Spectroscopic Observations of the WZ Sge-Type Dwarf Nova GW Librae during the 2007 Superoutburst

Kazuo Hiroi, Daisaku Nogami, Yoshitomo Ueda, Yuuki Moritani, Yuichi Soejima, Akira Imada, Osamu Hashimoto, Kenzo Kinugasa, Satoshi Honda, Shin-ya Narusawa, Makoto Sakamoto, Ryo Iizuka, Kentaro Matsuda, Hiroyuki Naito, Takashi Iijima, and Mitsugi Fujii

1 Dept. of Astronomy, Kyoto University, Sakyo-ku, Kyoto 606-8502
2 Kwasan Observatory, Kyoto University, Yamashina-ku, Kyoto 607-8471
3 Dept. of Physics, Kagoshima University, 1-21-35 Korimoto, Kagoshima 890-0065
4 Gamma Astronomical Observatory, 6860-86 Nakayama, Takayama, Agatsuma, Gunma 377-0702
5 Nishi-Harima Astronomical Observatory, Sayo-cho, Hyogo 679-5513
6 GCOE Office, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, Aichi 464-8602
7 Astronomical Observatory of Padova, Asiago Section, Osservatorio Astrofisico, 36012 Asiago(Vi), Italy
8 Fujii-Bisei Observatory, 4500 Kurosaki, Tamashima, Okayama 713-8126

(Received 2009 February 4; accepted 2009 April 10)

Abstract

We carried out an international spectroscopic observation campaign of the dwarf nova GW Librae (GW Lib) during the 2007 superoutburst. Our observation period covered the rising phase of the superoutburst, maximum, slowly decaying phase (plateau), and long fading tail after the rapid decline from the plateau. The spectral features dramatically changed during the observations. In the rising phase, only absorption lines of Hα, Hβ, and Hγ were present. Around the maximum, the spectrum showed singly-peaked emission lines of Hα, He I 5876, He I 6678, He II 4686, and C III/N III as well as absorption lines of Balmer components and He I. These emission lines significantly weakened in the latter part of the plateau phase. In the fading tail, all the Balmer lines and He I 6678 were in emission, as observed in quiescence. We find that the center of the Hα emission component was mostly stable over the whole orbital phase, being consistent with the low inclination of the system. Comparing with the observational results of WZ Sge during the 2001 superoutburst, the same type of stars as GW Lib seen with a high inclination angle, we interpret that the change of the Hα profile before the fading tail phase is attributed to a photoionized region formed at the outer edge of the accretion disk, irradiated from the white dwarf and inner disk.

Key words: accretion, accretion disks — stars: dwarf novae — stars: individual (GW Librae) — stars: novae, cataclysmic variables

1. INTRODUCTION

Dwarf novae (DNe), a subclass of cataclysmic variables (CVs), are close binary systems, consisting of a primary star of white dwarf and a companion star of late-type main-sequence star (for a review, see Warner 1995; Hellier 2001a). Mass transferred from the surface of the companion to the primary by Roche-lobe over flow forms an accretion disk surrounding the white dwarf. DNe sometimes increase their luminosities dramatically. This sudden event is called an outburst, and is currently understood to be caused by the thermal instability of the accretion disk (for a review, see Osaki 1996), although the details of its process are not fully clarified. In DNe, the accretion disk is the dominant source of radiation in the optical band during outbursts. This enables us to investigate basic physics of an accretion disk by optical observations during outbursts.

SU UMa-type stars are one of the subgroups of DNe, having orbital periods shorter than 3 hr. These DNe characteristically show two kinds of outbursts: normal outbursts and superoutbursts. Compared with a normal outburst, a superoutburst is less frequent, and somewhat brighter. In addition, periodic modulations in brightness with a small amplitude of typically 0.1–0.3 mag, so-called superhumps, are observed only during superoutbursts.

A subset of SU UMa-type stars that has very long recurrence intervals of the outburst (>5 years) is called a WZ Sge-type star, and shows only superoutbursts (Kato et al. 2001, and references therein). This type of stars has the shortest orbital periods of ≈80 min among DNe, and is supposed to have quite low mass-transfer rates (e.g., Osaki 1995). The currently most debated issues regarding WZ Sge stars are the origin of early superhumps and rebrightenings. The early superhumps are observed at the very early phase of superoutbursts in WZ Sge stars before emergence of ordinary superhumps (see e.g., Kato et al. 1996; Ishioka et al. 2002; Osaki & Meyer 2002; Patterson et al. 2002; Nogami 2007). The rebrightening(s) often occurs a few to several days after the end of the plateau phase of the superoutburst in WZ Sge stars (and some of SU UMa stars with short orbital periods), although the recurrence cycle of the outburst is quite long, as mentioned above (see e.g., Nogami et al. 1997; Osaki et al. 2001, and references therein).
GW Lib was discovered during an outburst in 1983, and initially classified as a nova because of its large outburst amplitude (González & Maza 1983; Duerbeck 1987). Subsequent spectroscopic observations of GW Lib, however, showed that strong and narrow emission components superposed on broad Balmer absorption lines were present (Duerbeck & Setter 1987; Ringwald et al. 1996; Szkody et al. 2000). This leads to the conclusion that GW Lib is a DN with a remarkably low mass-transfer rate\(^1\).

In fact, GW Lib has an exceptionally short orbital period of $\sim 77$ min (Thorsten et al. 2002), which is nearly equal to the observed period minimum of normal hydrogen-rich CVs (see e.g. Patterson et al. 2003; Pretorius et al. 2007). The inclination of GW Lib was estimated to be $\sim 11^\circ$ from the comparison of the emission-line width with WZ Sge (Thorsten et al. 2002). Trigonometric parallax and proper motions indicate that the distance of GW Lib is 104 pc (Thorsten 2003). One of the most curious properties of GW Lib is that it is the first cataclysmic variable revealed to show non-radial photometric pulsations of the primary in optical (Warner & van Zyl 1998; van Zyl et al. 2000; Woudt & Warner 2002; van Zyl et al. 2004), although these pulsations were not detected in the long fading tail of the 2007 superoutburst (Copperwheat et al. 2009). The primary star of GW Lib is, hence, thought to be a ZZ Cet-type white dwarf. These pulsations are also present in UV (Szkody et al. 2002), but not observed in X-rays (Hilton et al. 2007).

At 2007 April 12.494 (UT), we received a VSNET message by R.Stubbings (vsnet-alert 9279) reporting that GW Lib was in outburst for the first time in 24 years since the discovery (for VSNET, see Kato et al. 2004b). Following this alert, we conducted an international spectroscopic observation campaign of GW Lib. Our observations started from the rising phase of this outburst (Narusawa et al. 2007). This is the second successful campaign of such intensive spectroscopic observations of a WZ Sge-type DN, next to the one on WZ Sge during the 2001 superoutburst (Nogami & Iijima 2004). Photometric observations during this outburst detected superhumps, confirming that this outburst is a superoutburst, and that GW Lib is really a member of WZ Sge-type DNe (Kato et al. 2008; Imada et al., in preparation; Uemura et al., in preparation).

\(^1\) From early on, some amateurs suggested that GW Lib was a DN with a large-amplitude outburst (Henkousei 109 (in Japanese)), and were monitoring it. This fact helped the rapid discovery of the 2007 superoutburst and the prompt observations.
Section 2 describes our observational protocols and log. We present the optical spectra obtained in our observations in section 3, and discuss the evolution of the accretion disk structure during the superoutburst in section 4. A summary is given in section 5.

2. OBSERVATION

Four observatories participated in this campaign: Asiago Astrophysical Observatory, Gunma Astronomical Observatory, Nishi-Harima Astronomical Observatory, and Fujii-Bisei Observatory. The Asiago Astrophysical Observatory is located in Italy, and the others are in Japan. Figure 1 shows the whole light curve of GW Lib during the 2007 superoutburst, generated from the data reported to the VSNET. As seen in figure 1, our observations covered the time from the rising phase of the superoutburst to the long fading tail. All of the obtained spectral data were reduced in a standard way using the IRAF package. Table 1 gives a journal of the observations.

2.1. Asiago Astrophysical Observatory

On 2007 April 13, 14, 15, 19, and 22, we took the spectra of a medium resolution (R ≈ 1000) with a Boller & Chivens spectrograph mounted on the 122-cm Galileo telescope of the Asiago Astrophysical Observatory, using a 512 × 512-pixel CCD detector. The integration times varied from 300 s to 1200 s, depending on the conditions.

2.2. Gunma Astronomical Observatory

At the Gunma Astronomical Observatory, observations were performed on 2007 April 14, 25, 27, May 2, 4, 11, and 19. The spectra of a low resolution (R ≈ 400 – 500) were obtained with the Gunma LOW resolution Spectrograph (GLOWS) mounted on a 150-cm Ritchey-Chretien telescope. To examine variability of the source on a short time-scale, we adopted relatively short integration times (30 s or 60 s), except for May 11 and 19.

2.3. Nishi-Harima Astronomical Observatory

We took the spectra of a medium resolution (R = 370 at Hα) with the optical spectrograph, MALLS, mounted on the 2.0-m NAYUTA telescope of the Nishi-Harima Astronomical Observatory on 2007 April 12 and 14. The integration times were 3600 s and 300 s on April 12 and 14, respectively.

2.4. Fujii-Bisei Observatory

Observations were performed on 2007 April 13, 16, 18, and 28 at the Fujii-Bisei Observatory. The low resolution (R = 600 at 5852 Å) spectra were taken with the
spectrograph, FBSPEC-2, mounted on a 28-cm Schmidt-Cassegrain telescope with an integration time of 600 s.

3. RESULT

Figure 2 shows the spectrum obtained on 2007 April 12, just in the rising phase of the superoutburst. We can see the blue continuum, on which deep Balmer absorption lines (Hα, Hβ, and Hγ) are superposed. There are no other prominent lines. This profile is characteristic of DNe in outburst.

Figure 3 displays all the “normalized” representative spectra of each day from 2007 April 12 to May 19. It is seen that Hβ, Hγ, and Hδ were consistently in absorption during the observations, except for during the fading tail (May 11 and 19). On the other hand, the profile of Hα dramatically changed. It was an absorption line in the rising phase of the superoutburst. Around the superoutburst maximum, it became an emission line, while it was again in absorption with a weak emission component in the latter part of the plateau phase. It finally turned to a strong emission line in the long fading tail. In addition to Balmer lines, many He lines were present in emission or in absorption. The high-excitation emission lines of He II 4686 and C III/N III were observed only around the superoutburst maximum.

We separate the whole observations into four periods, and examine the spectral features in each period. As denoted in figure 1, Period I is the rising phase (April 12), Period II is the former part of the plateau phase (April 13 to 19), Period III is the latter part of the plateau phase (April 22 to May 4), and Period IV is the long fading-tail phase (May 11 and 19). The maximum of the superoutburst belongs to Period II. Note that early superhumps were not observed in this system, and the genuine superhumps emerged around 2007 April 21, reaching its maximum amplitude on 2007 April 23 in Period III (see Uemura et al., in preparation; Imada et al. in preparation).

3.1. Period I: The rising phase (April 12)

Figure 4 shows the normalized spectrum on 2007 April 12 in Period I, during the rising phase, derived from the raw spectrum shown in figure 2. Only Balmer absorption lines of Hα, Hβ, and Hγ were seen without any significant wavelength shifts.

3.2. Period II: The former part of the plateau phase (April 13 to 19)

Figure 5 shows the normalized spectrum obtained on 2007 April 14 in Period II. This is a daily-averaged spectrum, combined of bluer and redder ones. Hα turned to a strong emission line from an absorption one in Period I. Although other Balmer lines still remained in absorption, Hβ and Hγ were accompanied by a weak emission component. We can also see that there were many He I absorption lines: He I 4026, 4120, 4388, 4471, 4713, 4922, and 5015. On the other hand, He I 5876, He I 6678 and high-excitation lines of He II 4686 and C III/N III were in emission. They, however, gradually disappeared in the latter of this period. All the emission lines were singly-
3.3. Period III: The latter part of the plateau phase (April 22 to May 4)

The normalized spectrum taken on 2007 April 25, a representative day in Period III, is shown in figure 6. This is the average of all the spectra obtained at the Gunma Astronomical Observatory on that day. It is seen that Hα turned to an absorption line with a narrow emission component, although it was in emission in Period II. He I 6678 also changed from an emission line into a very weak absorption one. We cannot clearly see the He I 5876 feature because of the low wavelength resolutions of the spectra obtained in this period. Other Balmer lines were still in absorption, but became deeper than in Period II. The emission components of Hβ and Hγ observed in Period II disappeared. The He I lines, except for He I 5876 and He I 6678, still remained in absorption.

3.4. Period IV: The long fading tail phase (May 11 and 19)

Figure 7 shows the normalized spectrum on 2007 May 19 in Period IV. This is the averaged spectrum taken at the Gunma Astronomical Observatory on that day. In this period, the signal-to-noise ratio was low due to the faintness of GW Lib. We can see, however, that Hα, Hβ, Hγ, and He I 6678 were present in emission. Note that the FWHM of Hα was ≈22 Å on 2007 May 19, which is 1.5 times broader than that on 2007 April 14, ≈13 Å, just after the superoutburst maximum (both data were obtained with the same instrument at the Gunma Astronomical Observatory and hence direct comparison can be made.).
Fig. 8. Hα profile variations as a function of orbital phase on April 14, 25, 27, May 2, and 4. The dot-dashed line corresponds to the rest-frame wavelength of Hα. There is no clear variation of the central wavelength of the emission component with orbital phase within our low-resolution spectra.
In this subsection, we explore the evolution of the structure of the accretion disk in the superoutburst, mainly using the Hα profile variation as described in section 3. The changes of the spectral features, shown in figure 9, are summarized in section 4.2.1.

4.2.1. Summary of Spectral Change

We detected only Balmer absorption lines of Hα, Hβ, and Hγ (see figure 4) in the rising phase of the superoutburst. Around and just after the superoutburst maximum, the emission lines of Hα, He I 5876, He I 6678, He II 4686, and C III/N III were observed as well as the absorption lines of Balmer components and He I (see figure 5). These high-excitation emission lines of He II 4686 and C III/N III became much fainter by the fourth day from the superoutburst maximum. In the latter part of the plateau, Hα turned to an absorption line with a weak emission component, and He I 6678 also changed into a weak absorption line (see figure 6). Other Balmer and He I components remained to be absorption lines, and the Balmer components became deeper. In the long fading tail, only emission lines of Hα, Hβ, Hγ, and He I 6678 were observed (see figure 7). The profile variability of He I 6678 was almost the same as that of Hα during our observations, except for April 12.

4.2.2. Line Forming Mechanisms

The absorption/emission profile of Hα contains key information to understand the evolution of the accretion disk structure. Generally, an absorption line is formed when the continuum emitter is optically thick with a normal temperature gradient along the vertical axis (i.e., the temperature decreases toward its surface). On the other hand, an emission line can be produced from (1) an optically thin, collisionally excited plasma, or (2) a photoionized one, or (3) a temperature inversion layer of an optically thick matter. In DNe, photoionization of an outer disk is expected by irradiation from the white dwarf and the inner (hence hotter) part of the accretion disk. The temperature inversion layer may be formed on the surface of the disk by local heating by magnetic activities or other mechanisms; in the following discussion, we do not discuss the last possibility, however, since there is no observational evidence for it in DNe at present.

4.2.3. Similarity between GW Lib and WZ Sge

For reference, we compare the spectral evolution of GW Lib observed in our data, and that of WZ Sge during the 2001 superoutburst reported by Baba et al. (2002) and Nogami & Iijima (2004), the same type of DNe as GW Lib seen with a high inclination. In both stars, the spectra showed Balmer absorption lines in the rising phase. Around and just after the superoutburst maximum, Hα, He II 4686, and C III/N III turned to be emission lines in both systems. An asymmetric spiral structure was seen in the doppler map of Hα and He II in WZ Sge, which are considered to be connected with the early superhumps (Osaki & Meyer 2002; Kato 2002). The region forming these emission lines is located around the edge of the accretion disk in the Doppler map.

4.2.4. Evolution of the Accretion Disk Structure

Based on the comparison of spectral features between GW Lib and WZ Sge during their superoutbursts, we propose the following scenario for the evolution of the accretion disk that is commonly applicable to both systems. From the results of WZ Sge, we consider that photoionization is the most likely origin of the observed emission lines. If they were instead produced from an optically thin, collisionally excited plasma, the temperatures of those regions producing Hα and He II lines would be different by factor ∼ 4. In reality, however, the Doppler maps of WZ Sge show that both lines are emitted at similar radii in the accretion disk (Baba et al. 2002; Nogami & Iijima 2004),
Fig. 9. Blow up of figure 3, showing the profiles from 4000 Å to 5000 Å (left) and around Hα (right). Bottom corresponds to Period I and II, middle to Period III, top to Period IV.
where the temperature is expected to be different by at most factor 2. We note that this photoionized region is very likely to be optically thin, considering the presence of the spiral structure.

- **Rising phase:** The whole disk is optically thick and is expanding in the rising phase of the superoutburst. This situation means that irradiation from the white dwarf and the inner part of the accretion disk was not yet effective at our first observation during the rising phase. This is also consistent with the “UV delay” phenomenon that an increase of the ultraviolet flux lags that of the optical flux by about 1 day (e.g. VW Hyi, Hassall et al. 1983; SS Cyg, Pudaln & Holberg 1984; WX Hyi, Hassall et al. 1985; RX And, Pringle & Verbunt 1984). The UV delay is interpreted to represent the time the mass accreted from the outer edge of the accretion disk takes to reach the white dwarf (Mineshige 1988; Duschl 1989; Meyer & Meyer-Hofmeister 1989; Livio & Pringle 1992; King 1997).

- **Maximum to plateau:** The disk then forms an outer extended region, which starts to be strongly photoionized by the increasing UV photons from the white dwarf and inner disk after around the maximum. The photoionized region must be sufficiently large to subdue a solid angle, since the intensity of the emission component was dominant in the Hα profile around the maximum. While the superoutburst is continuing in the plateau phase, the region shrinks as the matter is accreted into smaller radii. Such geometrical evolution of the accretion disk during the outburst is theoretically expected (Osaki 1996) and is actually indicated by observations of other DNe in eclipse (e.g. U Gem: Smak 1984; Z Cha: O'Donoghue 1986; IP Peg: Wood et al. 1989, and Wolf et al. 1993). The decrease of the UV photon flux also reduces the intensity of the emission lines. The higher energy photons decreases more rapidly, causing the faster decay of He II emission lines compared with Hα.

- **Fading phase:** In the long fading tail, the whole accretion disk turns to be optically thin (without irradiation), and hence produces emission lines by collisional excitation. This situation is the same as in quiescence (Szkody et al. 2000), although the accretion disk is somewhat brighter, and hence the broad Balmer absorption features produced by the white dwarf are apparently weaker, than in quiescence.

### 4.2.5. Difference between GW Lib and WZ Sge

A difference between GW Lib and WZ Sge is found in the Hα component in the latter part of the plateau phase. In GW Lib, all the emission lines of Hα, He II 4686, and C III/N III significantly weakened from the earlier epoch. In WZ Sge, while the He II 4686 and C III/N III lines weakened, the Hα intensity remained much stronger compared with GW Lib. The peak separations of the He II 4686 and C III/N III of WZ Sge became wider, indicating that the region producing high excitation lines shrunk into small radii. This is consistent with our picture of the disk evolution. The difference in the Hα profile between the two stars may be related to the rebrightening in WZ Sge after the main superoutburst, which was not observed in GW Lib. The mechanism of the rebrightening is still an open question. Some authors, nevertheless, have suggested that significant mass is left around the bright accretion disk (e.g. Kato et al. 1998; Hellier 2001b; Osaki et al. 2001), and in fact Uemura et al. (2008) found a large cool region around a hot accretion disk by near-infrared observations of SDSS J102146.44+234926.3, a WZ Sge-type DN, during the rebrightening phase. By contrast, GW Lib did not have this region during the plateau phase, which could not cause a rebrightening and a strong Hα emission line.

### 5. SUMMARY

1. We have compiled a large number of optical spectroscopic data of GW Lib taken by the international observation campaign during the 2007 superoutburst. The observations started from the very beginning of the superoutburst, covering the rising phase, maximum, plateau, and long fading phase. We find that the profiles of spectral lines dramatically changed during the superoutburst.

2. Comparing our results with those of WZ Sge, the same type of DNe viewed with a high inclination angle, we construct a unified picture for the evolution of the accretion-disk structure in superoutburst applicable to these systems.

3. In the rising phase of the superoutburst, all Balmer lines are in absorption. We consider that the whole accretion disk is optically thick and is extending toward the white dwarf. The UV delay is consistently explained.

4. Around the maximum, the spectrum showed singly-peaked emission lines of Hα, He I 6678, He II 4686, and C III/N III superposed on absorption lines of Balmer components and He I. We interpret that the emission lines are produced by photoionization of an optically thin region formed at the outer part of the disk, irradiated from the white dwarf and the inner part of the disk. The emission components significantly weakened in the latter part of the plateau phase. This can be explained by the shrinkage of the optically-thin region due to accretion and by decrease of irradiation.

5. In the fading tail, all Balmer lines were emission lines, as observed in quiescence. We consider that the whole disk is optically thin and emits lines by collisional excitation in this state.

The authors are thankful to amateur observers for continuously reporting their valuable observations to VSNET. We are also indebted to Taichi Kato for his useful comments on the draft. This work is partly supported by Research Fellowships of Japan Society for the Promotion of Science for Young Scientists (A1), and by the Grant-in-Aid for the Global COE Program “The Next Generation of Physics, Spun from Universality and Emergence” from the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan.
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