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PHOTOMETRIC PROPERTIES OF FOUR NEW VARIABLE STARS IN THE VICINITY OF BR CAM

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ABSTRACT

We present photometric results for four new variable stars discovered in the vicinity of the ZZ Ceti-type pulsating white dwarf BR Cam. Observations were performed on 5 nights in November 2003 using the 1.8m telescope at Bohyunsan Optical Astronomy Observatory with no filter, on 3 nights in December 2003 using the 0.61m telescope at Sobaeksan Optical Astronomy Observatory with V, I filters, and on 3 nights in October 2004 using the 1.0m telescope at Mt. Lemmon Optical Astronomy Observatory with V, I filters. We estimated their periods from the phase-match technique for one eclipsing binary and the multiple frequency analysis for three pulsating stars. By considering the light curve shape, period and amplitude difference between two passbands, we classified the objects by their variability types as follows: V1 (USNO-A2.0 1425-05691757) is a W UMa-type eclipsing binary with an orbital period of $0^{d}.4641$; V2 (USNO-A2.0 1425-05703335) is a multi-periodic δ Sct-type pulsating star with a dominant period of $0^{d}.0649$; V3 (USNO-A2.0 1425-05699659) is also a δ Sct-type pulsating star with a period of $0^{d}.1408$; and V4 (USNO-A2.0 1425-05707705) is a RR Lyr-type pulsating star with a period of $0^{d}.2643$.

Key words : stars: binaries: eclipsing – stars: variables: δ Sct – stars: individual: BR Cam

I. INTRODUCTION

In the last few years, the number of photometric surveys searching for variable objects using large-format CCD cameras has increased greatly. Intending to monitor as many stars as possible, some projects concentrate on bright field stars with 10cm-class small apertures while others work on deep observing in crowded fields or clusters with 1m-class telescopes. The scientific goals are diverse - to detect transit events by extrasolar planets across bright field stars (e.g., the STARE* and PSST* projects) or faint F∼M spectral type main-sequence stars in open clusters (e.g., the EXPLORE O/C* and PISCES* projects), to discover microlensing events of stars in the Magellanic Clouds or the Galactic bulge (e.g., the MACHO* or OGLE* projects), and to hunt for Gamma Ray Bursts or variable stars (e.g., the ROTSE* or ASAS* projects). The surveys have discovered immense numbers of new variable stars using time-series CCD images.

The tremendous amount of data could create problems in identifying the physical characteristics of the new variables. For example, Jin et al. (2003, 2004) found many mis-classifications of the type of variability. They did this by performing follow-up observations of 49 δ Sct-type pulsating stars which had been discovered and classified by the ROTSE-I group (Akerlof et al. 2000). The team had, in fact, identified 91 δ Sct-type stars among their 1781 periodic variables. After comparing V and I amplitudes, Jin et al. confirmed only six HADS (High Amplitude Delta Sct-type pulsating stars) among their 49 follow-up objects and 37 of the remaining targets turned out to be W UMa-type eclipsing binaries. From the Fourier decomposition analysis of the ROTSE-I data, they suggested that most of the supposed 42 ROTSE-I δ Sct-type stars which they did not observe, are not HADS but really W UMa-type eclipsing binaries.

During the multi-site campaign (PI: G. Vauclair) concentrating on the ZZ Ceti-type pulsating white dwarf BR Cam (=G191-16, $RA_{2000} = 04^{h}\ 59^{m}\ 27^{s}$, $DEC_{2000} = +55° 25' 6''$, $V=+16^{m}.0$) on November 2003 using a 1.8m telescope at Bohyunsan Optical Astronomy Observatory (BOAO), we discovered serendipi-

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*STARE: STellar Astrophysics & Research on Exoplanets; see http://www.hao.ucar.edu/public/research/stare/stare.html
*PSST: Planet Search Survey Telescope; Dunham, Mandushev, & Taylor 2004
*EXPLORE O/C: EXtrasolar PLanet Occultation REsearch of Open Clusters; von Braun et al. 2004
*PISCES: Planets In Stellar Clusters Extensive Search; Mochejska et al. 2004
*MACHO: MAssive Compact Halo Objects; see http://wwwmacho.mcmaster.ca
*OGLE: Optical Gravitational Lensing Experiment; see http://sirius.astrouw.edu.pl/~ogle
*ROTSE: Robotic Optical Transient Search Experiment; see http://www.rotse.net
*ASAS: All Sky Automated Survey; see http://archive.princeton.edu/~asas

TABLE 1.
OBSERVING LOG

Observing date	Start H.J.D.	Running time	Seeing	N_{OBS}(Filter)	Telescope
2003-11-21	2452965.12198	$5^{h}.77$	$3''.5$	638(None)	BOAO 1.8m
2003-11-22	2452965.96642	$9^{h}.66$	$2''.9$	1320(None)	BOAO 1.8m
2003-11-23	2452966.94596	$10^{h}.40$	$2''.6$	1079(None)	BOAO 1.8m
2003-11-24	2452968.18222	$3^{h}.94$	$2''.6$	548(None)	BOAO 1.8m
2003-11-25	2452968.99049	$1^{h}.37$	$3''.5$	158(None)	BOAO 1.8m
2003-12-03	2452977.35384	$0^{h}.72$	$3''.2$	6(V), 7(I)	SOAO 0.61m
2003-12-09	2452983.34193	$1^{h}.32$	$3''.0$	12(V), 12(I)	SOAO 0.61m
2003-12-15	2452989.20413	$4^{h}.69$	$3''.1$	40(V), 41(I)	SOAO 0.61m
2004-10-07	2453285.90189	$2^{h}.99$	$2''.7$	35(V), 36(I)	LOAO 1.0m
2004-10-09	2453287.90587	$2^{h}.89$	$3''.0$	35(V), 36(I)	LOAO 1.0m
2004-10-11	2453289.91796	$2^{h}.38$	$2''.7$	23(V), 21(I)	LOAO 1.0m

tously a new variable star in the vicinity of BR Cam. In order to clarify its variable type, follow-up observations with V and I filters were carried out using the 0.61m telescope at Sobaeksan Optical Astronomy Observatory (SOAO) and the 1.0m telescope at Mt. Lemmon Optical Astronomy Observatory (LOAO). In addition to the new variable star, we found three other new variables in the wide observing fields of SOAO and LOAO. In this paper, we present photometric results for these four new variable objects. Observations and data reductions are given in Section II. We describe the photometric properties of the new variable stars in Section III and summarize the results in Section IV.

II. OBSERVATION AND DATA REDUCTION

We carried out CCD photometric observations of the ZZ Ceti-type star BR Cam for five consecutive nights beginning on November 21, 2003 using a SiTe 2K CCD camera attached to the BOAO 1.8m telescope. The CCD chip has 2048×2048 pixels and a pixel size of 24μm. The field of view (FOV) of a CCD image is about $11'.6\times11'.6$ ($0''.34$ pixel^{-1}) at the f/8 Cassegrain focus of the telescope. Ordinary, readout time for a full frame is about 100 seconds. Because BR Cam has multiple periods which are as short as several hundred seconds (Vauclair et al. 1989), we had to decrease readout time. We set up a 2×2 binning mode and subframe definition, resulting in a CCD image with 230×240 pixels (FOV $2'.6\times2'.7$). Then readout time decreased to 7 seconds. Exposure time was 18 seconds and we used no filter due to the faintness and short periods of BR Cam.

We discovered a new variable star in the BOAO data from a quick analysis, but could not decide if it is a W UMa-type eclipsing binary or an RR Lyr-type pulsating star. So, follow-up observations with V and I filters were performed at SOAO and LOAO. First, we obtained time-series CCD images for 3 nights in December, 2003 using another SiTe 2K CCD camera attached to the SOAO 0.61m telescope. The CCD chip also has 2048×2048 pixels and a pixel size of 24μm. The FOV of a CCD image is about $20'.5\times20'.5$ ($0''.60$ pixel^{-1}) at the f/13.5 Cassegrain focus of the telescope. Exposure times were about 180 seconds for the V filter and 120 seconds for the I filter, depending on atmospheric condition.

Then, we observed the same field for 3 nights in October, 2004 using a Kodak 2K CCD camera attached to the LOAO 1.0m telescope. The Korea Astronomy Observatory had installed the telescope at Mt. Lemmon in Arizona, USA, during September 2003 and has been operating it by remote control from Korea via a network connection since that time. The CCD chip has 2084×2084 pixels and a pixel size of 24μm. The FOV of a CCD image is about $22'.2\times22'.2$ ($0''.64$ pixel^{-1}) at the f/7.5 Cassegrain focus of the telescope. Typically, exposure time was 160 seconds for the V filter and 50 seconds for the I filter. The two SiTe CCD chips were cooled to −100°C using Liquid Nitrogen coolant, and the Kodak CCD chip was cooled only to −20°C using a thermoelectric cooler. Therefore, at LOAO we took a few tens of dark frames during our observations in order to correct dark noise. The detailed observing log is listed in Table 1.

Using the IRAF/CCDRED package, we processed time-series CCD frames to correct bias level and pixel-to-pixel inhomogeneity of quantum efficiency (flat fielding). For the CCD images obtained at LOAO, we also corrected thermal dark noise. In order to get instrumental magnitudes of stars, a simple aperture photometry was applied using the IRAF/DAOPHOT package. The aperture radius was chosen to be about twice the seeing disk. Then, differential magnitudes were calculated from the standard differential photometric method. A star near to BR Cam, USNO-A2.0 1425-059694050 ($RA_{2000} = 04^{h}\ 59^{m}\ 25^{s}.29$, DEC_{2000} =

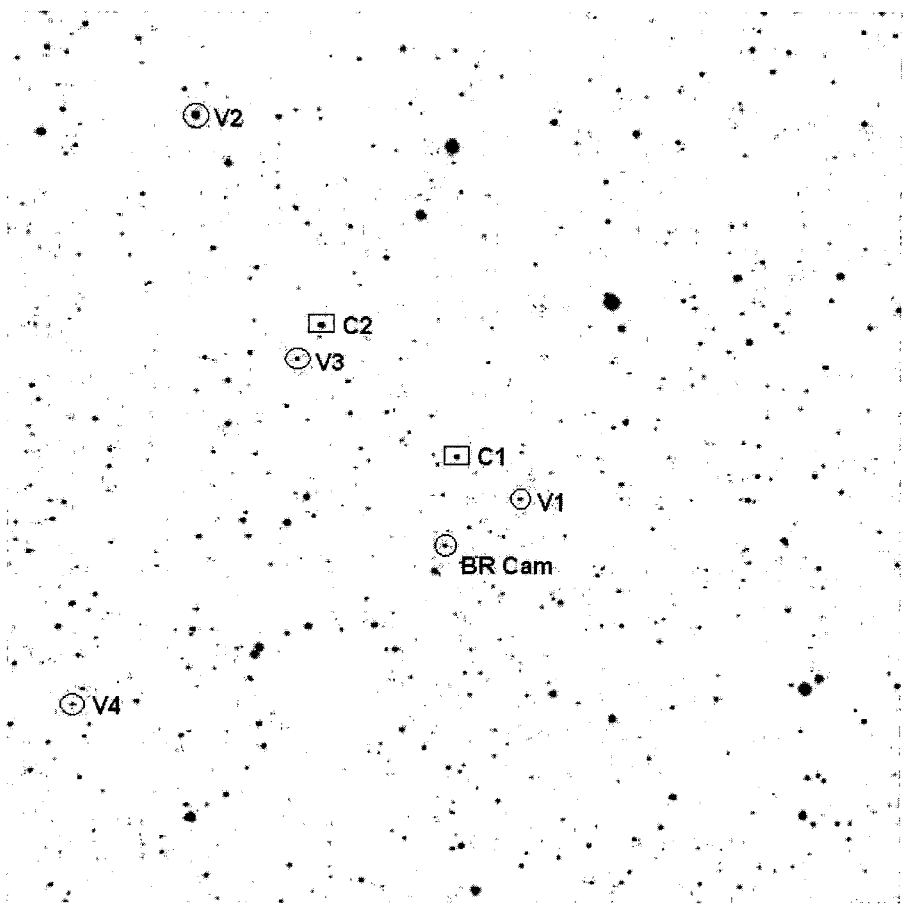

Fig. 1.— A CCD image observed with the SOAO 0.61m telescope (FOV: $20\overset{\prime}{.}5\times20\overset{\prime}{.}5$). Four new variable stars, V1~V4, in the vicinity of the ZZ Ceti-type variable BR Cam are identified by circles. The two comparison stars, C1 and C2, are denoted by rectangles. North is up and east is to the left.

$+55^\circ\ 27'\ 18\overset{\prime\prime}{.}8$, $B = +15\overset{\mathrm{m}}{.}0$, $R = +13\overset{\mathrm{m}}{.}8$), was used as a comparison star (C1). A second star, USNO-A2.0 1425-05698802 ($RA_{2000} = 04^{\mathrm{h}}\ 59^{\mathrm{m}}\ 46\overset{\mathrm{s}}{.}64$, $DEC_{2000} = +55^\circ\ 30'\ 17\overset{\prime\prime}{.}8$, $B = +14\overset{\mathrm{m}}{.}8$, $R = +13\overset{\mathrm{m}}{.}2$), was used as a check star (C2). A few tens of stars in the observing field were also monitored to check for variability. We adjusted the small difference of mean differential magnitudes between the SOAO and LOAO data. A finding chart of the four new variables and the two comparison stars is shown in Figure 1.

III. PHOTOMETRIC RESULTS

Light curves of the four new variable stars are displayed in Figure 2. Their periodic light variations are clearly shown, in contrast to the constant brightness of the check star C2. We now describe the observational characteristics of the new variable stars.

(a) V1 (USNO-A2.0 1425-05691757)

Unfiltered light variations at BOAO show well-defined sinusoidal curves with a period about $0\overset{\mathrm{d}}{.}23$ and an amplitude about $0\overset{\mathrm{m}}{.}12$ (upper panel in Figure 2). With these data we could not determine whether V1 is a RR Lyr-type pulsator with a period about $0\overset{\mathrm{d}}{.}23$ or a W UMa-type eclipsing binary with an orbital period about $0\overset{\mathrm{d}}{.}46$. So, we obtained two-passband data and examined the amplitude difference between V and I-bands. ΔV was estimated to be about $0\overset{\mathrm{m}}{.}13$ and ΔI about $0\overset{\mathrm{m}}{.}12$ and, as already noted, the amplitude with no filter was also about $0\overset{\mathrm{m}}{.}12$ (see Figure 3). This similarity of amplitudes for different passbands implies that V1 is not a RR Lyr-type pulsator but a W UMa-type eclipsing binary; pulsating stars have larger amplitude differences between passbands than do eclipsing binaries because luminosity changes of pulsating stars are caused mainly by variations in temperature. Jin et al. (2003, 2004) showed that $\Delta I/\Delta V$ is 0.92 for W UMa-type binaries and about 0.60 for HADS.

Several epochs of minimum brightness were observed

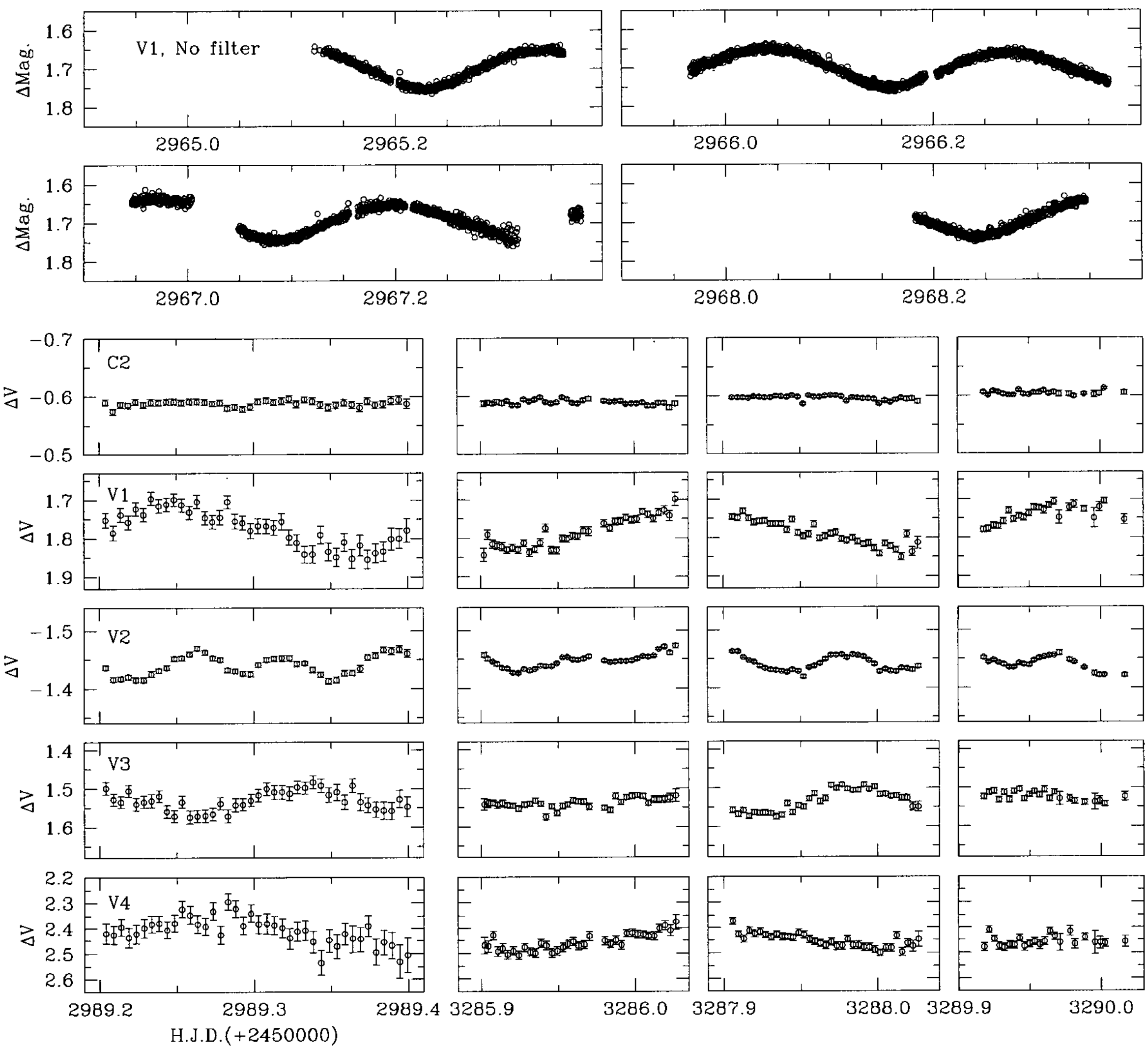

Fig. 2.— Differential magnitudes of the four new variable stars, Δm = m(star)−m(C1). (Upper) Light variations of V1 with no filter as observed at BOAO. (Lower) *V* filter brightness changes of V1∼V4 as observed at SOAO (H.J.D. 2452989.2) and LOAO (the other three dates). In the top lower panel, the luminosity of the check star C2 is also shown for comparison.

for V1, as is shown in Figure 2. So, we estimated these epochs by the well-known method by Kwee & van Woerden (1956) and derived the following ephemeris using the epochs listed in Table 2,

$$Min.H.J.D. = 2452965.2285(14) + 0.4640926(48) \times E.$$

The parenthesized numbers are the errors of the coefficients. A phased diagram for V1 is shown in Figure 3. It shows the typical light curve of a W UMa-type eclipsing binary, with the primary minimum a little deeper than the secondary one.

(b) V2 (USNO-A2.0 1425-05703335)

Differential magnitudes of V2 in the *V*-passband show very complicated curves and the amplitudes vary

TABLE 2.
MINIMUM EPOCHS OF V1

H.J.D.	Filter	Type
2452965.22719(7)	None	Min. I
2452966.15786(6)	None	Min. I
2452967.08575(5)	None	Min. I
2452968.24227(4)	None	Min. II
2452989.3636(8)	*V*,*I*	Min. I
2453285.9164(4)	*V*	Min. I

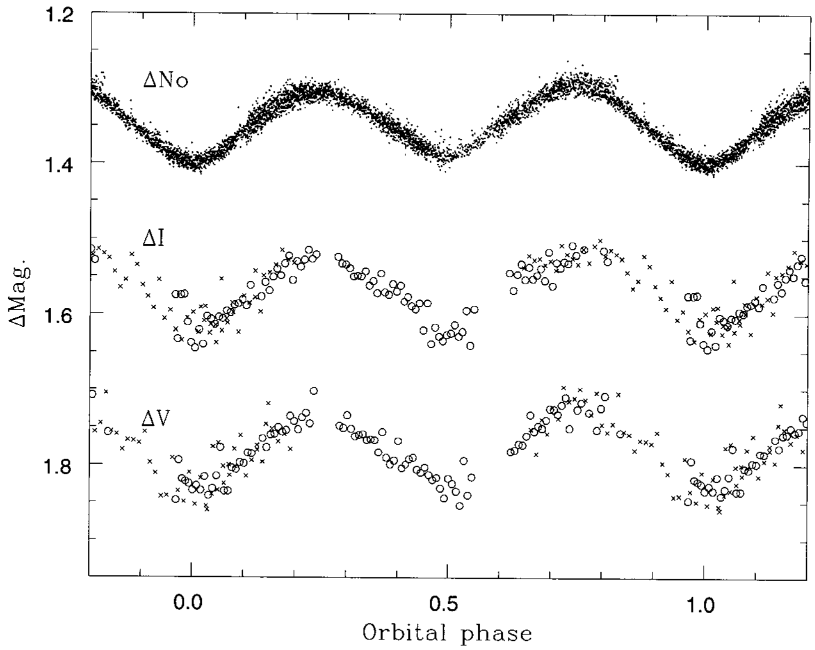

Fig. 3.— A phased diagram for V1. Observations are represented by different symbols: dots from BOAO with no filter (top), open circles from LOAO and crosses from SOAO with I filter (middle) and V filter (bottom).

from cycle to cycle (Figure 2), indicating that multiple periods are superimposed. In order to estimate the periods of V2, we applied the multiple frequency analysis using a Discrete Fourier Transform (DFT) and a linear least squares fitting method (Kim & Lee 1996).

Power spectra of V-band data are shown in Figure 4. The spectral window in the top panel shows strong side bands, particularly at 0.5 c/d (cycles per day) multiplets. These side-lobes are produced by the daily observation gaps, the observing time difference of about 0.4 day between SOAO and LOAO data, and short observing runs less than 5 hours each night. After successive prewhitening for each frequency peak in the next three panels of Figure 4, we derived frequencies of f_1 = 15.396 c/d, f_2 = 8.614 c/d and f_3 = 14.692 c/d. Some additional peaks at lower frequency still exist in the last panel of the figure but their signal-to-noise amplitude ratios (S/N) are smaller than 4.0, the empirical criterion proposed by Breger et al. (1993). Results of the analysis are summarized in Table 3.

The short period of about 1.56 hours for the dominant mode, the multiple periodicity and the small amplitudes suggest that V2 is a δ Sct-type pulsating star. At present, it is difficult for us to identify the pulsating modes for the three frequencies because of our limited information, but f_3 is very close to f_1, possibly implying that f_3 is a non-radial frequency.

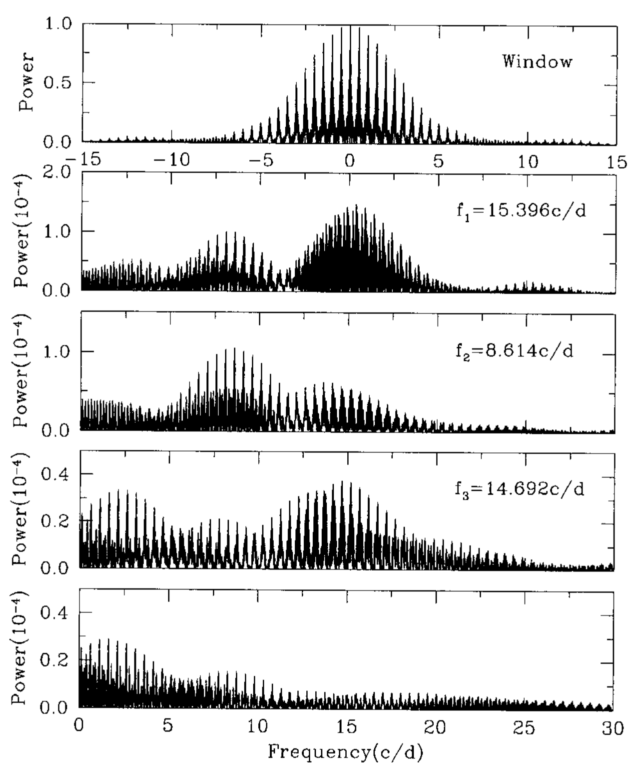

Fig. 4.— Power spectra of V2 with ΔV data. A window spectrum is shown in the top panel. The successive pre-whitening procedure shows three frequencies of f_1 = 15.396 c/d, f_2 = 8.614 c/d and f_3 = 14.692 c/d.

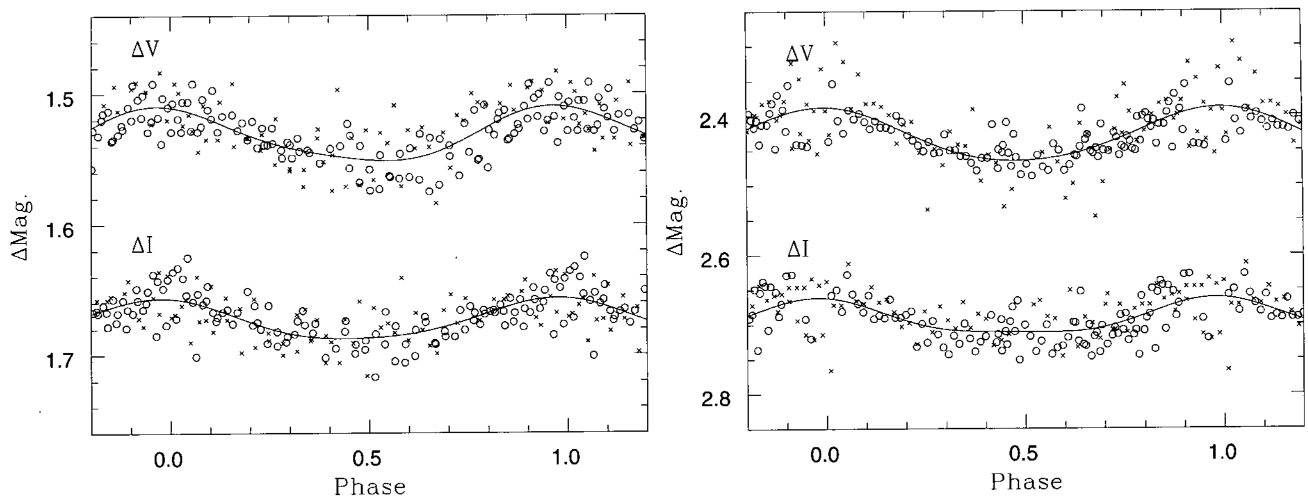

Fig. 5.— Phased diagrams for V3 (left) and V4 (right). Observing data are represented by different symbols, open circles from LOAO and crosses from SOAO with V filter (upper) and I filter (lower). The curves are synthetic ones from the second order harmonic fit.

TABLE 3.
MULTI-FREQUENCY ANALYSIS OF V2 WITH V FILTER

Frequency	$A_j^\dagger$	$\phi_j^\dagger$	S/N‡
f_1=15.396 c/d	10.3 ±.8 mmag	−0.67 ±.08	8.8
f_2= 8.614	9.5 ±.8	−1.01 ±.08	7.5
f_3=14.692	7.0 ±.9	+2.27 ±.12	4.4
Deviations	6.79 mmag		

$\dagger$: $V = V_o + \Sigma_j\ A_j \cos\{2\pi f_j(t - t_o) + \phi_j\}$, t_o = $H.J.D.$2453000.0
$\ddagger$: S/N = (power for each frequency / mean power after prewhitening for all frequencies)$^{1/2}$

(c) V3 (USNO-A2.0 1425-05699659) and V4 (USNO-A2.0 1425-05707705)

Light variations of V3 and V4 show slightly asymmetric curves, i.e., steeper increasing slopes than decreasing ones and flat minima, in comparison with the symmetric curves of V1. The light curve shapes therefore imply that two variables are pulsating stars. We applied multiple frequency analyses to estimate their variable periods. In the V-passband, the dominant frequencies for V3 and V4 are 7.102 c/d ($0^{\rm d}.1408$) and 3.784 c/d ($0^{\rm d}.2643$), respectively, and other reliable frequencies were not detected. The S/N ratios of these frequencies are 5.47 for V3 and 5.46 for V4, indicating that they are real. Figure 5 displays phased diagrams for V3 and V4.

In order to examine light curve shapes and amplitude differences between the two passbands, we applied Fourier decomposition analyses, even though the data quality is not so good. We derived synthetic curves from second order harmonic fits (i.e., f_1 as well as f_2=2×f$_1$) using the following equation

$$\Delta V = Constant + \Sigma_{j=1,2}\ A_j \cos\{2\pi f_j t + \phi_j\},$$

where t runs from 0.0 to 1.0 and f_1 is 1.0 cycle per pulsation. In order to examine the V-band light curve shape, we calculated the Fourier decomposition parameter $\phi_{ji} = i\times\phi_j - j\times\phi_i$. The values of ϕ_{21} = 3.8±0.7 for V3 and ϕ_{21} = 2.9±1.1 for V4 are close to the high probability region of ϕ_{21} = 3.5 ∼ 5.0 for HADS or RR Lyr-type stars and differ greatly from the 0.0 or 2×π values for W UMa-type eclipsing binaries (Jin et al. 2003, 2004). A value of ϕ_{21} = 0.0 indicates a flat maximum brightness commonly noted in eclipsing binaries and $\phi_{21} = \pi/2$ points to the flat minimum seen in pulsating stars. The ratios of the amplitudes of the curves for the two passbands, $\Delta I/\Delta V$, are about 0.74 for V3 and V4. It may be a little higher than 0.60 for HADS (Jin et al. 2003, 2004), mainly caused by the poor data quality, but should be lower than 0.92 for W UMa-type binaries. On the basis of period, amplitude differences between passbands and light curve shapes (i.e., the Fourier decomposition parameter ϕ_{21}), we suggest that V3 is a δ Sct-type pulsating star and V4 is an RR Lyr-type pulsator.

IV. SUMMARY

During the multi-site observations of the ZZ Ceti-type pulsating white dwarf BR Cam, we discovered a new variable star in our small observing field of 2.6×2.7 arcmin^2 at BOAO. Follow-up observations were performed with V and I-passbands to clarify whether this is a pulsating star or an eclipsing binary. From these observations, we found three additional new variables

TABLE 4.
PHYSICAL PARAMETERS OF FOUR NEW VARIABLE STARS

Stars	RA_{2000}	DEC_{2000}	$B^{\dagger}$	$R^{\dagger}$	Period	Epoch‡	ΔV	Type
V1	$04^h\ 59^m\ 15^s.17$	$+55°\ 26'\ 21''.6$	$+16^m.3$	$+15^m.5$	$0^d.4641$	2452965.2285	$\approx 0^m.13$	W UMa
V2	$05^h\ 00^m\ 06^s.62$	$+55°\ 35'\ 01''.5$	$+13^m.8$	$+12^m.5$	$0^d.0649$	-	$\approx 0^m.05$	δ Sct
V3	$04^h\ 59^m\ 50^s.56$	$+55°\ 29'\ 32''.4$	$+16^m.3$	$+15^m.2$	$0^d.1408$	2452989.342	$\approx 0^m.05$	δ Sct
V4	$05^h\ 00^m\ 26^s.16$	$+55°\ 21'\ 47''.2$	$+17^m.1$	$+15^m.6$	$0^d.2643$	2452989.276	$\approx 0^m.10$	RR Lyr

† : from the USNO-A2.0 catalogue (Monet et al. 1998)
‡ : at minimum brightness for an eclipsing binary and maximum brightnesses for pulsating stars

in the wider observing field of about 21×21 arcmin^2 at SOAO and LOAO. By considering observational properties such as periods, amplitude differences between passbands and light curve shapes, we classified the variability types.

Photometric results for the four new variable stars are summarized in Table 4. We identified that V1 is a W UMa-type eclipsing binary and the others V2 $\sim$ V4 are pulsating stars with rather short periods and small amplitudes.

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