Multicolor Photometry of an Outburst of a New WZ Sge-Type Dwarf Nova, OT J012059.6+325545

Shinichi NAKAGAWA, Ryo NOGUCHI, Eriko IINO, Kazuyuki OGURA, and Katsura MATSUMOTO
Osaka Kyoiku University, 4-698-1 Asahigaoka, Kashiwara, Osaka 582-8582
katsura@cc.osaka-kyoiku.ac.jp
Koyama Astronomical Observatory, Kyoto Sangyo University, Motoyama, Kamigamo, Kita-ku, Kyoto 603-8555
and
Makoto UEMURA
Hiroshima Astrophysical Science Center, Hiroshima University, 1-3-1 Kagamiyama, Higashi-Hiroshima, Hiroshima 739-8526

(Received 2012 January 28; accepted 2013 February 16)

Abstract

We present our photometric studies of a newly discovered optical transient, OTJ012059.6+325545, which underwent a large outburst during the period between 2010 November and 2011 January. The amplitude of the outburst was ~8 mag. We performed simultaneous multicolor photometry using g', Rc', and i'-band filters from the early stage of the outburst. Time-resolved photometry during its early stage revealed periodic variations with double-peaked profiles, which are referred to as early superhumps, with amplitudes of ~0.08 mag. After rapid fading in the main outburst, we found rebrightening phenomena, which occurred at least nine times. The large amplitude of the outburst, early superhumps, and rebrightening phenomena are typical features of WZ Sge-type dwarf novae. We detected color variations within early superhump modulations, which established this object as the second system of WZ Sge-type dwarf nova, next to V445 And. We carried out numerical calculations of the accretion disk to explain both of the modulations and the color variations of the early superhump. This modeling of the disk height supports the idea that height variations within the outer disk can produce early-superhump modulations, though we cannot rule out an idea that temperature asymmetry may also play a role.

Key words: accretion: accretion disks — stars: binaries: close — stars: dwarf novae — stars: individual (OT J012059.6+325545)

1. Introduction

Dwarf novae are a subclass of cataclysmic variables that consists of a white dwarf with an accretion disk and a late-type main-sequence (secondary) star transferring its material to the accretion disk (Warner 1995 for a review). Dwarf novae show sudden increases of their brightness, which are called (normal) outbursts. The outburst is currently understood to be triggered by a thermal instability of the accretion disk (e.g., Hoshi 1979).

SU UMa-type dwarf novae are one of the subgroups of dwarf novae with orbital periods shorter than 2 hr, and show superoutbursts. Superoutbursts are caused by tidal instability of the disk (Whitehurst 1988; Osaki 1989), and are different from normal outbursts in the observed features and their mechanisms. Superoutbursts show larger amplitudes and longer durations (lasting for more than 10 d) than normal outbursts. The thermal-tidal-instability model expects that the tidal instability occurs when the disk expands beyond the 3:1 resonance radius during a superoutburst (Osaki 1996 for a review); then, the disk should be transformed to an eccentric form, and should undergo a slow precession (Vogt 1981; Osaki 1985; Whitehurst & King 1991). This acts as a trigger of superhumps, which are short-term modulations with amplitudes of about 0.3–0.4 mag; their period is a few percent longer than the binary’s orbital period (Vogt 1974; Warner 1975).

WZ Sge-type dwarf novae are an extreme subgroup of SU UMa-type stars. The interval of two successive superoutbursts (supercycle) can be several years up to decades (O’Donoghue et al. 1991; Osaki 1995). SU UMa-type stars usually exhibit several normal outbursts during one supercycle, but WZ Sge-type ones show superoutbursts only, and their amplitudes are significantly larger (6–8 mag) than those of SU UMa-type stars. Furthermore, WZ Sge-type stars present two unique behaviors remaining to be understood: early superhumps and post-superoutburst rebrightenings. These peculiarities of WZ Sge-type stars have not been well understood due to the low frequency of their superoutbursts.

Early superhumps are observed in very early phases of superoutbursts before ordinary superhumps emerge, and the period of the early superhumps is almost in agreement with the orbital period (e.g., Kato et al. 1996; Ishioka et al. 2002; Osaki & Meyer 2002; Patterson et al. 2002). A candidate that causes early superhumps is a two-armed spiral pattern excited by tidal dissipation, which is generated by the 2:1 resonance (Osaki & Meyer 2002). Other theoretical models of early superhumps based on tidal distortion of the disk have been proposed (Smak 2001; Kato 2002; Ogilvie 2002). Maehara, Hachisu, and Nakajima (2002) succeeded in reproducing the light curves of the early superhumps of BC UMa,
The exposure times were 15–180 s for the observations. The dates of the observations covered the period of OT J012059.59 +325545 (or sometimes OT J012059.59 +325545.0; hereafter referred to as OT J0120). A bright outburst of the object was detected at 12.3 mag by K. Itagaki on 2011 November 30.50663 (vsnet-alert 12431).

We carried out simultaneous g'-R'-C' and i'-band multicolor photometry, from the day following the outburst detection to the rebrightening phase. There is a quiescent counterpart of OT J0120 in the Sloan Digital Sky Survey DR8 database with magnitudes of $g = 20.09$, $r = 20.24$, and $i = 20.52$. Hence, the amplitude of the outburst was ~8 mag. Based on this large amplitude, OT J0120 was considered to be a new candidate for the WZ Sge-type dwarf nova.

2. Observations

Simultaneous multiband optical observations were performed with ADLER (Araki telescope Dual-band imaging) attached to the 1.3 m ARAKI telescope at Koyama Astronomical Observatory (KAO), and with an Andor DW436 CCD camera attached to the 51 cm telescope at Osaka Kyoiku University (OKU). ADLER is an imager that can take images simultaneously in two optical bands. We obtained time-series data that enabled us to study short-term variations, using a simultaneous photometry mode of ADLER for g'- and i'-band observations and the Andor camera for R'-band observations. The dates of the observations covered the periods from 2010 December 1 to 2011 January 8 at KAO and from 2010 December 1 to 2011 January 19 at OKU. The exposure times were 15–180 s for the g'- and i'-band observations, and 10–180 s for the R'-band observations; we also obtained calibration frames. We measured the magnitudes of the object and comparison stars using the APHOT package of IRAF (Image Reduction and Analysis Facility) for the R'-band data. We also performed the standard aperture photometry for the g'- and i'-band data using the DAOPHOT package of IRAF in a software developed by MI (one of the authors) for the KAO data reduction pipeline. As comparison stars, we used NOMAD 1229-0022689 for g'- and i'-band observations, and NOMAD 1229-0022670 ($B = 12.529$, $V = 12.577$, and $R = 12.610$) for the R'-band observations during the main outburst phase, and then NOMAD 1229-0022691 ($B = 16.260$, $V = 16.130$, and $R = 16.460$) for the post outburst phase. Since there were no measurements of the g'- and i'-magnitudes of NOMAD 1229-0022689 at that time, we performed the absolute photometry with the g'- and i'-bands using standard stars in a clear night, and made correction for the airmass observing standard stars at different altitudes. As a result, we estimated the g' and i' magnitudes of NOMAD 1229-0022689 to be $g' = 14.256 \pm 0.060$ and $i' = 13.648 \pm 0.056$. We measured the constancy of the comparison stars using other local stars, and confirmed no significant variation in the brightness of the comparison stars during our observations.

3. Results

3.1. Light-Curve Analysis

Figure 1 shows a light curve with all of the photometric observational data that we obtained. In this paper, we denote the number of days elapsed since the detection of the outburst by $T$, and $T = 0$ corresponds to JD = 2455531. We divided the data into four phases according to the features of the light curve: the early-superhump phase (from $T = 1$ to $T = 10$), the ordinary-superhump phase (from $T = 11$ to $T = 20$), the rapidly fading phase (from $T = 23$ to $T = 27$), and the rebrightening phase (from $T = 28$ to $T = 50$). After our first observation on $T = 1$, the flux decreased from $R_C = 13.0$ to 15.3 during 23 d at a slow declining rate of $\sim 0.10$ mag d$^{-1}$.

We examined the rates of decline during both the early- and ordinary-superhump phases in the R'-band, which were 0.14 mag d$^{-1}$ and 0.09 mag d$^{-1}$, respectively. The large-decline rate in the early-superhump phases is typical of superoutbursts of WZ Sge-type stars (e.g., Nogami et al. 1997). We then detected a rapid fading in the outburst on $T = 24$. The rapid-fading stage continued at a decline rate of 0.65 mag d$^{-1}$, examined in the R'-band until $T = 25$ when the object had been $g' = 16.8$. We made the first detection of a dramatic rebrightening, that increased the flux to $g' = 15.5$ at $T \sim 28$. In total, we detected nine rebrightenings, as marked by arrows in figure 7, while additional rebrightenings might have been overlooked in our observations. The average rising and fading rates of rebrightenings were 3.3 mag d$^{-1}$ and 0.95 mag d$^{-1}$, examined in the R'-band, respectively. We obtained the longest coverage of a rising trend on $T = 41$, which indicated ~0.59 mag in 0.14 d as a lower (shorter) limit of the rise time, or a timescale of $\tau \sim 0.25$ d when the time-series of flux $f(t)$ was supposed to be $f(t) = \exp(t/\tau) \times C$. As for the decay time, we similarly obtained a lower limit of $+0.23$ mag...
Fig. 1. $g'$-, $R_C$-, and $i'$-band light curves of the 2010 outburst of OT J0120. The horizontal axis displays time in days from BJD = 2455531.0 (the day of the first detection of this outburst). The blue pluses, green points, and red crosses represent $g'$-, $R_C$-, and $i'$-band observations, respectively.

Fig. 2. Samples of short-term modulations observed in the 2010 superoutburst of OT J0120. The upper panel shows the double-peaked modulations detected on $T = 1$. The lower panel shows the single-peaked modulations detected on $T = 16$.

in 0.26 d on $T = 29$, which was represented by $\tau \sim -1.1$ d. We found double-peaked modulations during $T = 1$–10, as shown in the upper panel of figure 2. Subsequently, the modulations decayed, and were replaced by single-peaked modulations, which were detected during $T = 11$–23. We estimated the periods of the two types of modulations by the Phase Dispersion Minimization (PDM) method (Stellingwerf 1978) using time-series data from which global declining trends were subtracted. The resulting period–theta diagrams are shown in figures 3 and 4. The errors were estimated by the Lafler–Kinman method (Fernie 1989). We used data obtained during $T = 1$–10 for figure 3 and during $T = 11$–23 for figure 4. The best-estimated periods of the double-peaked modulations and the single-peaked modulations are $0.057145 \pm 0.000002$ d and $0.057814 \pm 0.000012$ d, respectively. The period of the double-peaked modulations was $1.17\% \pm 0.02\%$, shorter than that of the single-peaked modulations, and was stable over the duration. Our analysis indicates that the double-peaked modulations observed during the early phase were early superhumps, and the single-peaked modulations observed during the late phase were ordinary superhumps. We thus conclude that OT J0120 is a WZ Sge-type dwarf nova, because of the existence of the early superhumps and the rebrightenings as well as the large amplitude of the outburst.

3.2. Superhump-Period Change

We searched for period changes of ordinary superhumps during the superoutburst by the following method. A template light curve of the superhump was defined as a phase-averaged light curve of superhumps obtained during the ordinary-superhump phase. We then shifted the maximum timing of the template light curve around an eye-estimated maximum of each observation by a step of 0.0001 d, and calculated the variance of each test. Finally, the timings of the maxima were determined by minimizing variances, which are given in table 1. The cycle count ($E$) is defined as $E = 0$ at the first superhump maximum that we observed. A linear ephemeris of the superhump maxima is given by BJD (maximum) = 2455544.9890(3) + 0.057814(12)$E$. The resulting $O - C$ diagram is shown in figure 5. We can see

Fig. 3. Period-theta diagram obtained from a PDM analysis for double-peaked modulations.

Fig. 4. Period-theta diagram obtained from a PDM analysis for single-peaked modulations.
Table 1. Times of superhump maxima.

| BJD$^* - 2455500$ | Error | $E$ (cycle) | $O - C$ (10$^{-3}$ d) |
|------------------|-------|------------|----------------------|
| 44.98824         | 1.4   | 0          | -0.8                 |
| 45.16403         | 2.4   | 3          | 1.6                  |
| 47.12334         | 2.1   | 37         | -4.7                 |
| 47.99036         | 2.4   | 52         | -4.8                 |
| 49.95567         | 2.8   | 86         | -5.0                 |
| 50.93637         | 3.1   | 103        | -7.1                 |
| 50.99367         | 3.1   | 104        | -7.6                 |
| 54.01186         | 3.8   | 156        | 4.5                  |
| 54.06916         | 3.8   | 157        | 4.0                  |
| 54.93267         | 3.9   | 172        | 0.4                  |
| 54.98806         | 3.9   | 173        | -2.0                 |

$^*$ Barycentric Julian Date (Eastman et al. 2010).

Fig. 5. $g'$- and $R_C$-band light curves and $O - C$ versus cycle count ($E$). Upper panel: $O - C$ versus cycle count ($E$) of superhumps. Lower panel: $g'$- and $R_C$-band light curves. The blue pluses and red points represent $g'$- and $R_C$-band observations, respectively.

Fig. 6. Phase-averaged light curve on $T = 1$. The squares represent $g'$-band observations. The diamonds represent the $g' - R_C$ color and the circles represent the $g' - i'$ color plus a 0.05 offset.

4. Discussions

4.1. Period of the Short-Term Modulations

The superhump period of OT J0120 is significantly shorter than those of general SU UMa-type dwarf novae, and is typical of WZ Sge-type dwarf novae. The estimation of the superhump period excess is important for studying dwarf novae, because it gives a way of estimating the mass ratio, and thereby we can investigate the evolutionary status of objects. WZ Sge-type dwarf novae are especially useful for the study on such subjects because those orbital periods are close to the suspected period minimum of CVs; thus, the phenomenology of the WZ Sge-type outburst behavior is a vital example concerning studies of the evolutionary states of CVs. However, no direct measurement of the orbital period of OT J0120 has been performed; no eclipsing phenomenon has been detected, and no periodic variation has been observed in quiescence. Thus, we calculated the superhump period excess from the early superhump period, that is likely to be equal to the orbital period (Patterson et al. 1981; Kato et al. 1996). The superhump-period excess is

$$
e = \frac{P_{\text{SH}}}{P_{\text{orb}}} - 1 = \frac{P_{\text{SH}}}{P_{\text{ESH}}} - 1 = (1.17 \pm 0.02) \times 10^{-2},$$

(1)
where \( P_{\text{SH}} \), \( P_{\text{orb}} \), and \( P_{\text{ESH}} \) are the superhump, the orbital, and the early-superhump periods, respectively. This value may be a lower limit if there is a certain level of precession in the disk. Kato et al. (2009) refined an empirical relation between the superhump-period excess and the mass ratio. We derived the mass ratio, \( q = (M_1/M_2) = 15.2 \), from the superhump-period excess, which was estimated based on our observations. The extreme mass ratio and the inferred short orbital period are strong characteristics of the evolved CV, such as WZ Sge, which reinforces the principle that WZ Sge-type dwarf novae, including OT J0120, are evolved CVs that are close to, or have passed beyond, the minimum orbital period of the CVs (sometimes called “period bouncers,” Patterson 1998).

Olech et al. (2003) and Soejima et al. (2009) found that short \( P_{\text{SH}} \) systems showed period changes of superhumps with three stages in the \( O - C \) diagram. Kato et al. (2009) reported general characteristics of the superhump-period change, based on observations of the superoutbursts of 199 dwarf novae. They discovered that the period change in the superhump period can be categorized into three stages: (A) an early stage of superhump evolution having a longer \( P_{\text{SH}} \), (B) a middle segment with a stabilized period, usually with a positive \( \dot{P} \), and (C) a late stage with a shorter stable superhump period. Figure 5 shows the \( g^- \) and \( R_C \)-band light curves and the \( O - C \) versus cycle count, \( E \), during the 2010 superoutburst of OT J0120. In general, the \( O - C \) diagram of the superhumps abruptly varies at the timing of entering to a rapidly fading phase among WZ Sge-type stars (see figure 33 of Kato et al. 2009). The \( O - C \) variation of OT J0120 can be interpreted as being a transition from stage B to stage C; the object was in stage B during the period between \( E = 3 \) and 157, in which the period derivative was positive. Then, an abrupt decline of \( O - C \) was seen in \( E = 172 \) and 173 at the beginning of the rapidly fading phase. This abrupt decline could be a sign of transition to stage C. Hence, the characteristics of the \( O - C \) of superhump during the 2010 superoutburst of OT J0120 were consistent with those of other WZ Sge-type stars. We estimated the period derivative during stage B to be \( P_{\text{dot}} = \dot{P}/P = (2.7 \pm 0.4) \times 10^{-5} \).

### 4.2. Rebrightening

Figure 7 shows a magnified view of the light curve around the rebrightening phase. We can see rebrightenings more than nine times, and those amplitudes were 1–2 mag. The whole feature of the light curve in this phase is similar to that of the 2001 outburst of WZ Sge (Ishioka et al. 2002). The minimum following the first rebrightening was fainter than the later ones. Such a deep minimum can be also seen in the last dip. Those characteristics were also analogous to the 2001 outburst of WZ Sge. It is possible that we missed another deep dip, taking the durations of our observations into account.

Kato et al. (2009) discussed the relation between \( P_{\text{dot}} \) and light-curve shapes of the rebrightening of WZ Sge-type stars. They classified the rebrightening into four types based on their light-curve shapes: long-duration rebrightening (type-A), multiple rebrightening (type-B), single rebrightening (type-C), and no rebrightening (type-D) (see figure 37 of Kato et al. 2009). The 2010 superoutburst of OT J0120 is considered to be a type-A outburst based on this classification. Figure 8 shows \( P_{\text{dot}} \) against \( P_{\text{SH}} \). The figure includes the data reported in Kato et al. (2009) and our result concerning OT J0120. The filled circles, filled squares, open triangles, and open circles represent type-A, type-B, type-C, and type-D outbursts, respectively. Our result is shown by an open diamond. OT J0120 has \( P_{\text{dot}} \) close to those of known type-A objects. This supports that type-A objects tend to have a smaller \( P_{\text{SH}} \) and a smaller \( P_{\text{dot}} \) among WZ Sge stars. OT J0120 had the largest \( P_{\text{SH}} \), and showed the largest \( P_{\text{dot}} \) among the type-A objects.

### 4.3. Color Variations of Early Superhumps

Early superhumps are considered to be caused by a vertically expanded disk, which is, for example, explained by scenarios proposed by Kato (2002) or Osaki and Meyer (2002). Matsui et al. (2009) discovered that the light source of the early superhump of V455 And is associated with a low-temperature...
component. Our observation confirmed that OT J0120 also became redder at both its primary and secondary maxima of the early superhump. This supports the argument that light sources of the early superhump are expanded low-temperature components in outer regions of the disk.

We performed numerical calculations that enabled us to estimate the vertical structure of the disk, assuming that the early superhump was caused by vertical deformations of the disk. The early-superhump mapping, which was developed by one of the authors (MU), reconstructs disk structures by the Markov chain Monte Carlo method based on Bayesian statistics (Uemura et al. 2012). The selected parameters for our calculations are summarized in table 2; we assumed that the early superhump was caused by vertical deformations of the disk. The shade represents the disk height, i.e., brighter regions are higher. The scale bar at the right side is represented in units of disk radius ($r$). The secondary star is located at ($x$, $y$) = (1.0, 0.0).

Table 2. Model parameters for the early-superhump mapping.

| Parameter      | Value |
|----------------|-------|
| $\sigma$ (mag) | 0.01  |
| $R_{out}/a$    | 0.58  |
| $R_{in}/a$     | 0.023 |
| $T_{in}$ (K)   | 223500|
| Inclination angle ($^\circ$) | 60.0 |
| Mass ratio ($M_1/M_2$) | 15.2 |

Fig. 9. Height map of the disk calculated from data obtained on December 1 ($T = 1$). The horizontal ($x$) and vertical ($y$) axes are represented in units of binary separation ($a$). The horizontal axis indicates the center of the secondary, and the vertical axis the motion of the secondary. The shade represents the disk height, i.e., brighter regions are higher. The scale bar at the right side is represented in units of disk radius ($r$). The secondary star is located at ($x$, $y$) = (1.0, 0.0).

Fig. 10. Comparison of the light curve reproduced from the disk map (dashed lines) and the observed data (bars). The horizontal axis displays the orbital phase, and the vertical axis the relative magnitudes of the $g'$, $R_{C}$, and $i'$ bands. We define the zero point of magnitudes as the average in each band.

The best-fit temperatures for an inclination angle of 60$^\circ$ were $T_{in} = 223500$ K and $T_{out} = 20000$ K.

Figure 9 shows a disk map calculated for an inclination angle of 60$^\circ$. Comparisons between the reproduced light curves from the calculated disk and the observed light curves are presented in figure 10. It shows that the reproduced light curves are almost in accordance with the observational data. We can see elevated structures in the lower-right and the upper-left regions in figure 9. In addition, an armed structure extends from the lower-right elevated area to the upper-right inner region. These structures were seen even if we assumed other inclination angles, such as 40$^\circ$ and 50$^\circ$. The calculations were based on the assumption of an axi-symmetric distribution of temperature on the disk, which could actually be axi-asymmetric due to the spiral wave, so that the armed structure at smaller radii may be a high-temperature region at larger radii. The map reconstructed on the former hypothesis successfully reproduced the 2:1 resonance radius for the system. We assumed that the inner radius of the disk was $R_1$, and supposed that the inclination angle is lower than 65$^\circ$ on the basis of the absence of eclipses. The lower limit of the inclination angle of OT J0120 is poorly known. Kato (2002) reported that WZ Sge-type binaries with higher inclination angles tended to indicate larger amplitudes of early superhumps. According to this trend, the detection of the early superhump with an amplitude of 0.08 mag indicates a moderate inclination angle of OT J0120. We thus performed a calculation on the assumption of an inclination angle of 60$^\circ$. We estimated the disk temperature in the same way as Uemura et al. (2012). The inner ($T_{in}$) and outer ($T_{out}$) temperatures of the disk were estimated from the averaged color at each night. The color index on $T = 1$ was $g' - i' = -0.408$. The best-fit temperatures for an inclination angle of 60$^\circ$ were $T_{in} = 223500$ K and $T_{out} = 20000$ K.
observed light curves, and formed a similar pattern of the disk to that of the theoretical model for a tidally deformed disk (e.g., Ogilvie 2002). Such a distorted disk is expected to have a two-armed pattern, while in our calculations there is no sign of the armed structure where the maximum occurred in the lower-left region in figure 9. It is therefore suggested that the tidal force would not be sufficient to explain the structure of the disk leading to early superhumps.

5. Summary

We performed simultaneous-multicolor photometry of the 2010 outburst of OT J0120. The outburst exhibited large amplitudes (~8 mag), early superhumps, and post-superoutburst rebrightenings. The parameters obtained from period analyses, such as the superhump-period excess or $P_P$, were consistent with those of other WZ Sge-type stars discovered so far. The rebrightenings were recorded nine times, and the whole light curve was similar to that of the 2001 outburst of WZ Sge. These results indicate that OT J0120 is a new member of WZ Sge-type stars. We found color variations of the early superhumps based on the observations during the earliest phase of the outburst. The phase-averaged light curve of the early superhump showed that the humps were redder at the maximum timing, and the characteristic of the color variation was consistent with that of V455 And (Matsui et al. 2009). In order to explain such modulations of the early superhump, we performed calculations to reconstruct the disk structure by adopting a Bayesian model under some assumptions, such as an axi-symmetric temperature distribution on the disk. The resulting disk maps indicated that the two vertically elevated structures facing each other at the outer region of the disk could reproduce the observed color variations, though we cannot rule out the idea that temperature asymmetry may also play a role.

This work was partly supported by the Private University Strategic Research Foundation Support Program of the Ministry of Education, Culture, Sports, Science and Technology of Japan (S0801061) and a Grand-in-Aid from the Ministry of Education, Culture, Sports, Science and Technology of Japan (22540252).

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