $Q_3 = 0.016$–0.0185 for $n = 0, 1, 2$, and 3, respectively).

A value of $Q = 0.031$ for 25.5769 cycles day^{-1} is less than 0.032, but this fits Q_0 if we take into account the error; $Q = 0.0244$ for 32.3182 cycles day^{-1} fits Q_1. Two suspicious frequencies do not fit any of the pulsation constants given by Fitch (1981), and therefore these may be nonradial frequencies or possibly a combination of terms with an unknown alias. However, there is a strong possibility that these might be artifacts of the reduction technique. For accurate identification, further consecutive night observations are required.

H97 derived a relation between [Fe/H] and period ratio (π_1/π_0) for seven double-mode variables:

$$\pi_1/\pi_0 = -0.0044[\mathrm{Fe/H}] + 0.7726. \quad (4)$$

They argued that the theoretical models (Andreasen 1983) give a steeper dependence of π_1/π_0 on [Fe/H] than the observed dependence. Figure 6 of H97 has been modified in Figure 4. The disagreement of the observational and theoretical relation is evident.

To produce better agreement, helium depletion in the surface layers and the use of the new OPAL opacities in the stellar models were suggested. However, we propose another possibility to explain the uncertain second period. H97, Z99, and KS99 give $f_1 = 32.6443$, 31.5912, and 31.0813 cycles day^{-1}, respectively, implying that π_1/π_0 is 0.783, 0.810, and 0.823. Different values of f_1 cause different π_1/π_0. In our case, $\pi_1/\pi_0 = 0.791$ gives $f_1 = 32.3182$ cycles day^{-1}. If we take $[\mathrm{Fe/H}] = -2.40$ from McNamara (1997), π_1/π_0 is about 0.79 for the theoretical metallicity-period ratio relation. The results by H97, Z99, and KS99 are somewhat smaller or much larger, but our result gives the best agreement. However, there is still disagreement on the relationship between metallicities and period ratios in Figure 4. For a complete comparison of observational and theoretical relationships between [Fe/H] and π_1/π_0, more accurate observational determinations of [Fe/H] for metal-poor double-mode variables and more models are needed.

It would be interesting to determine whether the pulsation properties are different before and after the maximum variation of the $O - C$ values in 1999. Because the amount of total light can be changed if BL Cam is a binary system, there may be a pulsational difference before and after the maximum variation of $O - C$. Since the coefficients of the synthetic light curves reflect the pulsational properties, the coefficients by Z99 before maximum and by our new 245 data set after maximum were compared. It was noted that five frequencies corresponding to the nonradial mode around the first frequency identified by Z99 had all disappeared, but two new frequencies appeared (see Table 2). However, this difference might be due not only to possible changes in the physical structure but also to different data reduction procedures.

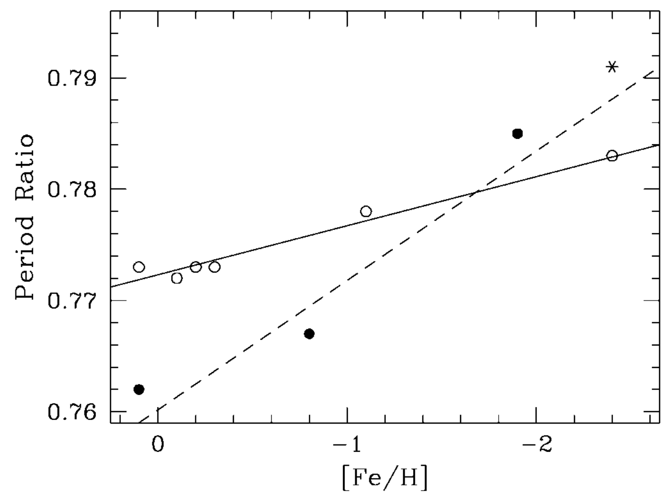

FIG. 4.—Plot of period ratio vs. [Fe/H] for observed double-mode variables (*open circles*) and model double-mode variables (*filled circles*) by H97. The solid line is a linear fit to the stars, while the dashed line is a linear fit to three model stars. The asterisk represents $\pi_1/\pi_0 = 0.791$ for BL Cam.

B observations were carried out to determine the oscillation modes using the phase difference of $\phi_V - \phi_{B-V}$ as well as A_{B-V}/A_V, as proposed by Watson (1988). However, this was not done because of the poor quality of the $B-V$ data and the relatively small number of data points.

5. CONCLUSIONS

All-sky photometry and profile reduction procedures were performed on BL Cam. It was found that BL Cam is an optical double star and that there are variations in $O - C$. Through a period search, five frequencies were identified; interestingly, all were closely spaced nonradial frequencies around when the first frequency identified by Z99 had disappeared. Rather, it was found that, except for f_0, $2f_0$, and f_1, all other frequencies do not fit the radial-mode frequencies.

We investigated the relationship between [Fe/H] and π_1/π_0 derived by H97 and showed that higher values of π_1/π_0 for metal-poor stars in theoretical models can be explained by a reliable determination of the second period. BL Cam is an extreme case among double-mode variables in its metallicity, period, period ratio, and space motion.

Only three double-mode SX Phe variables are known: BL Cam, V2314 Oph (Martin & Rodríguez 1995), and BQ Psc (Kim, Jeon, & Kim 2002). Therefore, there is not enough information on metal-poor double-mode pulsators. If more new double-mode SX Phe variables can discovered and if their pulsational and evolutionary properties can be thoroughly investigated, differences between metal-poor and metal-rich double-mode variables will be better understood. This requires long-term observations. Although BL Cam is faint ($\langle V \rangle =$ 13.10), spectroscopic observations are essential. In order to confirm the periodic variation of the $O - C$ values, BL Cam should be observed for at least 10 more years.

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