SDSS J080434.20+510349.2: Eclipsing WZ Sge-Type Dwarf Nova with Multiple Rebrightenings

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Abstract

We observed the 2006 superoutburst of SDSS J080434.20+510349.2 during its plateau phase, rebrightening phase, and post-superoutburst final decline. We found that this object is a grazing eclipsing system with a period of 0.0590048(2)d. Well-defined eclipses were only observed during the late stage of the superoutburst plateau and the depth decreased during the subsequent stages. We determined the superhump period during the superoutburst plateau to be 0.059539(11)d, giving a fractional superhump excess of 0.90(2)%. During the rebrightening and post-superoutburst phases, persisting superhumps have periods longer than those of superhumps during the plateau phase: 0.059632(6)d during the rebrightening phase and 0.05969(4)d during the final fading. This phenomenon is very well in line with the previously known long-period “late superhumps” in GW Lib, V455 And, and WZ Sge. The amplitudes of orbital humps between different states of rebrightenings suggest that these humps do not arise from the classical hot spot, but are more likely to be a result of projection effect in a high-inclination system. There was no clear evidence for an enhanced hot spot during the rebrightening phase. We also studied previously reported “mini-outbursts” in the quiescent state, and found evidence that superhumps were transiently excited during these mini-outbursts. The presence of grazing eclipses and distinct multiple rebrightenings in SDSS J080434.20+510349.2 would provide a unique opportunity for understanding the mechanism of rebrightenings in WZ Sge-type dwarf novae.

Key words: accretion, accretion disks — stars: dwarf novae — stars: individual (SDSS J080434.20+510349.2) — stars: novae, cataclysmic variables

1. Introduction

Dwarf novae (DNe) are a class of cataclysmic variables (CVs), which are close binary systems consisting of a white dwarf and a red-dwarf secondary transferring matter via Roche-lobe overflow. SU UMa-type dwarf novae are a class of DNe exhibiting superhumps during their long, bright outbursts (superoutbursts), which is believed to be a result of tidal...
instabilities caused by the 3:1 orbital resonance in the accretion disk [see e.g., Vogt (1980); Warner (1985) for basic observational properties; see Osaki (1996) for a theoretical review].

WZ Sge-type dwarf novae (see e.g., Bailey 1979; Downes 1990; Kato et al. 2001) are a subgroup of dwarf novae characterized by large-amplitude (typically ~ 8 mag) superoutbursts with long (typically ~ 10 yr) recurrence times. Although it has been proposed that the properties of outbursts in WZ Sge-type dwarf novae can be basically understood within the framework of the thermal–tidal disk-instability model (see e.g., Osaki 1989) without requiring an enhanced mass-transfer (Osaki 1995; Osaki & Meyer 2003), the existence of enhanced mass-transfer still remains controversial (cf. Patterson et al. 2002; Steeghs et al. 2001; Hameury et al. 1997).

WZ Sge-type dwarf novae are known to show several unusual properties during outburst, which are rarely seen in ordinary SU UMa-type dwarf novae. They include double-wave early superhumps with periods close to the orbital periods during the early stage of superoutbursts (Kato 2002), which are considered to be a result of 2:1 resonance (Osaki & Meyer 2002). The frequent existence of post-superoutburst rebrightenings is also characteristic of WZ Sge-type dwarf novae. Imada et al. (2006) classified these rebrightenings by their morphology (see also the activity sequence in Kato et al. 2004). Type-A superoutbursts (long-lasting distinct plateau after the termination of the main superoutburst) and Type-B superoutbursts (superoutburst followed by distinct multiple rebrightenings) are unique to WZ Sge-type dwarf novae. Up to now, several objects are known to have shown Type-B superoutbursts at least once: UZ Boo, EG Cnc (Patterson et al. 1998a; Kato et al. 2004), AL Com (Uemura et al. 2008), 1RXS J023238.8–0839.1, OT J074727.6+1050349.2 (hereafter SDSS J0804) was discovered by Szkody et al. (2006). The first-ever recorded, 2006 outburst was detected by E. Pavlenko (vsnet-alert 8874). Pavlenko et al. (2007) and Shears et al. (2007) reported the detection of superhumps, and discussed the WZ Sge-type nature of this object. The object is renowned for its eleven post-superoutburst rebrightenings (Pavlenko et al. 2007; for details of the light curve of the rebrightenings, see e.g., Pavlenko et al. 2009; subsection 3.1 in this paper), surpassing the record of six rebrightenings in EG Cnc. Zharikov et al. (2008) reported the detection of two “mini-outbursts” one year after the 2006 superoutburst, and reported a double-humped quiescent light curve having a period of 0.05900 d. Pavlenko (2009) reported that a 12.6-min periodicity, which can be attributed to pulsations of the white dwarf, emerged during the interval 2006–2008.

2. Observation and Data Analysis

The observations are composed of those obtained at Crimean Astrophysical Observatory (CrAO in table 1) using the 2.6-m telescope and FLI 1001E CCD (BJD 2453799, March 4 and BJD 2453856–2453857, Apr 30–May 1), the 60-cm telescope and an Ap47p CCD (BJD 2453812–2453813, March 17 and 18) during rebrightening phase, the 38-cm telescope and an ST-7 CCD during the final fading (BJD 2453816–2453828, April 21–May 13, except April 30 and May 1), and observations during the rebrightening and post-superoutburst phases: Maehara (Mh in table 1) using a 25-cm telescope and an ST-7 XME CCD camera and Nakajima (Nh) using a 25-cm telescope and a CV-04 CCD camera, Shugarov (Shu) using a 70-cm telescope and an Ap47p CCD at Sternberg Astronomical Institute (SAI), Moscow, and at Terskol, Caucasus using a 60-cm telescope and an S2C CCD. The details of CrAO, SAI, and Terskol observations will be given by E. Pavlenko et al. (in preparation). Maehara and Nakajima used a common comparison star, TYC2 3414.1011.1 (V = 11.30, B – V = +0.44), and performed aperture photometry with IRAF1 and FitsPhoto 4.1.2 respectively, after standard flat-fielding and dark subtractions. The exposure times of both observers were 30 s. Brady (BXS) used a 40-cm telescope and an ST8XME CCD. The exposure time was 180 s. We also incorporated observations by P. de Ponthière (DPP), G. Klingenberg (GK), and J. Shears (JSh) published in Shears et al. (2007). The times of observations were converted to Barycentric Julian Dates (BJD) before the analysis.

In measuring the times of (super)humps, we first corrected for systematic differences between the observers, and then subtracted the general trend by fitting low-order (typically three to five) polynomials for the superoutburst plateau and the final fading phase. For the complex rebrightening phase, we subdivided the light curve into segments of ~ 1-d duration, and subtracted the trend by fitting third-order polynomials to individual segments that had sufficient numbers of data points.

We measured the times of superhump maxima by numerically fitting a template superhump light curve around the times of observed maxima. This fitting methods have been proven to give three-times the precision compared to eye estimates. We did not use the full superhump cycle, but used phases −0.3 to 0.3 in order to pick the features of the hump maxima. We used a phase-averaged (and spline-interpolated) mean light curve of superhumps of GW Lib during the 2007 superoutburst (A. Imada et al., in preparation; Kato et al. 2008) as the template superhump.

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

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

| Start* | End*   | Mean magnitude | Error  | $N^\dagger$ | Observer/Site | Filter$^\ddagger$ |
|--------|--------|----------------|--------|-------------|---------------|-------------------|
| 53799.3370 | 53799.4855 | 13.089 | 0.003 | 387 | CrAO | V |
| 53800.3022 | 53800.6019 | 13.157 | 0.002 | 714 | DPP | C |
| 53800.3022 | 53800.6936 | 13.226 | 0.003 | 262 | GK | C |
| 53800.3270 | 53800.4053 | 13.180 | 0.004 | 100 | JSh | C |
| 53800.5040 | 53800.7613 | 13.487 | 0.004 | 80 | BXS | C |
| 53800.7085 | 53800.7109 | 13.385 | 0.021 | 2 | BXS | C |
| 53801.3282 | 53801.6449 | 13.506 | 0.004 | 547 | DPP | C |
| 53801.5080 | 53801.7985 | 13.970 | 0.010 | 136 | BXS | C |
| 53801.5080 | 53801.6936 | 15.064 | 0.016 | 10 | BXS | C |
| 53803.0274 | 53803.0671 | 15.012 | 0.025 | 29 | Njh | C |
| 53804.1999 | 53804.2779 | 15.266 | 0.021 | 8 | Shu | R |
| 53805.1897 | 53805.1897 | 15.537 | — | 1 | Shu | R |
| 53806.5063 | 53806.5063 | 13.88 | — | 1 | BXS | C |
| 53808.1013 | 53808.1677 | 14.683 | 0.007 | 168 | Mhh | C |
| 53809.0442 | 53809.2232 | 15.026 | 0.005 | 427 | Mhh | C |
| 53810.0594 | 53810.2185 | 13.491 | 0.002 | 504 | Mhh | C |
| 53811.5575 | 53811.5575 | 15.10 | — | 1 | BXS | C |
| 53812.0013 | 53812.1722 | 14.197 | 0.013 | 186 | Mhh | C |
| 53812.2004 | 53812.4951 | 16.373 | 0.012 | 65 | CrAO | R |
| 53812.5107 | 53812.5107 | 13.77 | — | 1 | BXS | C |
| 53813.2053 | 53813.2489 | 14.205 | 0.023 | 9 | CrAO | R |
| 53813.9362 | 53814.1537 | 14.720 | 0.003 | 544 | Mhh | C |
| 53814.9190 | 53815.1756 | 13.481 | 0.003 | 464 | Njh | C |
| 53815.1552 | 53815.2421 | 13.436 | 0.002 | 301 | Mhh | C |
| 53815.5159 | 53815.7091 | 14.048 | 0.011 | 40 | BXS | C |
| 53816.0380 | 53816.2360 | 14.157 | 0.005 | 469 | Mhh | C |
| 53816.0967 | 53816.2028 | 14.207 | 0.008 | 99 | Njh | C |
| 53816.2489 | 53816.4769 | 14.609 | 0.008 | 98 | CrAO | R |
| 53817.2745 | 53817.3938 | 14.725 | 0.014 | 55 | CrAO | R |
| 53817.9192 | 53818.1567 | 13.687 | 0.005 | 275 | Njh | C |
| 53818.9198 | 53819.1555 | 14.719 | 0.006 | 425 | Njh | C |
| 53819.4225 | 53819.4487 | 15.039 | 0.014 | 12 | CrAO | R |
| 53819.9167 | 53820.1485 | 13.471 | 0.003 | 396 | Njh | C |
| 53821.2211 | 53821.4482 | 14.650 | 0.006 | 106 | CrAO | R |
| 53821.6416 | 53821.6416 | 15.14 | — | 1 | BXS | C |
| 53822.2184 | 53822.3824 | 14.868 | 0.011 | 77 | CrAO | R |
| 53823.2288 | 53823.4449 | 14.262 | 0.009 | 94 | CrAO | R |
| 53823.9468 | 53824.1574 | 14.786 | 0.008 | 341 | Njh | C |
| 53823.9987 | 53824.1651 | 14.727 | 0.005 | 420 | Mhh | C |
| 53824.3207 | 53824.3207 | 14.945 | — | 1 | Terskol | R |
| 53824.7377 | 53824.7377 | 15.16 | — | 1 | BXS | C |
| 53824.9737 | 53824.9960 | 13.512 | 0.015 | 25 | Njh | C |
| 53825.1800 | 53825.2558 | 13.506 | 0.004 | 183 | Mhh | C |
| 53825.9262 | 53826.1050 | 14.203 | 0.005 | 325 | Njh | C |
| 53826.0139 | 53826.2084 | 14.252 | 0.008 | 323 | Mhh | C |
| 53826.2293 | 53826.4553 | 14.776 | 0.008 | 104 | Terskol | R |
| 53827.2101 | 53827.2689 | 13.877 | 0.003 | 70 | Terskol | R |
| 53827.9254 | 53828.0650 | 14.091 | 0.012 | 36 | Njh | C |
| 53828.0679 | 53828.2160 | 14.245 | 0.005 | 385 | Mhh | C |
| 53828.2510 | 53828.4373 | 14.684 | 0.008 | 83 | CrAO | R |
| 53828.5254 | 53828.5254 | 14.95 | — | 1 | BXS | C |
| 53828.9242 | 53828.9905 | 15.111 | 0.012 | 119 | Njh | C |
| 53829.2372 | 53829.4310 | 15.162 | 0.011 | 91 | CrAO | R |
Table 1. (Continued)

| Start*   | End*   | Mean magnitude | Error  | N † | Observer/Site | Filter‡ |
|----------|--------|----------------|--------|-----|---------------|---------|
| 53830.2624 | 53830.4592 | 14.228         | 0.008  | 109 | CrAO          | R       |
| 53830.9355 | 53830.9553 | 14.610         | 0.031  | 14  | Njh           | C       |
| 53831.2388 | 53831.5057 | 15.289         | 0.017  | 121 | CrAO          | R       |
| 53832.2429 | 53832.3537 | 15.773         | 0.007  | 148 | Terskol       | R       |
| 53832.9323 | 53833.1366 | 13.783         | 0.004  | 370 | Njh           | C       |
| 53833.9342 | 53834.1025 | 14.938         | 0.008  | 535 | Mhh           | C       |
| 53836.2744 | 53836.3005 | 15.315         | 0.057  | 12  | CrAO          | R       |
| 53836.7084 | 53836.7084 | 15.93          | —      | 1   | BXS           | C       |
| 53839.0047 | 53839.0103 | 15.813         | 0.030  | 8   | Njh           | C       |
| 53839.2298 | 53839.4737 | 15.678         | 0.025  | 96  | CrAO          | R       |
| 53841.5345 | 53841.5345 | 16.00          | —      | 1   | BXS           | C       |
| 53842.3025 | 53842.3111 | 15.718         | 0.053  | 5   | CrAO          | R       |
| 53845.5435 | 53845.5435 | 16.495         | 0.292  | 2   | BXS           | C       |
| 53847.2571 | 53847.2878 | 15.952         | 0.032  | 14  | CrAO          | R       |
| 53848.2584 | 53848.4358 | 15.975         | 0.011  | 82  | CrAO          | R       |
| 53849.2920 | 53849.3139 | 16.050         | 0.015  | 11  | CrAO          | R       |
| 53850.2500 | 53850.4200 | 16.104         | 0.012  | 78  | CrAO          | R       |
| 53851.2624 | 53851.2798 | 16.119         | 0.090  | 8   | CrAO          | R       |
| 53852.5674 | 53852.5674 | 16.55          | —      | 1   | BXS           | C       |
| 53852.5888 | 53852.5888 | 16.36          | —      | 1   | BXS           | C       |
| 53853.2874 | 53853.4418 | 16.151         | 0.017  | 63  | CrAO          | R       |
| 53854.2914 | 53854.4387 | 16.198         | 0.013  | 68  | CrAO          | R       |
| 53855.2543 | 53855.4105 | 16.211         | 0.014  | 74  | CrAO          | R       |
| 53856.2632 | 53856.4095 | 16.223         | 0.009  | 112 | CrAO          | V       |
| 53856.5491 | 53856.5491 | 16.67          | —      | 1   | BXS           | C       |
| 53857.2975 | 53857.3700 | 16.246         | 0.011  | 64  | CrAO          | V       |
| 53865.3793 | 53865.3962 | 16.340         | 0.063  | 6   | CrAO          | R       |
| 53866.3781 | 53866.3893 | 16.336         | 0.060  | 6   | CrAO          | R       |
| 53869.4136 | 53869.4342 | 16.481         | 0.032  | 10  | CrAO          | R       |

* BJD—2400000.
† Number of observations.
‡ C indicates unfiltered observations.

template, which is one of the best-sampled objects among all SU UMa-type dwarf novae, and has the least scatter. Although the actual superhumps in SDSS J0804 may be slightly different from the superhump profile of GW Lib, this difference has been confirmed to insignificantly affect the period analysis.

The summary of observations, with mean magnitudes, are listed in table 1.

3. Results and Discussions

3.1. Rebrightenings

SDSS J0804 exhibited eleven rebrightenings (table 2). During the rebrightenings, hump features (a combination of superhumps and orbital humps, see subsection 3.5 for details) were clearly observed (figure 1). As discussed in Pavlenko et al. (2009), these rebrightenings showed a faster rise and a slower decline, suggesting that they are outside-in type, dwarf nova-type outbursts. The overall feature of the rebrightenings was similar to those of EG Cnc, although the mean intervals of rebrightenings was much shorter in SDSS J0804 [2.6(4) d] than in EG Cnc [6.9(3) d].

Table 2. Rebrightenings of SDSS J0804.

| BJD—2400000 | Magnitude |
|-------------|-----------|
| 53806.5*    | 13.9      |
| 53810.1     | 13.4      |
| 53812.4     | 13.5      |
| 53815.2     | 13.4      |
| 53817.9     | 13.6      |
| 53820.0     | 13.4      |
| 53823.2†    | 14.1      |
| 53825.2     | 13.5      |
| 53827.2†    | 13.9      |
| 53830.2†    | 14.1      |
| 53832.9     | 13.7      |

* Single observation.
† Maximum not observed.

3.2. Orbital Period

We analyzed the quiescent data in Zharkov et al. (2008). A Phase Dispersion Minimization (PDM: Stellingwerf 1978) period analysis of the de-trended data clearly indicates the
Fig. 1. Light curve of SDSS J0804 during the rebrightening phase. (Upper) Overall light curve. Eleven rebrightenings are clearly visible. (Lower) Enlarged light curves showing hump features. The numbers in each panels indicate truncated BJD (BJD–2453800). The intervals of ticks at the lowest panels are 0.2 d.

presence of a single very stable period of 0.0590016(4)d (figure 2). We basically confirmed the results in Zharikov et al. (2008) and identified this period to be the orbital period ($P_{\text{orb}}$).

We then analyzed the stage of rebrightenings after removing their global trend. A period analysis yielded a stable period of 0.059006(2)d and a broader signal arising from super-humps with periods of around 0.0597–0.0598d (figure 3). The phase-averaged profile shows a strong hump and a shallow dip-like fading following the hump. By analogy with WZ Sge (Patterson et al. 2002), we identified this dip-like fading as
shallow eclipses. We measured the epoch of the photometric minimum of BJD 2453820.3705(5) based on the phase-averaged light curve. The system does not appear to show a distinct sharp eclipse of the hot spot, as in WZ Sge (cf. Patterson et al. 2002).

By using epochs of eclipses during rebrightenings and final fading, we identified one of two minima with a mean epoch BJD 2454114.2150(6) in quiescence as being likely eclipses based on an analogy with quiescent light curves of WZ Sge (Patterson et al. 1998b) and V455 And (Araujo-Betancor et al. 2005). The times of the eclipses (including those recorded during superoutburst, see subsection 3.3) are listed in table 3. There possibly remains cycle 0.5 or 1 ambiguity in selecting the eclipse in quiescence.

A direct PDM analysis of the combined data during the rebrightening, post-superoutburst, and quiescent phases yielded a mean period of 0.0590031(5)d.

3.3. Eclipses during Superoutburst Plateau

The light curve on the first night of observation (2006 March 4–5, late stage of the superoutburst plateau, figure 4) clearly shows the presence of recurring eclipses other than superhumps. These eclipses in outburst were prominently seen on 2006 March 4–5, but were almost absent on March 5–7 (during the stage of rapid fading).

There was a systematic 0.004–0.005d difference between the epochs of eclipses during the superoutburst plateau and the rebrightenings (cf. table 3). This difference can be understood if a different portion of the accretion disk is eclipsed during different states. We disregarded eclipses during the superoutbursts in determining the orbital ephemeris [equation (1)], since this period better represents light curves during most of the observed epochs than the period determined from all eclipses. The given ephemeris thus has this degree of uncertainty, and needs to be verified by further observations. This uncertainty does not affect the following analysis of superhumps:

Min(BJD) = 2453799.3654(7) + 0.0590048(2) E. \hspace{1cm} (1)

The appearance of distinct eclipses only during the superoutburst plateau can be understood as being a result of the luminous portion (hot state) of the accretion disk expanding during the outburst, as predicted by the disk-instability theory. The system is thus a grazing eclipser whose eclipses are only prominent when the radius of the accretion disk sufficiently expands.

3.4. Superhumps during the Main Superoutburst

We measured the times of superhump maxima outside the eclipses after removing observations within 0.07 P_{orb} of the eclipses. The analyzed data covered the last part of the

Table 3. Eclipse minima of SDSS J0804.

| E  | Minimum* | Error | O − C † |
|----|----------|-------|---------|
| 0  | 53799.3607 | 0.0005 | −0.0047 |
| 1  | 53799.4200 | 0.0005 | −0.0044 |
| 2  | 53799.4786 | 0.0008 | −0.0048 |
| 356| 53820.3705 | 0.0005 | −0.0006 |
| 924| 53853.8865 | 0.0005 | 0.0007  |
| 5336| 54114.2150| 0.0005 | −0.0010 |

* BJD−2400000.
† Against equation (1).
superoutburst plateau and the rapid fading stage (table 4). It is evident that the times of the superhump maxima can not be expressed by a single constant period. The difference in $O-C$ between $E = 40$ and $E = 44$ is too large to be considered as a real period change. Since all the maxima for $44 \leq E \leq 49$ have orbital phases of 0.70–0.79, they most likely represent a projection effect in a high-inclination system (Osaki & Meyer 2003, figures 2 and 3; Kato et al. 2009; we call them orbital humps in this paper for simplicity).

We disregarded this portion and obtained a mean superhump period ($P_{SH}$) of 0.05954(3)d ($E \leq 40$) from the times of maxima. A PDM analysis of the corresponding segment of the data yielded a period of 0.059539(11)d (figure 5), and we adopt this as being the representative $P_{SH}$ of this object. The fractional superhump excess, $\epsilon = P_{SH}/P_{orb} - 1$, for this period is 0.90(2)%. As in most of WZ Sge-type dwarf novae (Kato et al. 2009), a shortening of the superhump period toward the end of the superoutburst as frequently seen in the majority of ordinary SU UMa-type dwarf novae, was absent. The present period is significantly shorter than the $P_{SH}$ of 0.059713(7)d (Pavlenko et al. 2007). This difference was caused by incorrect times of observations for the first night used in Pavlenko et al.

**Table 4.** Superhump maxima of SDSS J0804 (2006).

| $E$  | Maximum | Error  | $O-C$ | Phase | $N$  |
|------|---------|--------|-------|-------|------|
| 0    | 53799.3495 | 0.0002 | -0.0050 | 0.73 | 64  |
| 1    | 53799.4081 | 0.0002 | -0.0056 | 0.72 | 71  |
| 2    | 53799.4679 | 0.0005 | -0.0049 | 0.74 | 93  |
| 17   | 53800.3611 | 0.0003 | 0.0009 | 0.88 | 120 |
| 18   | 53800.4204 | 0.0004 | 0.0010 | 0.88 | 93  |
| 19   | 53800.4794 | 0.0005 | 0.0009 | 0.88 | 88  |
| 20   | 53800.5380 | 0.0004 | 0.0003 | 0.87 | 89  |
| 21   | 53800.5997 | 0.0005 | 0.0029 | 0.92 | 66  |
| 22   | 53800.6587 | 0.0006 | 0.0027 | 0.92 | 29  |
| 23   | 53800.7142 | 0.0018 | -0.0009 | 0.86 | 11  |
| 34   | 53801.3769 | 0.0009 | 0.0110 | 0.09 | 22  |
| 35   | 53801.4313 | 0.0011 | 0.0062 | 0.01 | 43  |
| 37   | 53801.5517 | 0.0011 | 0.0083 | 0.05 | 67  |
| 38   | 53801.6114 | 0.0041 | 0.0088 | 0.06 | 82  |
| 39   | 53801.6706 | 0.0016 | 0.0089 | 0.07 | 14  |
| 40   | 53801.7292 | 0.0010 | 0.0083 | 0.06 | 14  |
| 44   | 53801.9438 | 0.0020 | -0.0137 | 0.70 | 65  |
| 47   | 53802.1262 | 0.0013 | -0.0088 | 0.79 | 61  |
| 48   | 53802.1847 | 0.0015 | -0.0095 | 0.78 | 74  |
| 49   | 53802.2415 | 0.0014 | -0.0118 | 0.74 | 74  |

$^a$BJD−2400000.
$^b$Against Max = 2453799.3545 + 0.059160 $E$.
$^c$Orbital phase.
$^d$Number of points used to determine the maximum.

**Fig. 4.** Light curve of SDSS J0804 on 2006 March 4–5, late stage of the superoutburst plateau. Recurring eclipses (ticks) are present.

**Fig. 5.** Period analysis of SDSS J0804 during the main superoutburst. (Upper) PDM analysis. (Lower) Phase-average profile. The phase zero refers to equation (1).
3.5. Hump Features during the Rebrightening Phase

Phase-averaged light curves during the rebrightening phase at different brightness levels are shown in figure 6. The profiles of the orbital variation were similar regardless of the brightness level. Since the system luminosity varied by more than a factor of two between levels, the amplitude of the orbital humps is expected to vary by a similar factor if the orbital humps (assuming a constant luminosity) arise from the hot spot (cf. Patterson et al. 2002), as in dwarf novae in quiescence. The relatively constant amplitude of the orbital humps indicates, on the contrary, that the luminosity of the orbital humps varies proportionally to the system luminosity. This result is consistent with a projection effect, and is contrary to what it expected for a hot spot from an enhanced mass-transfer, strengthening the argument in Osaki and Meyer (2003).

We performed a period analysis during the rebrightening stage after removing the global trend of rebrightenings and subtracting the mean orbital variation. A PDM analysis has yielded a strong superhump signal with a mean period of 0.059659(5)d (figure 7).

We measured the times of humps during the rebrightening phase using two methods. Since the variation was extremely complex, we give both results for complementary purposes and for a comparison with previous studies.

The first method directly used the light curve after removing the global trend of rebrightenings (table 5). These maxima correspond to the times presented in Pavlenko et al. (2009). Since these times consisted of a mixture of orbital humps and superhumps, we selected maxima for their orbital phases $0 < \text{phase} < 0.6$. The selected maxima for $E \geq 219$ can be very well expressed by a single constant period of 0.059631(11)d.

The second method used the light curve subtracted for the mean orbital light curve during rebrightening. This method is expected to be more sensitive to superhumps, while there remains a possibility of an effect of the variation in the orbital light curve. The extracted times are listed in table 6. For the interval $E \leq 135$ and $236 \leq E \leq 536$, the $P_{\text{SH}}$ was almost constant at 0.059632(6)d. We regard this period as being the representative $P_{\text{SH}}$ during the rebrightening phase. The period is 0.15(3)% longer than the $P_{\text{SH}}$ during the superoutburst plateau. The unusual cyclic $O-C$ variation reported in Pavlenko et al. (2009) was probably caused by contamination by the orbital humps.

3.6. Final Fading Stage

After a sequence of eleven rebrightenings, this object entered the stage of final slow fading. In contrast to EG Cnc (Patterson et al. 1998a; Kato et al. 2004), the fading trend of the final fading was on a smooth extension of the minima during the rebrightening phase. Osaki et al. (1997) and Osaki et al. (2001) interpreted the jump in EG Cnc as representing a decrease of the viscosity in the accretion disk. The apparent lack of this feature in SDSS J0804 suggests that a stepwise decrease in the viscosity is not required to terminate the rebrightening activity.

A phase-averaged orbital light curve of SDSS J0804 during 2006 April 21–May 13 is shown in figure 8. Although the orbital hump remained strong, the eclipse became less prominent. The reduction of the eclipse feature suggests
that the luminous portion of the accretion disk had shrunk compared to the rebrightening phase. After subtracting the mean orbital light curve, the superhump signal with a period of $0.05969(4)\text{d}$, 0.25(6)$\%$ longer than the superhump period during the superboutburst plateau, was strongly detected (figure 9; table 7). This period suggests that the superhump period further lengthened during the post-rebrightening phase.

The $O - C$ variation of superhumps in SDSS J0804 during the entire course of the outburst is shown in figure 10. The period of superhumps continuously increased during the rebrightening and post-superoutburst phases, and the epochs of superhumps during the superboutburst plateau, rebrightening phase, and final fading phase can be smoothly linked by a period derivative of $P = 0.5 \times 10^{-5}$. The existence of a longer $P_{SH}$ during the post-superoutburst stage is similar to GW Lib, V455 And, and WZ Sge (Kato et al. 2008).

3.7. Light Variation during Mini-Outbursts

We analyzed the “mini-outbursts” reported in Zhurikov et al. (2008). The phase-averaged light curves during the two mini-outbursts had similar shape, and were distinct from that in quiescence (figure 11). The light curve during these mini-outbursts somewhat resembles the orbital light curve during the rebrightening and final fading phases. The sharp eclipse

| $E$ | Maximum$^*$ | Error | $O - C$$^\ddagger$ | Phase$^\ddagger$ | $N^\ddagger$ |
|-----|-------------|--------|---------------------|----------------|-----------|
| 0   | 53808.1456  | 0.0012 | -0.0280             | 0.80           | 92        |
| 16  | 53809.1186  | 0.0017 | -0.0109             | 0.29           | 93        |
| 67  | 53812.1589  | 0.0006 | -0.0175             | 0.82           | 82        |
| 97  | 53813.9750  | 0.0016 | 0.0063              | 0.60           | 81        |
| 98  | 53814.0333  | 0.0010 | 0.0049              | 0.59           | 94        |
| 99  | 53814.0945  | 0.0010 | 0.0063              | 0.62           | 95        |
| 113 | 53814.9276  | 0.0011 | 0.0031              | 0.75           | 43        |
| 114 | 53814.9797  | 0.0026 | -0.0046             | 0.63           | 66        |
| 115 | 53815.0426  | 0.0013 | -0.0014             | 0.69           | 66        |
| 116 | 53815.0963  | 0.0026 | -0.0074             | 0.60           | 66        |
| 117 | 53815.1632  | 0.0013 | -0.0021             | 0.72           | 119       |
| 118 | 53815.2211  | 0.0011 | -0.0021             | 0.72           | 119       |
| 124 | 53815.5799  | 0.0005 | 0.0018              | 0.80           | 7         |
| 125 | 53815.6401  | 0.0016 | -0.0013             | 0.82           | 7         |
| 126 | 53816.6949  | 0.0040 | -0.0062             | 0.75           | 7         |
| 132 | 53816.0552  | 0.0011 | -0.0044             | 0.86           | 91        |
| 133 | 53816.1142  | 0.0023 | 0.0052              | 0.85           | 98        |
| 134 | 53816.1727  | 0.0021 | -0.0064             | 0.85           | 114       |
| 135 | 53816.2305  | 0.0025 | -0.0083             | 0.83           | 53        |
| 136 | 53816.2897  | 0.0022 | 0.0089              | 0.83           | 16        |
| 137 | 53816.3504  | 0.0016 | -0.0079             | 0.86           | 16        |
| 138 | 53816.4084  | 0.0028 | -0.0097             | 0.84           | 16        |
| 164 | 53817.9919  | 0.0027 | 0.0205              | 0.68           | 33        |
| 166 | 53818.1102  | 0.0034 | 0.0194              | 0.68           | 59        |
| 180 | 53818.9415  | 0.0013 | 0.0142              | 0.77           | 64        |
| 181 | 53819.9884  | 0.0011 | 0.0114              | 0.74           | 65        |
| 182 | 53819.9564  | 0.0013 | 0.0097              | 0.72           | 66        |
| 183 | 53819.1184  | 0.0007 | 0.0120              | 0.77           | 60        |
| 197 | 53819.9420  | 0.0007 | -0.0009             | 0.73           | 64        |
| 198 | 53820.0015  | 0.0011 | -0.0011             | 0.74           | 66        |
| 199 | 53820.0620  | 0.0007 | -0.0003             | 0.76           | 56        |
| 200 | 53820.1226  | 0.0008 | 0.0005              | 0.79           | 58        |
| 219 | 53821.2671  | 0.0007 | 0.0099              | 0.18           | 16        |
| 220 | 53821.3327  | 0.0025 | 0.0158              | 0.30           | 17        |
| 221 | 53821.3826  | 0.0027 | 0.0059              | 0.14           | 17        |
| 236 | 53822.2765  | 0.0030 | 0.0036              | 0.29           | 17        |
| 237 | 53822.3364  | 0.0010 | 0.0038              | 0.31           | 16        |
| 252 | 53823.2432  | 0.0011 | 0.0145              | 0.68           | 15        |
| 253 | 53823.3027  | 0.0009 | 0.0143              | 0.68           | 13        |
| 254 | 53823.3565  | 0.0018 | 0.0084              | 0.60           | 17        |
| 255 | 53823.4205  | 0.0024 | 0.0126              | 0.68           | 17        |
these variations can naturally be attributed to superhumps, although it was insufficient to trigger a true outburst. The brightness increase may be understood as being a result of increased tidal dissipation.

### 3.8. SDSS J0804 as a WZ Sge-Type Dwarf Nova

Based on the presence of eleven rebrightenings, we classified the superoutburst as Type-B according to a classification scheme by Imada et al. (2006). The apparent absence of flat quiescence between rebrightenings, short (~3 d) recurrent time of rebrightenings, and the relatively small (1.5–2.0 mag) amplitudes of rebrightenings might place the superoutburst environment of SDSS J0804 in the WZ Sge instability strip (Pavlenko 2009). We regard that superhumps were transiently excited during these mini-outbursts, although it was insufficient to trigger a true outburst. The brightness increase may be understood as being a result of increased tidal dissipation.
Fig. 8. Phase-averaged orbital light curve of SDSS J0804 during 2006 April 21–May 13 (post-superoutburst final fading).

Fig. 9. Period analysis of SDSS J0804 during the final fading phase after subtracting the mean orbital variation. (Upper) PDM analysis. (Lower) Phase-average profile.

Fig. 10. $O - C$ variation of superhumps in SDSS J0804 during the entire course of the outburst. (Upper) $O - C$. Open squares indicate humps coinciding with the phase of orbital humps. Filled squares are humps outside of the phase of orbital humps. We used a period of 0.05963 d for calculating the $(O - C)$'s. During the rebrightening phase, hump times after subtracting the orbital variations were used. The period of superhumps continuously increased during the rebrightening and post-superoutburst phases. The dashed curve represents a quadratic fit with $P/P = +0.5 \times 10^{-5}$. (Lower) Light curve. Eleven rebrightenings were recorded following the superoutburst plateau. The early stage of the superoutburst was not observed.
Table 7. Maxima of humps during the final fading phase of SDSS J0804.

| $E$ | Maximum* | Error | $O - C$† | Phase‡ | $N$§ |
|-----|----------|-------|---------|-------|-----|
| 0   | 53847.2738 | 0.0014 | 0.0006 | 0.94  | 14  |
| 18  | 53848.3548 | 0.0025 | 0.0067 | 0.26  | 17  |
| 19  | 53848.4031 | 0.0020 | −0.0047 | 0.08  | 17  |
| 51  | 53850.3153 | 0.0040 | −0.0035 | 0.49  | 16  |
| 52  | 53850.3733 | 0.0167 | −0.0052 | 0.47  | 16  |
| 101 | 53853.3053 | 0.0021 | 0.0007 | 0.16  | 16  |
| 102 | 53853.3723 | 0.0014 | 0.0080 | 0.30  | 9   |
| 103 | 53853.4283 | 0.0015 | 0.0043 | 0.25  | 15  |
| 118 | 53854.3104 | 0.0038 | −0.0095 | 0.20  | 16  |
| 119 | 53854.3824 | 0.0014 | 0.0029 | 0.42  | 17  |
| 120 | 53854.4294 | 0.0022 | −0.0099 | 0.21  | 8   |
| 135 | 53855.3516 | 0.0111 | 0.0165 | 0.84  | 16  |
| 151 | 53856.2922 | 0.0006 | 0.0017 | 0.78  | 32  |
| 152 | 53856.3514 | 0.0006 | 0.0026 | 0.73  | 18  |
| 153 | 53856.4073 | 0.0009 | −0.0026 | 0.73  | 18  |
| 168 | 53857.3026 | 0.0023 | −0.0031 | 0.91  | 21  |
| 169 | 53857.3614 | 0.0031 | −0.0041 | 0.90  | 23  |

* BJD−2400000.
† Against Max = 2453847.2732 + 0.059718 $E$.
‡ Orbital phase.
§ Number of points used to determine the maximum.

Fig. 11. Phase-averaged light curves during mini-outbursts. (Upper) The first mini-outburst, (Middle) the second mini-outburst, (Lower) quiescence.

intermediate between Type-A and Type-B.

Although Shears et al. (2007) argued that the amplitude of the outburst (up to 5 mag) is relatively small for a WZ Sge-type dwarf nova, this is probably because the early stage of the superoutburst was missed. If the evolution of the superoutburst was similar to that of V455 And, another high-inclination WZ Sge-type dwarf nova, the true maximum might have reached 11 magnitude. The high orbital inclination probably partly contributes to the low outburst amplitude. The overall behavior of the superhumps, however, and their $O - C$, persistent long-period superhumps even after the rebrightening phase, and the low $\epsilon$ all support the classification of this object as a genuine WZ Sge-type object. The detection of early superhumps during future superoutbursts is awaited.

Only two systems with Type-B superoutbursts have been measured for $\epsilon$: EG Cnc (0.6%) and AL Com (0.9%). The $\epsilon$ (0.9%) of SDSS J0804 is similar to those of previously known systems.

Although no 2MASS counterpart of this object was detected, we performed quiescent infrared photometry using OAO/ISLE (Yanagisawa et al. 2006, 2008) in 2007 March, about one year after the superoutburst. The infrared magnitudes were estimated to be $J = 17.29(0.05)$, $H = 16.97(0.05)$, and $K_s = 16.41(0.06)$, respectively. The resultant color indices (assuming mean $V = 17.1$ at this epoch, Zharikov et al. 2008) $V - J = +0.2$ and $J - K_s = +0.9$ are compatible with an insignificant contribution in the near-infrared, as expected from the small $\epsilon$ and, consequently, a small mass of the secondary (cf. Osaki 1985).

The presence of grazing eclipses is expected to provide a powerful tool for diagnosing the variation of the disk radius and the luminosity of the superhump light source or the hot spot. Being the single known eclipsing object exhibiting distinct multiple rebrightenings, detailed observations of the next superoutburst of SDSS J0804 are expected to provide
a wealth of clues for understanding the origin of multiple rebrightenings in WZ Sge-type dwarf novae.

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