Photometric Observation and Numerical Simulation of Early Superhumps in BC UMa during the 2003 Superoutburst

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Abstract

We carried out time-resolved photometric observations of an SU UMa type dwarf nova, BC UMa, during its superoutburst in February 2003. We detect early superhumps (or outburst orbital humps) during the first two days of the outburst. The period of early superhumps is 0.06258(13) d and the amplitude is 0.04 mag. After the early superhump phase, common superhumps with an amplitude of 0.3 mag and a period of 0.064466(16) d developed. The change rate of superhump periods ($\dot{P}_{sh}$/$P_{sh}$) was positive through the superoutburst. The superhump period excess ($\varepsilon$ = $P_{sh}$/$P_{orb}$ - 1) is 3% and we derive a mass ratio of 0.13. This is twice as large as that of WZ Sge, suggesting that the mechanism of early superhumps in BC UMa is not the 2:1 resonance which was proposed in WZ Sge.

We have modelled early superhump light curves including irradiation effects of the accretion disk and secondary star by the white dwarf and accretion disk. The observed early superhumps can be reproduced when two-armed spirals appear on the accretion disk.

We have found the long term data taken from AAVSO, VSOLJ and VSNET shows BC UMa has normal outbursts with a maximum magnitude of $m_V$ ~ 13 and two types of superoutbursts: one has a short duration (around 10 days) and faint maximum magnitude ($m_V$ ~ 12.5), the other has a long duration (around 20 days) and bright maximum ($m_V$ ~ 11 - 11.5). BC UMa is the first example of dwarf novae showing the two types of superoutbursts. The supercycle of BC UMa is between 600 days and 1000 days. This is shorter than WZ Sge type dwarf novae and longer than normal SU UMa type stars. This phenomenon suggests that BC UMa is an intermediate dwarf nova between WZ Sge and SU UMa.

Key words: accretion, accretion disks — stars: dwarf novae — stars: individual (BC UMa) — stars: novae, cataclysmic variables

1. Introduction

Dwarf novae are a class of cataclysmic variables (CVs), which are close binary systems consisting of a white dwarf and a red dwarf or a main sequence star. SU UMa type dwarf novae are a subgroup of dwarf novae characterized by having two types of outbursts: normal outbursts (short duration and faint maximum brightness) and superoutbursts (long and bright maximum) (e.g. Warner 1985). A unique property of superoutbursts is the appearance of superhumps. Superhumps are small-amplitude periodic modulations that are observed only during the superoutburst. Superhump periods are a few percent longer than the orbital period.

WZ Sge type dwarf novae are a subtype of SU UMa type, properties of which are common to SU UMa type dwarf novae in showing superoutbursts and superhumps. Remarkable properties of WZ Sge type are an extremely long recurrence time (~ 10 yr), a very large outburst amplitude (exceeding 6 mag), a long duration (~ a month or more) and lack of normal outbursts. Early superhumps are observed only in early stages of superoutbursts of WZ Sge type dwarf novae. Early superhumps are doubly-waved humps with a period nearly equal to the orbital period (Bohusz & Udalski 1979, Patterson et al. 1981, Kato et al. 1996, Nogami et al. 1997, Matsumoto et al. 1998, Kato et al. 2001, Ishioka et al. 2001, Ishioka et al. 2002, Patterson et al. 2002). Their amplitudes are smaller than 0.2 mag. Early superhumps of WZ Sge show a small bump at orbital phase of 0.1-0.2, a small dip at 0.3-0.4 and large bump at 0.6-0.7 (Ishioka et al. 2002). Osaki & Meyer (2002) proposed that early superhumps are caused by two-armed dissipation pattern on the accretion disk (Lin & Papaloizou 1979). In dwarf novae with an extremely small mass ratio, the accretion disk can expand beyond the 2:1 resonance radius when an outburst occurs. Strong two-armed dissipation pattern appears due to the 2:1 resonance, and doubly-waved periodic modulations are observed. The another model of early superhumps is proposed by Kato (2002). This model is an application of the tidal distortion effect on accretion disks (Smak 2001; Ogilvie 2002). Kato (2002) proposed that
both the two-armed spiral structures in Doppler maps and early superhumps can be explained by irradiation of an elevated accretion disk due to the tidal distortion effect.

BC UMa was discovered by Romano (1964) as a dwarf nova with an outburst amplitude of 7 mag. Howell et al. (1990) detected humps with a period of 91 min and an amplitude of 0.25 mag in the quiescence phase. A spectrum taken by Mukai et al. (1990) during a faint state shows both absorption and emission components in its Balmer lines and TiO band feature at 760 nm. Mukai et al. (1990) estimated several system parameters as below: the spectral type of the secondary is later than M5, the distance is 130–400 pc, and the absolute magnitude ($M_V$) is 11.0–13.5 mag. Patterson et al. (2003) carried out time-resolved photometry during the 2000 April superoutburst. They detected early superhumps with a period of 0.06256(8) d during the first 4 days of its superoutburst as well as superhumps with a period of 0.06452(9) d after that. They also obtained the radial velocity curve and determined the orbital period to be 0.06261(4) d. The period of the early superhumps is equal to orbital period within the errors. The superhump period excess is 3%.

Schmeer (2003) reported an outburst of BC UMa at 2003 February 1.205(UT). We started time-resolved photometry on February 1.603(UT), 9 hours after we received the outburst report. In this paper we report our observations during the superoutburst in February 2003 and we have further modelled light curves of early superhumps.

2. Observation

We observed BC UMa at Saitama and Mie in Japan. Our observation logs and instruments are summarized in Table 1. All frames were dark-subtracted and flat-fielded before photometry. The Saitama frames were processed by the aperture photometry package in IRAF. The frames obtained at Mie were processed by the aperture photometry packages, FITS Photo, developed by Kazuo Nagai. The magnitudes were measured by using the local standard stars, TYC2 3454.875.1 (Mie) and GSC 3454.0868 (Saitama). The constancy of brightness of the comparison stars during the run was checked by using GSC 3454.0817.

Because each observer used different filters and comparison stars, all data were adjusted to match V-band magnitude obtained at Mie. The barycentric correction was applied to the observation time before analysis.

3. Results

3.1. Early superhumps

Fig. 1 shows the long-term light curve of the 2003 February superoutburst. According to the AAVSO, VSOLJ, and VSNET data, BC UMa was fainter than 13.7 mag 7 hours before the outburst detection and 16 hours before we have started the time-series photometry. This suggests that our observations cover the early phase of the superoutburst. Daily light curves are depicted in Fig. 2. On the first and second nights (February 1 and 2), the object showed small ($\Delta m_V \sim 0.04$) variation. We applied the Phase Dispersion Minimization (PDM) method (Stellingwerf 1978) to the data which obtained on February 1 and 2 after subtraction of the slow decay trend. The resultant period - theta diagram is shown in Fig. 3. Fig. 4 shows the phase-averaged light curve of the small amplitude modulations during the early phase of superoutburst. The shape of the modulations is double-peak and each peak in an orbital cycle has different amplitudes. These properties are similar to that of early superhumps in WZ Sge-type dwarf novae (e.g. Ishioka et al. 2002). The best estimated period of this variation is 0.06258±0.00013 d. The error was estimated by the Lalder-Kinman method (Fernie 1989). This period is equal to the orbital period (0.062605±0.000011 d: Patterson et al. 2003) within the errors. The early superhump period of known WZ Sge-type dwarf novae is nearly equal to the orbital period (e.g. Ishioka et al. 2002). Thus we concluded that these modulations are the early superhumps.

Ishioka et al. (2002) reported that the early superhump period of WZ Sge itself is slightly shorter (~0.05%) than the orbital period. Because of low accuracy of the early superhump period, we could not confirm the difference between the orbital period and the early superhump period.

3.2. Superhumps

From the third night (February 3), common superhumps clearly appeared. On February 3 (BJD 2452674), BC UMa showed small brightening. In EG Cnc, the same kind of brightening was also observed (Matsumoto et al. 1998, Patterson et al. 1998). These behavior suggest development of the 3:1 resonance. After removing the daily trend of brightening and decline, we also analyzed the data between 2003 February 3 and 12 by the PDM method. Fig. 5 shows the resultant period-theta diagram. The best estimated superhump period ($P_{sh}$) of $P_{sh} = 0.06448\pm0.00006$ d is equal to that in the 2000 February superoutburst ($P_{sh} = 0.06452\pm0.00009$ d: Patterson et al. 2003) within the errors. The superhump period excess is 3.9±0.1%. Fig. 6 shows the phase-averaged light curve of superhumps from the data during the superoutburst plateau phase. The mean amplitude of the common superhumps was $\Delta m_V \sim 0.2$. 

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1 IRAF is distributed by the National Optical Astronomy Observatories for Research in Astronomy Inc. under cooperative agreement with the National Science Foundation.

2 FITS Photo is an aperture photometry software developed by Kazuo Nagai. This software is available at http://www.geocities.jp/nagai-kazu/index-e.html.
Table 1. Log of observations.

| Start-End (UT) | Exposure time(s) | Flame number | Filter | Instrument |
|---------------|------------------|--------------|--------|------------|
| 2003 Feb. 1.603-1.822 | 40               | 213          | no     | S          |
| 1.620-1.868   | 60               | 163          | V      | M          |
| 2.542-2.867   | 45               | 322          | V      | M          |
| 3.543-3.799   | 30               | 299          | V      | M          |
| 3.694-3.837   | 40               | 143          | no     | S          |
| 5.569-5.869   | 30               | 305          | V      | M          |
| 6.576-6.873   | 30               | 399          | V      | M          |
| 6.743-6.870   | 40               | 138          | no     | S          |
| 9.591-9.826   | 30               | 210          | V      | M          |
| 9.617-9.661   | 40               | 61           | no     | S          |
| 11.768-11.865 | 30               | 118          | V      | M          |
| 12.551-12.858 | 30               | 400          | no     | M          |

S: 20cm Newtonian + SBIG ST-7E (Saitama, Japan),
M: 25cm SCT + MUTOH CV-04(Mie, Japan)

3.3. Superhump period change

We estimated superhump maximums by the following way:

1. We determine nightly "model superhump light curve" from the phase averaged superhump light curve of each night.
2. We shift the maximum timing of the model light curve around the eye estimated maximum in a 0.0001 days step, and calculate each sum of square of difference between the model light curve and the observation for each test maximum timings.
3. The maximum timing is determined by minimizing the sum of square of residuals divided by the number of data used to calculate the sum.

The errors of maximum timings were determined to satisfy a 99% confidence level.

The times of superhump maxima are given in table 2. The cycle count ($E$) is defined as $E = 0$ at the first superhump maximum we observed. A linear ephemeris of the

Fig. 1. Long-term light curve of the 2003 February superoutburst. Filled-squares are our CCD observations. Open circles are visual observations and the downward arrows are the upper limits taken from AAVSO, VSOLJ, and VSNET.

Fig. 2. Daily light curves of the 2003 February superoutburst. Each daily dataset is shifted as follow: -0.2 on Feb. 1, 0.0 on Feb. 2, +0.3 on Feb. 3, +0.5 on Feb. 5, +0.7 on Feb. 6, +0.8 on Feb. 9, +1.0 on Feb. 11, +1.2 on Feb. 12.
Fig. 3. Period - theta diagram obtained by the PDM period analysis for the data between February 1 and 2.

Fig. 4. Phase-averaged light curve of early superhumps. Since the exact binary phase is unknown for BC UMa, the phase was taken arbitrarily so that the early superhump maximum phase fit to that of Fig. 7 of Patterson et al. (2003).

Fig. 5. Period - theta diagram obtained by the PDM period analysis for the data between February 3 and 12.

Fig. 6. Phase-averaged light curve of common superhumps. The superhump phase was defined as superhump maximum at phase 0.

Table 2. Times of superhump maxima

| BJD - 2450000 | Error | E | \(O - C\) |
|---------------|-------|---|-----------|
| 2674.1061     | 0.0021| 0 | -0.0007   |
| 2674.1717     | 0.0011| 1 | -0.0006   |
| 2674.2367     | 0.0013| 2 | 0.0000    |
| 2674.2992     | 0.0016| 3 | -0.0020   |
| 2676.1047     | 0.0027| 31| -0.0015   |
| 2676.1700     | 0.0046| 32| -0.0006   |
| 2676.2338     | 0.0033| 33| -0.0013   |
| 2676.3628     | 0.0022| 35| -0.0012   |
| 2677.1384     | 0.0030| 47| 0.0008    |
| 2677.2018     | 0.0038| 48| -0.0003   |
| 2677.2683     | 0.0031| 49| 0.0018    |
| 2677.3334     | 0.0029| 50| 0.0024    |
| 2680.1096     | 0.0051| 93| 0.0067    |
| 2680.2377     | 0.0029| 95| 0.0059    |
| 2682.2898     | 0.0062| 127| -0.0049  |
| 2683.1290     | 0.0050| 140| -0.0037  |
| 2683.1989     | 0.0114| 141| 0.0018    |
| 2683.2603     | 0.0087| 142| -0.0013   |
| 2683.3248     | 0.0113| 143| -0.0013   |

* Using equation (1).

superhump maximum timings is given by

\[
\text{BJD(maximum)} = 2452674.1078(11) + 0.064463(13) E . (1)
\]

Fig. 7 shows the \(O - C\) diagram for these superhump maximum timings. The \(O - C\)s between \(E = 0\) (February 3) and \(E = 95\) (February 9) can be well represented by

\[
O - C \text{(days)} = 1.04(\pm0.26) \times 10^{-6} E^2 - 1.9(\pm2.5) \times 10^{-5} E + 9.6(\pm5.1) \times 10^{-4} . \tag{2}
\]

The quadratic term corresponds to \(\dot{P}_\text{sh}/P_\text{sh} = (+3.2 \pm 0.8) \times 10^{-5} \text{ [cycle count}^{-1}]. \)
responds to the following equation (Patterson et al. 1998):

\[ \xi = \frac{q}{(1.1q + 4.3)}. \]  

(3)

The superhump excess of BC UMa is 3.0% and this corresponds to \( q = 0.13 \). This mass ratio is twice the mass ratio of WZ Sge (\( q = 0.06 \), Skidmore et al. 2002), and as large as that of RZ Leo (\( q = 0.14 \), Ishioka et al. 2001).

Osaki & Meyer (2002) proposed that the light source of early superhumps in a dwarf nova with an extremely low mass ratio like WZ Sge is the two armed dissipation pattern by the 2:1 resonance. But in dwarf novae with \( q > 0.08 \), the accretion disk cannot extend to the 2:1 resonance radius. So we assume the light source of early superhumps in BC UMa is two armed spiral shocks on the accretion disk (e.g., Makita et al. 2000).

Mukai et al. (1990) reported that the spectral type of the secondary star in BC UMa is later than M5. So we assume a 0.1\( \text{M}_\odot \) secondary star with a surface temperature of 3000K. Our adopted values for the mass and surface temperature of the secondary star are consistent with the results of Ciardi et al. (1998). Then the mass of the white dwarf is 0.77\( \text{M}_\odot \) from the mass ratio of 0.13. The surface temperature of the white dwarf in an SU UMa-type star Z Cha is \( T_{\text{eff}} = 17400 \text{K} \) immediately after the outburst (Wood et al. 1993). Gänsicke et al. (2005) determine the effective temperature of the white dwarf in BC UMa to be 15200±1000 K at around 100 days after the superoutburst. So we assume the surface temperature of the white dwarf to be 15000 K.

A circular orbit is assumed. We also assume the surfaces of the white dwarf, secondary star and accretion disk emit photons as a blackbody at a local temperature. The size and thickness of accretion disk are assumed as follows:

\[ \frac{R_{\text{disk}}}{a} = \left( \frac{7}{5} \right)^2 (1 + q)^4 \left( \frac{R_{L1}}{a} \right)^4, \]  

(4)

(Osaki & Meyer 2002), and

\[ h = \beta \frac{R_{\text{disk}}}{R_{\text{disk}}} \left( \frac{r}{R_{\text{disk}}} \right)^\nu, \]  

(5)

where \( R_{\text{disk}} \) is the radius of the accretion disk, \( a \) is the binary separation, \( q \) is the mass ratio(\( M_2/M_1 \)), \( R_{L1} \) is the distance from the center of the white dwarf to the inner Lagrangian point, \( h \) is the height of accretion disk surface from equatorial plane, and \( r \) is the distance from the center of the white dwarf. In the case of \( q = 0.13 \), the accretion disk radius is 0.52\( a \). We adopt \( \nu = 2 \).

Spiral structures of surface of the accretion disk are assumed in the same manner as that adopted by Hachisu et al. (2004), which is defined by

\[ z_1 = \max \left( 1, \frac{\xi_1}{\sqrt{\left( \frac{r}{R_{\text{disk}}} - \exp[-\eta(\phi - \delta)] \right)^2 + \epsilon^2}} \right), \]  

(6)

\[ z_2 = \max \left( 1, \frac{\xi_2}{\sqrt{\left( \frac{r}{R_{\text{disk}}} - \exp[-\eta(\phi - \delta - \pi)] \right)^2 + \epsilon^2}} \right), \]  

(7)

\[ h' = h \max(z_1, z_2), \]  

(8)

where \( h' \) is the height of accretion disk surface including the axisymmetric structure. The various disk parameters above are assumed to be \( \epsilon = 0.1, \xi_1 = 0.25, \xi_2 = 0.15, \eta = 0.2, \) and \( \delta = 110^\circ \) for Fig. 8.

The nonirradiated surface temperature is one determined by the viscous heating of the standard disk model (Shakura & Sunyaev 1973). The mass accretion rate is \( 1 \times 10^{-9} \text{M}_\odot/\text{yr} \) (Horne & Cook 1985). The outer rim of the disk is not irradiated by the white dwarf. The brightness temperature of the outer rim of the disk in an SU UMa-type star Z Cha is \( log T \sim 3.9 \) at 0.7 days after maximum (Horne & Cook 1985). We assumed the temperature of the outer rim of the disk to be 8000 K.

The surfaces of the white dwarf, the accretion disk, and the secondary star are divided into patches as shown in
Fig. 8. We assume that each patch emits photons as a single temperature blackbody. The patches of the disk and the secondary are irradiated by the front side patches of the white dwarf if there is no patch between them. The total luminosity of the binary system is calculated by summing up each luminosity from all visible patches. The detail of the numerical method adopted here was described in Hachisu & Kato (2001, 2003a, 2003b, 2003c). The surface patch elements are $32 \times 64 (\theta \times \phi)$ for the secondary, $64 \times 128 \times 2 (\theta \times \phi \times$ up and down side) for the accretion disk, and $16 \times 32$ for the white dwarf. The number of total time steps are 128 for one orbital period.

4.2. Numerical results

The best-fit light curve model is plotted in Fig. 9 together with our observational points (same as Fig. 4). We have changed the inclination angle ($i$), the thickness of the accretion disk ($\beta$), and four parameters of the asymmetric structure of the accretion disk ($\delta, \eta, \xi_1, \xi_2$) as shown in table 3. $\xi_1$ and $\xi_2$ are parameters for the enhancement of thickness on the spiral structures. $\delta$ means the position angle of the spiral structure and $\eta$ is a parameter of tightness of the spiral (large $\eta$ means the loose spiral and small $\eta$ means the tight spiral). These are the best set of parameters among those in table 3: $i = 60^\circ, \beta = 0.13, \xi_1 = 0.25, \xi_2 = 0.15, \delta = 110^\circ$, and $\eta = 0.2$.

The spectrum of BC UMa shows doubly-peaked Balmer emissions (Patterson et al. 2003). This indicates that the inclination is not low. But absence of eclipse in photometric data suggests $i < 70^\circ$. The best estimated inclination is also consistent with these observational results.

The $i$ and $\beta$ affect the total brightness of binary system and the amplitude of orbital modulations. $\xi_1$ and $\xi_2$ affect the amplitude of two bumps of the early superhump. $\delta$ affects the phases of bumps. $\eta$ affects the shape of early superhumps, especially at large $\beta$. At $\delta = 110^\circ, \xi_1$ affects the amplitude of the bump around phase 0.6 and $\xi_2$ affects the amplitude of the bump around phase 0.1. $\xi_1, \xi_2$ and $\eta$ also affect the total brightness. But the total brightness is more sensitive to $i$ and $\beta$ than to $\xi_1, \xi_2$ and $\eta$. Thus the distance to BC UMa are mainly affected by the inclination angle and the thickness of the accretion disk. By comparing the apparent magnitudes of BC UMa during the early superhump phase with the calculated $V$ magnitudes, we have estimated the distance of BC UMa to be $d = 270 \pm 20$ pc (this error does not include the ambiguity of our model itself).

5. Discussion

5.1. Distance

In this subsection, we estimate the distance to BC UMa based on the maximum magnitude of normal outbursts. We analyzed the data of the AAVSO International Database, VSOLJ and VSNET and found some normal outbursts.

Warner (1987) proposed an empirical relationship between the absolute magnitudes at the normal outburst maximum and the orbital periods, i.e.,

$$M_V (\text{max}) = 5.74 - 0.259 P_{\text{orb}}(h).$$

To estimate the correct maximum magnitude of normal outbursts, we searched for outburst observations which satisfy the following conditions:

C1 The duration of an outburst was a few days.

C2 Within one day before the outburst was detected, some observers checked that BC UMa was in faint state.

C3 More than two observers detected the outburst.

The first condition C1 is the definition of normal outburst (Warner 1985), and the second one C2 is used to determine the true maximum magnitude. Because most of data are visual observations, we pose the third condition C3 to exclude the misidentification or any other errors.

We found two normal outbursts which satisfy all the conditions above and one normal outburst which falls short of the second condition as shown in table 4. The maximum magnitude of normal outbursts is $13.1 \pm 0.1$ (the error is the typical error for visual observations). The orbital period of BC UMa is $0.062605 \pm 0.000011$ d (Patterson et al. 1998), corresponding to $M_V=5.35 \pm 0.23$. Following Warner’s (1987) equation we assume the inclination effect

$$\Delta M_V (i) = -2.5 \log \left(1 + \frac{3}{2} \cos i \cos^2 \theta \right).$$

The inclination angle of the best-fit numerical model of early superhumps ($i = 60^\circ$) corresponds to $\Delta M_V = 0.145$. Thus the absolute magnitude of BC UMa is $M_V = 5.50 \pm 0.23$. Assuming the apparent maximum magnitude, $m_V = 13.1 \pm 0.1$, the distance is calculated to be $330 \pm 70$ pc. This value is consistent with the distance estimated by our numerical model ($270 \pm 20$ pc) and Gänsicke et al. (2005), value of $285 \pm 42$ pc from the FUV flux within the errors.

5.2. Supercycle, duration and amplitude of superoutburst

In this subsection, we estimate the recurrence time of superoutbursts, the durations and amplitudes of superoutbursts from the data of AAVSO, VSOLJ and VSNET,
Table 3. Tested parameters

| $i$  | 45°, 50°, 55°, 60°, 65°, 70°, 75° |
|------|----------------------------------|
| $\beta$ | 0.05, 0.07, 0.09, 0.11, 0.13, 0.15 |
| $\eta$ | 0.1, 0.2, 0.4 |
| $\delta$ | 10°, 20°, 30°, 40°, 50°, 60°, 70°, 80°, 90°, 100°, 110°, 120°, 130°, 140°, 150°, 160°, 170° |
| $\xi_1$ | 0.15, 0.20, 0.25, 0.30 |
| $\xi_2$ | 0.10, 0.15, 0.20, 0.25 |

Table 4. Normal outbursts and superoutbursts observed by AAVSO, VSOLJ, and VSNET.

| Date  | JD     | duration(days) | maximum magnitude | type  |
|-------|--------|----------------|-------------------|-------|
| 1982 May 20 | 2445109 | 21-22†         | 11.0              | super |
| 1987 May 8  | 2446924 | 4-7†           | 13.1              | normal |
| 1990 Sep. 9 | 2448143 | 15-19†         | 10.9              | super |
| 1992 Aug. 18 | 2448852 | 9-13†          | 12.5              | super |
| 1994 Apr. 27 | 2449469 | 16-17†         | 12.0              | super |
| 1995 Jul. 6  | 2449904 | 3              | 13.0              | normal |
| 2000 Mar. 31 | 2451635 | 23             | 11.5              | super |
| 2001 Jun. 25 | 2452085 | 5              | 13.1              | normal |
| 2003 Jan. 31 | 2452671 | 11             | 12.6              | super |

* The discovery date
† Because of no observations within one day before the outburst detection or the end of outburst, we cannot determine the accurate outburst duration.

and we describe our discovery of two types of superoutbursts in BC UMa.

We searched for outburst observations which satisfy the last condition C3 in the previous section. Table 4 shows normal and superoutburst observations in AAVSO, VSOLJ, and VSNET data. The supercycle is from 600 days (no normal outbursts between superoutbursts) to 1000 days (one normal outburst between superoutbursts). This value is longer than that of typical SU UMa type star (several hundred days), but shorter than that of typical WZ Sge type dwarf novae (∆$V$ ∼ 7 for faint superoutbursts). The amplitude of bright superoutbursts are smaller than the outburst amplitude of typical WZ Sge type dwarf novae (∆$V$ = 7 – 8). The amplitude of bright superoutbursts are as large as that of WZ Sge type stars. But on Feb. 3 (BJD2452674), the data indicate a small brightening. The decline rate before the development of superhumps was nearly equal to that of plateau phase and the brightness before the appearance of superhumps was brighter than that after superhumps appeared. These phenomenon indicate that the small brightening on Feb. 3 was not the transition phase from the precursor outburst to the main superoutburst. Thus the 2003 superoutburst was not precursor-main type superoutburst (Osaki & Meyer 2003, Osaki 2005).

5.3. Brightening phenomenon at the superhump developing phase

The decline rate and average brightness of nightly data are shown in table 5. Overall decline rates of the plateau phase are 0.13 mag/day. This is the typical value for that of SU UMa type dwarf novae. But on Feb. 3 (BJD2452674), the data indicate a small brightening. The decline rate before the development of superhumps was nearly equal to that of plateau phase and the brightness before the appearance of superhumps was brighter than that after superhumps appeared. These phenomenon indicate that the small brightening on Feb. 3 was not the transition phase from the precursor outburst to the main superoutburst. Thus the 2003 superoutburst was not precursor-main type superoutburst (Osaki & Meyer 2003, Osaki 2005).

The same phenomenon were observed in EG Cnc (Patterson et al. 1998, Matsumoto et al. 1998) and V844
Early superhumps in BC UMa were discovered by Patterson et al. (2003) in the 2000 superoutburst. We confirmed the existence of early superhumps and its period is equal to the orbital period within the errors. The 2000 superoutburst had long duration (23 days) and large outburst amplitude (7 mag). But the 2003 superoutburst had short duration (11 days) and relatively small outburst amplitude (6 mag). Early superhumps was observed in both superoutbursts.

Early superhumps in WZ Sge type dwarf novae are explained by the 2:1 resonance model (Osaki & Meyer 2002). In dwarf novae with $q < 0.08$, the disk expands beyond the 2:1 resonance radius. A hydrodynamic simulation of the accretion disk in binary system with a low mass ratio showed that two-armed dissipation patterns appear near the 2:1 resonance radius (Lin & Papaloizou 1979). But the mass ratio of BC UMa ($q = 0.13$) is much larger than 0.08 and twice as large as that of WZ Sge ($q = 0.06$; Skidmore et al. 2002). This indicates that the disk does not expand beyond the 2:1 resonance radius.

The duration of the outburst is 11 days and the outburst amplitude is 6 mag for the 2003 superoutburst of BC UMa. But WZ Sge type stars have longer outburst durations (around 1 month) and larger outburst amplitudes (7-8 mag). The short duration and small outburst amplitude suggest that the stored mass in the accretion disk of BC UMa is smaller than that of WZ Sge type stars.

The 2:1 resonance radius in a dwarf nova with $q = 0.13$ is nearly equal to its inner critical Roche lobe radius. So if the accretion disk grows over the tidal truncation radius and near the inner critical Roche lobe radius during the bright superoutbursts, the 2:1 resonance may cause the early superhumps. But because of large mass ratio and small mass of accretion disk, the 2:1 resonance may not occur in BC UMa during the 2003 superoutburst.

According to the refined TTI model (Osaki & Meyer 2003), the accretion disk expands till the tidal truncation radius when a superoutburst with no precursor occurs. Absence of precursors in our observation for the 2003 superoutburst of BC UMa (see Fig.1) indicates that the disk of BC UMa expanded near the tidal truncation radius. Some numerical simulations of the accretion disk showed that tidally induced spiral shocks are excited on the accretion disk (e.g. Makita et al. 2000). Two-armed shocks develop in binary systems with a wide range of mass ratios (e.g. Matsuda et al. 1990). When the disk expands till the tidal truncation radius, strong tidal force acts on the disk material and then the spiral shocks appear on the disk. Our numerical results show that spiral structure on the disk can reproduce the early superhumps even in the dwarf novae with $q = 0.13$. This indicates that early superhumps in BC UMa is caused by the tidally induced spiral shocks on the accretion disk.

5.5. Superhump period change
The superhump period in SU UMa type dwarf novae generally decreases through a superoutburst. The decreasing rate is an order of $\dot{P}_{sh}/P_{sh} \sim 10^{-5}$ (Warner 1985; Patterson et al. 1993). The superhump period decrease was explained by the shrink of the accretion disk as a superoutburst progresses (Patterson et al. 1993). On the other hand, increases of the superhump periods were discovered in WZ Sge type dwarf novae (e.g. Nogami et al. 1997) and some SU UMa type dwarf novae (e.g. Semeniuk et al. 1997). The mechanism of the superhump period increases are not yet well understood.

Uemura et al. (2005) discovered a relation between the presence of precursor and the value of $P_{sh}/P_{sh}$ in TV Crv ($q = 0.16$, Uemura et al. 2005). TV Crv has two different types of superoutbursts; one with a precursor (called type A superoutburst) and the other without (called type B superoutburst). The period change depends on the presence/absence of a precursor. When type A superoutburst occurs, the period derivation is almost zero. On the other hand, in type B superoutburst, the period derivation is positive. The presence of two different types of superoutbursts can be interpreted with the refined thermal-tidal instability model (Osaki & Meyer 2003). In the case of type B superoutbursts, the disk has enough mass and can expand beyond the 3:1 resonance. Hence, the accretion disk still has a large amount of gas beyond the 3:1 resonance radius even a few days after the superoutburst maximum. Uemura et al. (2005) proposed that the growth mode of the eccentricity of the accretion disk continues to be excited when the accretion disk remains larger than the 3:1 resonance radius.

Because the mass ratio is $q = 0.13$ in BC UMa, the tidal truncation radius is enough larger than the 3:1 resonance radius. Thus the accretion disk of BC UMa may expand beyond the 3:1 resonance. The 2003 superoutburst of BC UMa was type B superoutburst (no precursor). The accretion disk still has a large amount of gas beyond the 3:1 resonance. Thus the eccentric mode continued to be excited, so that the changing rate of superhump period was positive.

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Table 5. Nightly decline rate and average magnitude during the 2003 superoutburst

| Date    | Decline rate (mag/day) | Average magnitude |
|---------|------------------------|-------------------|
| 2003 Feb. 1 | 0.09                  | 12.80             |
| Feb. 2  | 0.16                   | 13.00             |
| Feb. 3  | -0.01                  | 13.03             |
| Feb. 5  | 0.10                   | 13.28             |
| Feb. 6  | 0.24                   | 13.47             |
| Feb. 9  | 0.03                   | 13.80             |
| Feb. 11 | -∗                    | 14.08             |
| Feb. 12 | 0.44                   | 14.23             |

* The duration of time-series observation are not long enough.

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