Superhumps and Repetitive Rebrightenings of the WZ Sge-Type Dwarf Nova, EG Cancri

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Abstract

We report on time-resolved photometric observations of the WZ Sge-type dwarf nova, EG Cnc (Huruhata's variable), during its superoutburst in 1996–1997. EG Cnc, after the main superoutburst accompanied with development of superhumps typical of a WZ Sge-type dwarf nova, exhibited a series of six major rebrightenings. During these rebrightenings and the following long fading tail, EG Cnc persistently showed superhumps having a period equal to the superhump period observed during the main superoutburst. The persistent superhumps had a constant superhump flux with respect to the rebrightening phase. These findings suggest the superhumps observed during the rebrightening stage and the fading tail are a “remnant” of usual superhumps, and are not newly triggered by rebrightenings. By comparison with the 1977 outburst of this object and outbursts of other WZ Sge-type dwarf novae, we propose an activity sequence of WZ Sge-type superoutbursts, in which the current outburst of EG Cnc is placed between a single-rebrightening event and distinct outbursts separated by a dip. The post-superoutburst behavior of WZ Sge-type dwarf novae can be understood in the presence of considerable amount of remnant matter behind the cooling front in the outer accretion disk, even after the main superoutburst. We consider the premature quenching of the hot state due to the weak tidal effect under the extreme mass ratio of the WZ Sge-type binary is responsible for the origin of the remnant mass.

Key words: accretion, accretion disks — stars: novae, cataclysmic variables — stars: dwarf novae — stars: individual (EG Cancri)

1. Introduction

WZ Sge-type dwarf novae are an unusual subtype of SU UMa-type dwarf novae (Bailey 1979; Downes, Margon 1981; Patterson et al. 1981; O’Donoghue et al. 1991; Kato et al. 2001b). WZ Sge-type dwarf have properties common to SU UMa-type dwarf novae (Vogt 1980; Warner 1985; Warner 1995) in that they show superoutbursts and superhumps. The most unusual properties of WZ Sge-type dwarf novae are characterized by the extremely low frequency of outbursts (usually once in years to decades), the extremely large outburst amplitude (exceeding 6 mag) and long (in some cases reaching ~100 d before the quiescence is reached) duration, and the lack or extreme deficiency of normal (short) outbursts, which, in ordinary SU UMa-type dwarf novae, occur more frequently than superoutbursts (cf. Warner 1995).  

The origin of such unique characters has been long sought, both from the observational and theoretical sides. Two basic ideas have been historically proposed, just like a descendant from historical discussions on the mechanism of dwarf nova outbursts. One is the mass-transfer instability model, which assumes the outer atmosphere of the extreme low-mass secondary in WZ Sge-type dwarf novae become unstable to the irradiation from the outbursting accretion disk, thus giving rise to an enhanced mass-transfer from the secondary, which leads to a long-lasting superoutburst (the best historical example of this application being Patterson et al. 1981). The other is an application of the disk-instability model, which, with an assumption of very low quiescent viscosity of the accretion disk, can produce the main characteristics of WZ Sge-type dwarf novae, namely the long outburst intervals and the absence of normal outbursts (Smak 1993;
Osaki 1995b). The required quiescent viscosity \( \alpha_C \) to reproduce such long outburst intervals has been shown to be extremely small \( \alpha_C < 0.00005 \); Smak 1993; \( \alpha_C < 0.003 \); Osaki 1995b). These values of the required quiescent viscosity has usually been considered too small for a disk with a developed magneto-rotational instability Balbus, Hawley (1991), although this problem is recently becoming more positively resolved by considering a suppression of this instability in a cold disk with a low electric conductivity Gammie, Menou (1998).

The apparent difficulty with the low quiescent viscosity has historically invoked modifications of the disk-instability model exemplified by the truncated inner disk Lasota et al. (1995). This model supposed a cold steady-state solution during quiescence, and a slight variation in mass-transfer rate was supposed to be the cause of infrequent outbursts. Warner et al. 1996 proposed another possibility of the magnetically truncated disk. Although these truncated disks were successful in reproducing one of the characteristics of WZ Sge-type dwarf novae (the long recurrence time), these models with a high \( \alpha_C \) (~0.01) have been shown by Osaki 1998 to meet difficulties in reproducing long-lasting superoutbursts. Although there have been attempts (e.g. Buat-Ménard, Hameury 2002) to reproduce long outbursts by considering an enhanced mass-transfer during superoutbursts, the resultant light curve is very different from observation. Furthermore, the supposed observational evidence for an enhanced mass-transfer is excluded by later careful analysis (Osaki, Meyer 2003).

In addition to these outburst properties, WZ Sge-type dwarf novae are shown to have other properties common to all members, but are absent in ordinary SU UMa-type dwarf novae. One is the presence of early superhumps during the earliest stage of superoutbursts of WZ Sge-type dwarf novae (cf. Kato 2002). The early superhumps have a stable period almost identical with the orbital period [during the best observed 2001 superoutburst of WZ Sge, the period of the early superhumps was reported to be very slightly shorter than the orbital period (Ishioka et al. 2002)]. This feature was historically first detected and described in WZ Sge itself (Bohusz, Udalski 1979; Patterson et al. 1981), although the origin of this variation was not properly discussed or identified at this time. The common existence of early superhumps among WZ Sge-type dwarf novae has been progressively confirmed: AL Com (Kato et al. 1996; Howell et al. 1996; Patterson et al. 1996; Nogami et al. 1997a; Ishioka et al. 2002), HV Vir (Kato et al. 2001b; Ishioka et al. 2003), RZ Leo (Ishioka et al. 2001), and the main focus of this paper, EG Cnc (Matsumoto, Schmeer 1996; Matsumoto et al. 1998b).

The other is occasional “dips” (transient fading episodes lasting for one to several days) during the later stage of superoutburst, which was first clearly described in the 1978 outburst of WZ Sge (e.g. Ortolani et al. 1980),\(^2\)

\(^{1}\) This feature is also referred to as orbital superhumps (Kato et al. 1996) or outburst orbital hump (Patterson et al. 1998).

\(^{2}\) Richter (1992) was the first to discuss on the systematic tendency of the existence of “dips” in outbursts for stars with infrequent outbursts. This discussion, however, has been considered rather ambiguous mainly from the imaginary interpolation of the data, and from the general lack of knowledge of that time regarding individual dwarf-nova subtypes.

\(^{3}\) The dwarf nova V2176 Cyg, discovered by Hu et al. (1997), probably showed the same course of double superoutbursts (Vannmunster, Sarneckzy 1997; Novák et al. 2001). See also T. Kato, vsnet-alert 1195 (1997), (http://www.kusastro.kyoto-u.ac.jp/vsnet/Mail/alert1195/msg00245.html).

\(^{4}\) (http://www.kusastro.kyoto-u.ac.jp/vsnet/Mail/vsnet-alert/msg00195.html) and (http://www.kusastro.kyoto-u.ac.jp/vsnet/DNe/egcnc.html).

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CCD photometry using telescopes at Osaka Kyoiku University (OKU) and Ouda Station (Ohtani et al. 1992), Kyoto University. The initial results proving the existence of early superhumps ($P = 0.05877$ d) and the subsequent development of usual superhumps ($P = 0.06038$ d) were already discussed in our earlier paper (Matsumoto et al. 1998b). We discuss mainly on its peculiar late-stage phenomenon, particularly focusing on repetitive rebrightenings.

2. The Course of the 1996–1997 Outburst

2.1. Observations

The methods of observation and reduction were the same as in Matsumoto et al. (1998b). The observations at Osaka Kyoiku University were carried out using the 50-cm telescope at the Cassegrain focus (focal length = 6.0m) equipped with an Astronomed EEV 88200 CCD camera (1152 × 790 pixels) and a V-band filter. The observations at Ouda Station were carried out using the 60-cm telescope at the Cassegrain focus (focal length = 4.8m) equipped with a Thomson TH 7882 CCD camera (576 × 384 pixels). We used an interference filter designed to reproduce the Johnson V band. The 2 × 2 on-chip binning mode was used. The frames obtained at Osaka Kyoiku University were reduced using the IRAF.5 The frames obtained at Ouda Station were reduced with a microcomputer-based automatic aperture and PSF photometry packages developed by one of the authors (TK). We used GSC 1948.1452 ($V = 12.82$) as the local comparison star, whose constancy during the observation was confirmed to 0.01 mag using the check star GSC 1948.1193 ($V = 13.86$). Heliocentric correction were applied before the following analysis. Table 1 lists the log of CCD photometry.

2.2. Course of the 1996–1997 Outburst

Figure 1 represents the overall course of the outburst from CCD and visual observations reported to the VSNET, including the available V-band CCD observations, averaged to one to a few points per night. The object was first detected in outburst on 1996 November 30.917 UT at $m_{\text{vis}} \sim 12$ (Schmeer et al. 1996). The last available negative observation was done on November 22.685 UT, giving an upper limit of 13.3 (T. Watanabe, private communication). The early rise was unfortunately not observed due to the interference by the Moon. The outburst thus started some time between November 22 and 30. The existence of early superhumps (Matsumoto et al. 1998b), which are known to rapidly decay within several days of the maximum light of a WZ Sge-type superoutburst, and the recorded maximum brightness ($m_{\text{vis}} = 11.8$) close to that of the 1977 outburst, suggest that the detection by Schmeer was made within a few days of the start of the outburst.

The main superoutburst lasted until December 15 (HJD 2450438), followed by a precipitous decline. The object then faded close to or below $V = 16$. On December 20 (HJD 2450438), the first hint of rebrightening was recorded in the Ouda data. On the next night, the object reached the peak brightness of $V = 13.29$, and soon started fading rapidly. This rebrightening was first considered to be of the rather common phenomenon among short orbital-period SU UMa-type dwarf novae (e.g. V1028 Cyg: Baba et al. 2000, see also Kato et al. 1998), not necessarily confined to WZ Sge-type dwarf novae. The unique property of EG Cnc, however, emerged after this.

The star remained about 3 mag brighter than its quiescence, and again showed a rebrightening 7 days after its first one. Similar rebrightenings repetitively occurred six times in total (counting those exceeding $V = 14$ at maximum), separated by five to eleven days. Table 2 summarizes the observed post-superoutburst rebrightenings. Although there was a suggestion of two rebrightenings after the 1994 superoutburst of another WZ Sge-type candidate, UZ Boo (Kuulkers et al. 1996), a large number of repetitive brightenings had been never observed in any dwarf novae until this outburst of EG Cnc.

Table 2. List of rebrightenings.

| Date of maximum† | Magnitude‡ | $T$ (d)‡ |
|-----------------|-----------|---------|
| 50439           | 13.3      |        |
| 50446           | 13.4      | 7       |
| 50453           | 13.3      | 7       |
| 50458           | 13.2      | 5       |
| 50465           | 13.3      | 7       |
| 50475           | 13.2      | 10      |

*JD=2400000.  
†Maximum visual magnitude.  
‡Time since the preceding rebrightening.

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5 IRAF is distributed by the National Optical Astronomy Observatories, U.S.A.

6 Our own examination of the available data, together with those presented in Kuulkers et al. (1996), led to a less conclusive result regarding the separate occurrence of rebrightenings in UZ Boo. The firm conclusion has been hindered by the insufficient detection threshold, and by the unfavorable visibility condition just before the solar conjunction.


| Date       | Start–End (UT) | N  | Exp(s) | Mean V mag | Obs* |
|------------|----------------|----|--------|------------|------|
| 1996       |                |    |        |            |      |
| December   | 2.625 – 2.791  | 195| 30-90  | 12.38 OKU  |      |
|            | 3.625 – 3.708  | 66 | 60-80  | 12.51 OKU  |      |
|            | 7.679 – 7.811  | 208| 45     | 12.42 Ouda |      |
|            | 8.715 – 8.870  | 176| 60     | 12.48 Ouda |      |
|            | 9.629 – 9.755  | 195| 45     | 12.54 Ouda |      |
|            | 11.635 – 11.870| 345| 45     | 12.76 Ouda |      |
|            | 13.746 – 13.877| 166| 60     | 13.18 Ouda |      |
|            | 14.683 – 14.882| 322| 45     | 14.32 Ouda |      |
|            | 20.666 – 20.860| 112| 120    | 16.13 Ouda |      |
|            | 21.550 – 21.871| 478| 45-60  | 13.29 Ouda |      |
|            | 22.770 – 22.824| 49 | 80-90  | 14.10 Ouda |      |
|            | 23.555 – 23.856| 264| 90     | 15.39 Ouda |      |
|            | 24.555 – 24.870| 277| 90     | 15.92 Ouda |      |
|            | 25.586 – 25.697| 102| 60     | 15.59 Ouda |      |
|            | 26.700 – 26.883| 140| 45-60  | 16.23 Ouda |      |
|            | 27.619 – 27.883| 322| 60     | 16.22 Ouda |      |
|            | 30.600 – 30.871| 320| 45-90  | 15.84 Ouda |      |
|            | 31.519 – 31.745| 195| 90     | 16.30 Ouda |      |
|            | 1997 January   |    |        |            |      |
|            | 2.543 – 2.753  | 144| 90     | 16.25 Ouda |      |
|            | 3.862 – 3.863  | 2  | 120    | 16.35 Ouda |      |
|            | 4.473 – 4.888  | 721| 40-50  | 13.37 Ouda |      |
|            | 6.616 – 6.730  | 72 | 90     | 15.98 Ouda |      |
|            | 10.725 – 10.795| 82 | 60     | 13.92 Ouda |      |
|            | 11.640 – 11.804| 97 | 90     | 15.29 Ouda |      |
|            | 12.614 – 12.755| 78 | 90     | 16.32 Ouda |      |
|            | 13.665 – 13.751| 122| 90     | 16.23 Ouda |      |
|            | 15.647 – 15.811| 137| 90     | 16.27 Ouda |      |
|            | 19.756 – 19.745| 75 | 90     | 16.35 Ouda |      |
|            | 20.501 – 20.843| 284| 90     | 16.22 Ouda |      |
| February   | 1.664 – 1.669  | 5  | 90     | 17.17 Ouda |      |
|            | 3.433 – 3.439  | 5  | 120    | 17.38 Ouda |      |
|            | 5.443 – 5.454  | 6  | 180    | 17.29 Ouda |      |
|            | 27.512 – 27.697| 87 | 90-120 | 17.82 Ouda |      |
|            | 28.490 – 28.617| 61 | 150    | 17.78 Ouda |      |
| March      | 1.619 – 1.727  | 57 | 150    | 17.83 Ouda |      |
|            | 3.589 – 3.726  | 63 | 150    | 17.95 Ouda |      |
|            | 4.634 – 4.727  | 49 | 150    | 17.94 Ouda |      |
|            | 5.522 – 5.680  | 82 | 150    | 18.02 Ouda |      |
|            | 7.631 – 7.639  | 4  | 150    | 17.92 Ouda |      |
|            | 8.493 – 8.675  | 96 | 150    | 18.01 Ouda |      |
|            | 11.486 – 11.616| 58 | 180    | 18.09 Ouda |      |
|            | 28.431 – 28.516| 39 | 150    | 17.94 Ouda |      |
|            | 30.503 – 30.600| 50 | 150    | 18.25 Ouda |      |
|            | 31.469 – 31.604| 61 | 180    | 18.26 Ouda |      |
| April      | 1.435 – 1.602  | 58 | 240    | 18.15 Ouda |      |
|            | 13.455 – 13.463| 5  | 150    | 17.97 Ouda |      |
|            | 14.467 – 14.472| 4  | 150    | 17.73 Ouda |      |
|            | 24.442 – 24.450| 5  | 170    | 18.45 Ouda |      |
|            | 25.459 – 25.463| 3  | 150    | 18.55 Ouda |      |

*OKU: Osaka Kyoiku University, Ouda: Ouda Station (Kyoto University).
3. Superhumps and rebrightenings

3.1. Superhumps

As already described in Matsumoto et al. (1998b), doubly humped early superhumps were observed during the earliest two nights of our observations. Since the raw light curve was not presented in Matsumoto et al. (1998b), we present the light curve in figure 3. Then “textbook” superhumps (often referred to as common superhumps or ordinary superhump when discussing on WZ Sge-type stars) emerged (e.g. figure 4).

Figures 5 and 6 show the comparison of the profiles of these two kinds of superhumps between the recent three well-observed WZ Sge-type dwarf novae (the data of AL Com from Kato et al. 1996, HV Vir from Kato et al. 2001b). The periods (0.05877 d and 0.06038 d) used in folding the data of EG Cnc are our revised estimates, using the PDM (Phase Dispersion Minimization: Stellingwerf 1978) technique to the datasets for 1996 December 2–3 (the stage showing early superhumps) and 1996 December 7–13 (common superhumps), after subtracting the trend of linear decline in each dataset. The new best periods were determined using a minimum determination algorithm developed by one of the authors (TK).

The 1-σ errors for these periods were determined to be 0.00017 and 0.00001 d, respectively, using Fernie’s application to Lafler-Kinman class of statistics (Fernie 1989). Statistical F-tests yielded significance levels of the signals 87% (N = 261) and >99.9% (N = 805), respectively. As is evident from these figures, all of these three WZ Sge-type dwarf novae showed doubly peaked early superhumps, sometimes with a rather complex structure (cf. Kato 2002).

The smallness of the amplitude in EG Cnc probably suggests that this early modulation had already started to decay at the time of observations, or that this system has a low orbital inclination (cf. Osaki, Meyer 2002). The existence of these early superhumps, whose periods are
Fig. 3. Enlargement of the light curve of EG Cnc showing early superhumps.

Fig. 4. Enlargement of the light curve of EG Cnc showing common superhumps.

Fig. 5. Comparison of the profiles of early superhumps of the recent three well-observed WZ Sge-type dwarf novae. Each error bar represents the 1-σ error of each phase bin. All of them showed doubly humped superhumps during the earliest stage of superoutburst.

considered to be very close to the orbital periods (WZ Sge: Bohusz, Udalski 1979; Patterson et al. 1981; Ishioka et al. 2002; Patterson et al. 2002), AL Com: Patterson et al. 1996), is now regarded as an independent criterion for discriminating WZ Sge-type dwarf novae (Kato 2002). The common superhumps appearing later are very similar between different objects, and have almost identical profiles to those of ordinary SU UMa-type dwarf novae (cf. Vogt 1980; Warner 1985).

3.2. Superhumps during the Rebrightening Stage and the Fading Tail

We then analyzed short-term variation during the post-superoutburst rebrightening stage. We first divided the observations during these stages into the following three representative stages: (1) between rebrightenings (faint state between repetitive rebrightenings; data for 1996 December 26-31 and 1997 January 2 were used), (2) rebrightening maximum (around peak brightness of rebrightenings; the 1997 January 4 data were used; note that the unique period identification is improbable because of the short duration of the data segment), and (3) fading
Fig. 6. Comparison of the profiles of common superhumps of the recent three well-observed WZ Sge-type dwarf novae.

tail (1997 February 27 and after). We then removed the long-term trend of each dataset by subtracting a linear fit, and applied the PDM technique to the datasets. The resultant theta diagrams, together with those of the main superoutburst, are shown in figure 7 (the weaker signals arounds 0.0569 and 0.0643 d are one-day aliases, which are not true signals).

Although the result of the second set is less conclusive in terms of period, the common presence of signals (minima in theta) around 0.0603 d suggest\(^7\) that the period of usual (later) superhumps during the main superoutburst persisted throughout the rebrightening phase and the fading tail. Statistical F-tests yielded significance levels of the signals 59% \((N = 1041)\), 87% \((N = 716)\), and 84% \((N = 494)\) for the above three stages, respectively.

Figure 8 shows the phase-averaged light curves of individual data sets. The hump profiles, though amplitudes are very different, resemble each other and that of usual superhumps. This observation of strong superhump modulation after the main superoutburst safely preclude the possibility of the cooling white dwarf as a main source of

\(^7\) The best period determined solely from observations during the fading tail 0.06039(3) d, which agrees with the main superhump period within the estimated errors.
the fading tail of WZ Sge-type dwarf novae, as suggested by Smak (1993).

We further examined the evolution of these persistent superhumps with respect to the rebrightening stages. We used the data between 1996 December 20 and 23, which best covered the rebrightening (the second rebrightening). The resultant phase-averaged light curves are shown in figure 9, which again show the stability of the 0.0603-d persistent superhumps, despite that these persistent superhumps become weaker when the system brightens. Figure 10 shows the time-variation of the pulsed (superhump) flux and the total flux of the object. Both fluxes are shown in magnitude scale corresponding to apparent $V$ magnitudes (i.e. 10% flux modulations at mean magnitude $V = 14.0$ corresponds to a pulsed flux corresponding to $V = 16.5$). Despite the $\sim 3$ mag magnitude brightening of the system during the rebrightening, the pulsed (superhump) flux remained rather constant within a factor of two.

We then estimated the times of superhump maxima by eye examination of the light curve (except at the peak of rebrightening) and from the phase-averaged light curve (around the rebrightening maximum). The values,
Table 3. Times of superhump maxima.

| E | HJD−2450000 | Source | O−C | E | HJD−2450000 | Source | O−C |
|---|-------------|--------|-----|---|-------------|--------|-----|
| -39 | 422.882 | 2 | 0.007 | 128 | 432.959 | 2 | -0.008 |
| -38 | 422.943 | 2 | 0.008 | 129 | 433.020 | 2 | -0.007 |
| -23 | 423.853 | 2 | 0.011 | 159.5 | 434.862 | 2 | -0.008 |
| -7 | 424.809 | 2 | 0.000 | 209.5 | 437.890 | 2 | -0.002 |
| -6 | 424.872 | 2 | 0.003 | 214.5 | 438.188 | 1 | -0.006 |
| -5 | 424.935 | 2 | 0.005 | 215.5 | 438.252 | 1 | -0.003 |
| -4 | 424.993 | 2 | 0.003 | 216.5 | 438.311 | 1 | -0.004 |
| -3 | 425.055 | 2 | 0.004 | 223.5 | 438.728 | 2 | -0.010 |
| 0 | 425.236 | 1 | 0.004 | 230.5 | 439.158 | 1 | -0.003 |
| 1 | 425.299 | 1 | 0.007 | 235.5 | 440.856 | 2 | 0.003 |
| 10 | 425.900 | 2 | 0.003 | 260.5 | 440.974 | 2 | 0.000 |
| 12 | 425.961 | 2 | 0.004 | 261.5 | 441.039 | 2 | 0.005 |
| 13 | 426.022 | 2 | 0.005 | 262.5 | 441.091 | 1 | -0.004 |
| 17 | 426.263 | 1 | 0.004 | 263.5 | 441.163 | 1 | -0.008 |
| 18 | 426.324 | 1 | 0.004 | 264.5 | 441.214 | 1 | -0.002 |
| 25 | 426.743 | 2 | 0.000 | 265.5 | 441.288 | 1 | 0.012 |
| 26 | 426.805 | 2 | 0.002 | 291.5 | 442.855 | 2 | 0.008 |
| 27 | 426.861 | 2 | -0.002 | 307.5 | 443.820 | 2 | 0.006 |
| 28 | 426.923 | 2 | -0.001 | 387.5 | 448.654 | 2 | 0.005 |
| 32 | 427.165 | 1 | -0.001 | 487.5 | 454.700 | 2 | 0.008 |
| 33 | 427.225 | 1 | -0.001 | 503.5 | 455.675 | 2 | 0.017 |
| 41 | 427.707 | 2 | -0.002 | 521.5 | 456.760 | 2 | 0.014 |
| 42 | 427.768 | 2 | -0.002 | 538.5 | 457.787 | 2 | 0.014 |
| 43 | 427.828 | 2 | -0.002 | 586.5 | 460.690 | 2 | 0.016 |
| 44 | 427.892 | 2 | 0.001 | 668.5 | 465.638 | 2 | 0.009 |
| 45 | 427.950 | 2 | -0.001 | 684.5 | 466.599 | 2 | 0.003 |
| 65 | 429.162 | 1 | 0.002 | 720.5 | 468.783 | 2 | 0.011 |
| 67 | 429.282 | 1 | 0.001 | 738.5 | 469.858 | 2 | 0.002 |
| 68 | 429.343 | 1 | 0.002 | 752.5 | 470.704 | 2 | -0.002 |
| 93 | 430.846 | 2 | -0.006 | 853.5 | 476.812 | 2 | 0.003 |
| 94 | 430.909 | 2 | -0.003 | 868.5 | 477.716 | 2 | 0.001 |
| 95 | 430.970 | 2 | -0.003 | 885.5 | 478.740 | 2 | -0.003 |
| 96 | 431.031 | 2 | -0.002 | 934.5 | 481.700 | 2 | -0.004 |
| 100 | 431.272 | 1 | -0.003 | 1064.5 | 489.555 | 2 | -0.005 |
| 101 | 431.330 | 1 | -0.005 | 1083.5 | 490.699 | 2 | -0.009 |
| 104 | 431.510 | 2 | -0.007 | 1148.5 | 494.027 | 2 | -0.009 |
| 106 | 431.630 | 2 | -0.007 | 1513.5 | 516.678 | 2 | -0.015 |
| 107 | 431.691 | 2 | -0.007 | 1544.5 | 518.561 | 2 | -0.005 |
| 108 | 431.753 | 2 | -0.005 | 1613.5 | 522.717 | 2 | -0.019 |
| 110 | 431.870 | 2 | -0.007 | 1762.5 | 531.733 | 2 | -0.007 |
| 111 | 431.932 | 2 | -0.008 | 1794.5 | 533.669 | 2 | -0.005 |
| 112 | 431.992 | 2 | -0.008 | 1811.5 | 534.705 | 2 | 0.004 |
| 116 | 432.233 | 1 | -0.009 | 1845.5 | 536.755 | 2 | -0.001 |
| 117 | 432.295 | 1 | -0.007 | 1853.5 | 537.252 | 2 | 0.013 |
| 118 | 432.355 | 1 | -0.008 | 1861.5 | 537.727 | 2 | 0.004 |
| 125 | 432.780 | 2 | -0.006 | 1877.5 | 538.701 | 2 | 0.011 |
| 126 | 432.842 | 2 | -0.004 | 1886.5 | 539.240 | 2 | 0.007 |
| 127 | 432.900 | 2 | -0.006 |

*E > 159 are late superhumps.
†1. this work, 2. Patterson et al. (1998).
‡1. Against equation (1).
together with the literature values, are listed in table 3, with cycle counts \( E \) starting with \( E = 0 \) at HJD 2450425.236. The accuracy of maximum determination is typically 0.001 d during the main superoutburst, and 0.002 d during the rebrightening stage.

In order to see whether the observed maximum times can be expressed by a continuous period change of a coherent variation, or we need to introduce a discontinuous phase jump (cf. Kato et al. 2003a), we calculated residuals to linear fits to the observed times in both cases assuming the superhumps having no phase jump and a 0.5 phase jump. The latter (0.5 phase jump, or phase reversal) corresponds to the phenomenon what is called late superhumps (Haefner et al. 1979; Vogt 1983; van der Woerd et al. 1988; Hessman et al. 1992).

In the former case, the superhump period was confirmed to show a discontinuous change and larger \( O - C \) values (figure 11), while the latter case showed a more reasonable, smooth period change when we assume \( E > 159 \) maxima are late superhumps. This identification looks reasonable that \( E = 159 \) corresponds to the termination of the main superoutburst, at which a 0.5 phase jump is known to be most frequently observed (e.g. Haefner et al. 1979; Vogt 1983). In table 3, we provide \( E \) numbers assuming the 0.5 phase jump for \( E > 159 \).

A linear regression to the observed superhump times (table 3) yielded the following ephemeris:

\[
\text{HJD(maximum)} = 2450422.8750 + 0.060430E. \quad (1)
\]

The \( O - C \)'s given in table 3 were calculated against this linear regression (see figure 12). The superhump period initially increased during the main superoutburst and the first rebrightening, and the period started to decrease following the main superoutburst. A similar sequence of the superhump period change is frequently observed in other WZ Sge-type dwarf novae or infrequently outbursting SU UMa-type dwarf novae (e.g. Kato et al. 2001a; Ishioka et al. 2003; Uemura et al. 2003).

A quadratic fit to the observed \( O - C \)'s for \( E < 210 \) yielded a definitely positive period derivative of \( \dot{P}/P = +1.7(1) \times 10^{-5} \).

To summarize, the 0.0603-d superhump signal persisted throughout the rebrightening stage and the fading tail. Rebrightness do not seem to affect the profile, superhump phase and pulsed flux. These findings make a clear contrast to what are observed during the initial stages of an ordinary SU UMa-type superoutburst (Warner 1985). The repetitive brightenings less likely represent the start of another superoutburst in spite of accompanying superhumps. Instead, they bear more characteristics of normal outbursts. The persistent superhumps should be rather considered to be the consequence of a persistent eccentricity in the accretion disk, and rebrightening must have occurred independent of these superhumps.
4. Discussion

4.1. Outburst Statistics

As briefly discussed in section 1, no confirmed outburst was observed since the 1977 (discovery) outburst until 1995. In order to estimate the possibility of missed outbursts (owing to the observational gaps) we applied Monte-Carlo simulations on actual observations by the VSOLJ members. The total number of observations was 238, distributing between JD 2445344 and 2450933, spanning ~15 yr. The results were that 52% of simulated superoutbursts (the light curve was assumed to be identical with the present one) and 86% of simulated normal outbursts (maximum magnitude of 13.3 and decay rate of 1 mag d$^{-1}$ assumed) were missed. These probabilities can be considered as upper limits, since the VSOLJ database contains no observations by Huruhata himself, and the object had been equally intensively monitored by a number of skilled visual observers, including P. Schmeer. Though it is still premature to conclude on the previous occurrence of outbursts, the 1-σ lower limit of recurrence times of superoutbursts ($T_s$) and normal outbursts ($T_a$) can be set 4 and 1 yr, respectively, assuming the Poisson statistic of the outburst occurrence. The low number of outbursts has also been confirmed by the absence of a confirmed outburst in the VSNET observations after the 1996–1997 one.

These lower limits of recurrence times are located at the longest end of the distribution of $T_s$ among all SU UMa-type dwarf novae (e.g. Nogami et al. 1997b; Kato et al. 2003b).

4.2. Comparison with the 1977 Outburst

According to Huruhata (1983), the 1977 outburst started between 1977 November 9.8 and 12.8 UT. The brightest measured magnitude was 11.9 on 1977 November 12.8. Since the photometric sequence of the comparison stars by Huruhata closely matches the present scale (M. Huruhata, private communication), we can safely compare Huruhata’s values with our modern V-magnitudes. The object declined to 12.4 mag on November 22.8 UT, 10.9 d after the initial detection. The duration of the outburst indicates that the 1977 outburst was also a superoutburst. After an observational gap of 11 d, Huruhata (1983) further positively detected the variable on three films taken in two separate occasions in early December, giving estimates ~14.0 mag 21–22 d and 25 d after the initial detection.

Considering that the duration of the main superoutburst in 1996 did not exceed 23 d, even taking the observational gap into account, some of these December positive detections may be interpreted as a hint of rebrightenings, or a part of a second (super)outburst. The main difference from the 1996–1997 outburst is the faintness (14.0 mag) during this stage. It is, however, clear no evidence was found regarding repeated rebrightenings as in 1996–1997, and the 1977 outburst seems to more resemble the 1913 and 1946 outbursts of WZ Sge. It would be important to note the same star at times exhibit different patterns of activity.

4.3. Orbital Period

Based on our own analysis, we propose the period of early superhumps ($P = 0.05877$ d) to be the candidate orbital period. Patterson et al. (1998) alternatively proposed a different (0.05997 d) period, which is extremely close to the superhump period. We suspect that this period identification suffered from ambiguity from two reasons. The spectroscopic period by Patterson et al. (1998) was not directly from radial velocity variations but from a periodic variation of the asymmetry of the profile. We must note that this method of period determination could have suffered from the remaining eccentricity in the disk, as would be naturally expected from the long persistence of the superhumps. The photometric method was even more ambiguous; our own analysis of the early-stage variations gave a different result (Matsumoto et al. 1998b), which was also favored by quiescent photometry Matsumoto et al. (1998a). We absolutely need an independent determination from true radial velocity observation before concluding on the true identification of the orbital period. In this paper, we adopt our own identification ($P = 0.05877$ d) in the following discussion.

4.4. EG Cnc as a WZ Sge-Type Dwarf Nova

As Matsumoto et al. (1998b) pointed out, the optical behavior of the present outburst bears all the characteristics common to those of known WZ Sge-type dwarf novae. Table 4 summarizes the comparison of the observed properties between these objects. The late-stage behavior of superoutbursts has a wide range of diversity between objects, and even between different outbursts of the same object, in spite of the marked similarity of the general light curve and the time evolution of superhumps during the early stage of outbursts.

Phenomenologically, the superoutbursts of WZ Sge-type dwarf novae seem to make a continuous sequence ranging from superoutburst without noticeable rebrightenings (WZ Sge in 1913 and 1946), ones accompanied by a single rebrightening (EG Cnc in 1977; possibly HV Vir in 1992, cf. Kato et al. 2001b), double to multiple rebrightenings (EG Cnc in 1996–1997; UZ Boo in 1994: Kuulkers et al. 1996), and to two distinct outbursts separated by a “dip” (WZ Sge in 1978–1979, 2001; AL Com in 1961, 1995 and 2001), some of which may be double superoutbursts.

A similar idea of a continuum of types of outbursts of large-amplitude, infrequently outbursted dwarf novae (Tremendous Outburst Amplitude Dwarf Novae or TOADs: Howell et al. 1995a) was discussed in Howell et al. (1995b), who mainly treated the diversity of duration and brightness of superoutbursts in these systems. An ideal model of WZ Sge-type dwarf novae should reproduce this wide and continuous variety of outburst activity by changing some input parameters.
Table 4. Comparison of WZ Sge-type dwarf novae.

| Year of outbursts                  | EG Cnc* | AL Com† | HV Vir‡ | WZ Sge§ |
|-----------------------------------|---------|---------|---------|---------|
|                                   | 1977, 1996 | 1892, 1941, 1961 | 1929, 1939, 1970, 1981, 1992 | 1913, 1946, 1978, 1995, 2001 |
| Maximum magnitude                 | 11.9    | 12.0    | 11.5    | 7.0     |
| Minimum magnitude                 | 19.1    | 20.5    | 19.1    | 15.5    |
| Outburst amplitude (mag)          | 7.2     | 8.5     | 7.6     | 8.5     |
| Supercycle (yr)                   | 19?     | 10–20   | 10:     | 23–33   |
| Normal outbursts?                 | no?     | yes     | yes?    | no      |
| Superoutburst duration (d)        | >100    | >70     | >50     | 130     |
| Long fading tail                  | yes     | probably yes | yes    | yes    |
| Type(s) of rebrightening          | repeated short outbursts | superoutburst-like | probably yes (short?) | long (similar to AL Com) |
| Early superhumps                  | yes     | yes     | yes     | yes     |
| Period of early superhumps (d)    | 0.05877 | 0.05666 | 0.05708 | 0.05667 |
| Period of common superhumps (d)   | 0.06038 | 0.05722 | 0.05820 | 0.05721 |
| Superhump excess (%)              | 2.7     | 1.0     | 2.0     | 1.0     |
| Quiescent humps                   | ?       | double  | ?       | double+eclipses |

*This paper.
†Kato et al. (1996); Patterson et al. (1996); Nogami et al. (1997a).
‡Kato et al. (2001b); Ishioka et al. (2003); Leibowitz et al. (1994).
§Ishioka et al. (2002); Patterson et al. (2002); R. Ishioka et al. in preparation.
§§Calculated from the periods of early superhumps and common superhumps except for WZ Sge.

4.5. Are rebrightenings inside-out-type or outside-in-type outbursts?

In observationally interpreting the rebrightening phenomenon, discrimination of inside-out-type (heating wave originating from the inner accretion disk), or outside-in-type outbursts (Cannizzo et al. 1986; the terminology corresponding to type B and type A outbursts in Smak 1984), is potentially important: different parameters of the disk instability model predict different origins of the instability (e.g. Osaki 1996; Cannizzo 1996), which may provide a potential observational diagnostic to the underlying mechanisms.

A close examination of the light curve of each rebrightening revealed the presence of five rebrightenings which showed a rapid rise and one which showed a much slower rise. Figure 13 demonstrates enlarged light curves of each rebrightening. The first five rebrightenings showed rather common outburst behavior: an abrupt rise and a 3-mag fade in 3 d. The time needed for the rise is well confined to less than 0.4 d from the observations of the fourth and fifth rebrightenings. The sixth rebrightening is different, accompanied with a slow rise lasting more than a day before reaching maximum.

A similar phenomenon, but with a lesser amplitude, was also observed in time-resolved CCD photometry of the first rebrightening (figures 14 and 15). A fast-rising type rebrightening occurred around HJD 2450439, while a more slowly rising brightening followed at around HJD 2450443 (not counted as one of six major rebrightenings because of its faintness) shows much a slower rise and faint peak brightness (the faintness of the peak was also confirmed from the subsequent CCD observations reported to the VSNET). Although whether or not this small brightening can be treated in the same context of other (major) rebrightenings is an open question, the slow rising stage of this small brightening was more analogous to the sixth rebrightening, possibly implying the common underlying mechanism.

The existence of two types (fast-rising and slow-rising) of rebrightenings may represent the coexistence of inside-out-type and outside-in-type outbursts, more usual ones being the faster outside-in-type. The sixth rebrightening may be related to the former, “slow” rebrightening.

4.6. On the Interpretation of Rebrightenings

Since the disk instability theory predicts the cycle length of normal outbursts, for a certain range of parameters, is roughly inversely proportional to the mass-transfer rate (e.g. Ichikawa, Osaki 1994), it would be natural to attribute the increased outburst activity after the main superoutburst to an enhanced mass-transfer somehow caused by the superoutburst. Since the measured short outburst intervals (5–10 d) are one of the shortest even among frequently outbursting SU UMa-type dwarf novae (cf. Warner 1995; Nogami et al. 1997b), this interpretation would require (assuming no change in other parameters before and after the superoutburst) a mass-

We regard this phenomenon as a kind of rebrightening, not a result of flickering, since the duration (~1 d) of the phenomenon, as well as the continued slow rising for 7 hr, was much longer than the superhump period.
Fig. 13. Enlarged light curves of each rebrightening. The data are from VSNET visual observations and V-band observations from this work. The first five rebrightenings seem to show rather common outburst behavior: an abrupt rise and a 3-mag fade in three days. The time needed for the rise is well confined to less than 0.4 day from the 4th and 5th rebrightenings. The sixth rebrightening seems to be different, showing a slow rising trend more than a day before reaching maximum.

Fig. 14. Light curve showing the first rebrightening (HJD 2450439) and an immediately following small rebrightening (HJD 2450443).

Fig. 15. Enlarged light curve of the first rebrightening and a small rebrightening immediately following the first rebrightening. The rebrightening occurring around HJD 2450439 represents a “fast” rebrightening, while the small one (not counted as one of six major rebrightenings because of the faintness) occurring around HJD 2450443 shows a much slower rise and fainter peak brightness.

Transfer rate something between ordinary SU UMa-type dwarf novae and ER UMa stars (Kato, Kunjaya 1995; Robertson et al. 1995; Misselt, Shafter 1995; Nogami et al. 1995; Kato et al. 1999). The ER UMa stars are peculiar SU UMa-type stars which are proposed to have mass-transfer rates several times higher than in ordinary SU UMa-type dwarf novae (Osaki 1995a; Osaki 1995c).

Although the initial pattern and amplitudes of rebrightenings of EG Cnc closely resembled those of ER UMa stars, the enhanced mass-transfer and the enhanced hot spot brightness would not solely by themselves explain the later behavior, since the brightness of the system was shown to decrease gradually (see figure 1), even after the sixth rebrightening. This smooth decrease in brightness should require smoothly decreasing frequency of rebrightenings, which is contrary to the observation if the system brightness actually reflects the brightness of the hot spot or the mass-transfer rate.

Osaki et al. (1997) instead proposed a model to reproduce these rebrightenings, by assuming increased quiescent viscosity after the main superoutburst. This model, by adjusting the time dependence of the quiescent viscosity and its radial dependence through the disk, could at least reproduce the observed rebrightenings without an assumption of an enhanced mass-transfer.

Osaki et al. (1997) originally suggested that such increased quiescent viscosity is somehow related to the turbulent motion in the disk resulting from the tidal instability. They also proposed the extremely low mass-transfer rate in WZ Sge-type dwarf novae would be responsible for the slow circularization of the eccentric disk, leading to the slow decrease in the quiescent viscosity after the outburst and multiple rebrightenings never seen in usual dwarf no-
The underlying physical mechanism for the decay of the disk viscosity has been recently proposed by Osaki et al. (2001) by considering a decay of MHD turbulence under the condition of the low magnetic Reynolds numbers in the cold accretion disk (Gammie, Menou 1998).

A potential difficulty of this model (Osaki et al. 2001) is that the disk after the main superoutburst would not expand enough to trigger a second superoutburst as reported in AL Com (Nogami et al. 1997a). [Note that the outburst of AL Com after the “dip” was not composed of recurring small rebrightenings, as observed in the 2001 superoutburst of WZ Sge.]

Howell et al. (1996) and Kuulkers et al. (1996) proposed the idea that some material can be piled up just behind the cooling wave, causing it to be reflected as a heating wave, which they considered to cause an additional brightening.

Regarding the reason why such a condition is predominantly met in WZ Sge-type dwarf novae, or TOADs, Kuulkers et al. (1996) suggested that the stored disk material survives being depleted by accretion, owing to the low occurrence of normal outbursts in these systems. However, the degree of depletion of the disk mass during one supercycle is rather expected to affect the initial condition of superoutburst, but not necessarily that of the late-stage condition of superoutburst. As Osaki (1995b) has shown, the late stage of WZ Sge-type superoutbursts is expected to follow the same time-evolution as those of usual dwarf novae. The initial excessive matter is effectively accreted on a viscous time-scale; it is not still convincingly clear how the low occurrence of normal outbursts (or its precondition) naturally explains the unique late-stage phenomenon in WZ Sge-type superoutbursts. Though the discussion was more limited to SXTs, Cannizzo et al. (1995) could reproduce a similar pattern of rebrightenings by modifying the radial dependence of the α viscosity. This model, however, would suffer, as in the model proposed by Osaki et al. (1997), from the depletion of high-angular momentum matter necessary to invoke an immediate second superoutburst.

We alternately consider a possibility that the matter in the outer accretion disk may be left from being accreted during the main superoutburst, by way of the premature quenching of the hot state in the outer disk. We propose the weaker turbulence and resultant heating caused by the weaker tidal instability in the outer disk than in ordinary SU UMa-type dwarf novae can be responsible for this possibility. This weaker tidal torque can be reasonably achieved under conditions of extreme mass ratios in WZ Sge-type dwarf novae, which can hold the 3:1 resonance radius well inside the Roche lobe of the primary, or the maximum dimension of the expanded disk. This possibility was originally proposed in 1997 by Kato et al. 1997 and Kato et al. (1998), which was further explored by Hellier (2001) and Osaki et al. (2001). The unusual presence of Na D absorption line (Patterson et al. 1998) could be attributed to the cool reservoir in the disk required by this interpretation.

Superoutbursts in ordinary SU UMa-type dwarf novae are believed to be triggered when the disk radius, upon the ignition of the outburst, first reaches the radius of the 3:1 resonance during the normally outbursting cycle (Osaki 1989). The eccentricity wave (Lubow 1992) caused by the tidal instability should naturally start in the outermost region of the disk, and should propagate inward, accounting for the general decrease in the superhump period during superoutbursts of ordinary SU UMa-type dwarf novae (Lubow 1992).

In WZ Sge-type dwarf novae, however, the absence of normal outbursts may lead to an accumulation of a large amount of matter, leading to more violent expansion of the disk during superoutburst enabling the disk expanding beyond the 3:1 resonance. The above picture then predicts the eccentricity wave can propagate outward. The presence of positive period derivatives of superhump periods in some WZ Sge-type dwarf novae and infrequently outbursting, large-amplitude SU UMa-type dwarf novae (e.g. AL Com: Nogami et al. 1997a; V1028 Cyg: Baba et al. 2000; SW UMa: Semenik et al. 1997; Nogami et al. 1998; HV Vir: Ishioka et al. 2003; see also Kato et al. 2003c for a recent summary of period derivatives in SU UMa-type dwarf novae) would strengthen the idea of the relative difference in the location of generation and propagation of tidal instability between WZ Sge-type and ordinary SU UMa-type dwarf novae. The extremely low mass-ratios in WZ Sge-type dwarf novae could play the key role in generating tidal instability well inside the entire disk radius.

5. Summary

We obtained extensive CCD photometry during the 1996–1997 superoutburst of EG Cnc. This outburst showed an unprecedented series of six major rebrightenings spaced by 5–10 d. During this rebrightening stage and the following slow fading tail, photometric modulations with a period of 0.0603 d persisted, which is equal to the superhump period observed in the latter course of the main superoutburst. We suggest that the superhumps observed during the rebrightening stage and the fading tail are a “remnant” of usual superhumps, and are not a result of rebrightenings. By comparison with the 1977 outburst of this object and outbursts of other WZ Sge-type dwarf novae, we propose an activity sequence of WZ Sge-type superoutbursts, in which the current outburst of EG Cnc is placed between a single-rebrightening event and distinct outbursts separated by a dip. We propose a new potential explanation of post-superoutburst behavior of the WZ Sge-type dwarf novae, by considering the effect of extreme mass ratios in these binaries on the generation
and propagation of the tidal instability.

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