Swift observations of GW Lib: a unique insight into a rare outburst

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ABSTRACT
The second known outburst of the WZ Sge type dwarf nova GW Lib was observed in April 2007. We have obtained unique multiwavelength data of this outburst which lasted ∼ 26 days. AAVSO observers recorded the outburst in the optical, which was also monitored by WASP, with a peak V magnitude of ∼ 8. The outburst was followed in the UV and X-ray wavelengths by the Swift UVOT and XRT telescopes. The X-ray flux at optical maximum was found to be three orders of magnitude above the pre-outburst quiescent level, whereas X-rays are normally suppressed during dwarf nova outbursts. A distinct supersoft X-ray component was also detected at optical maximum, which probably arises from an optically-thick boundary layer. Follow-up Swift observations taken one and two years after the outburst show that the post-outburst quiescent X-ray flux remains an order of magnitude higher than the pre-outburst flux. The long interoutburst timescale of GW Lib with no observed normal outbursts support the idea that the inner disc in GW Lib is evacuated or the disc viscosity is very low.

Key words: accretion, accretion discs – stars: dwarf novae – stars: novae, cataclysmic variables – X-rays: stars – X-rays: binaries

1 INTRODUCTION

Dwarf novae (DNe) are non-magnetic cataclysmic variables (CVs) with accretion discs and with a white dwarf primary and a main sequence secondary star. They are relatively nearby sources which provide a laboratory for studying accretion disc physics in our Galaxy. The orbital periods of DNe are typically between 70 min and 10 h. From time to time, the disc goes into an outburst which is a brightening of the disc by 2–9 magnitudes and which can last from days to several weeks. The mechanism leading to a dwarf nova outburst is thought to be a disc instability which was first proposed by Hoshi (1979) (for a more detailed discussion see Lasota (2001)). After this luminous phenomenon, the system returns to quiescence which can last from ∼ 10 days to decades. The disc dominates the optical emission during an outburst. SU UMa type dwarf novae show superoutbursts which can last for several weeks and are characterized by superhumps, periodic brightenings whose recurrence times are slightly longer than the orbital period. Superhumps are thought to be due to a 3:1 resonance in the accretion disc (Whitehurst 1988). While most SU UMa types show normal outbursts and superoutbursts, a subset called the WZ Sge stars only have superoutbursts. A typical feature of superoutbursts is a plateau phase in the optical lightcurve lasting for several days.

GW Lib was discovered in 1983 when it went into an outburst (Maza & Gonzalez 1983). It was present in ESO B Survey plates at magnitude 18.5 preceding the 1983 outburst. GW Lib brightened by 9 magnitudes during the outburst and later faded back to the quiescent state and thus was classified as a nova. Later studies showed that the spectrum resembled a dwarf nova in quiescence (Duerbeck & Seitter 1987). Since 1983, no other outbursts of GW Lib had been observed until that of April 12, 2007 (Templeton 2007). This outburst, which was recorded by the AAVSO observers, WASP-South and by Swift, lasted for 26 days. The brightest optical magnitude was reached at ∼ 8 mag in the V band. GW Lib has been classified as a WZ Sge type star due to its short period (\(P_{\text{orb}} = 76.78\) min, Thorstensen 2002) and low accretion rate (van Zyl et al. 2004). Typical characteristics of WZ Sge type stars are short
orbital periods, low mass-transfer rates and extremely long recurrence times which can last for decades. GW Lib was the first observed CV in which the accreting white dwarf showed non-radial pulsations (Warner & van Zyl 1998). This phenomenon was not expected to be discovered in accreting binaries since they were considered to be too hot to be located in the DAV instability strip, although low mass transfer rates from the secondary would explain low net accretion rates onto the white dwarf, and thus a lower accretion heating of the white dwarf (van Zyl et al. 2000). The pulsations of white dwarfs are thought to be due to g-mode non-radial gravity waves (Koeper & Chanmugam 1990). In GW Lib, pulsations are seen near 230, 370 and 650 s in the optical (Szkydy et al. 2002). An XMM-Newton observation of GW Lib obtained in 2005 during its quiescent state reveals that these pulsations are also present in the XMM-Newton Optical Monitor (OM) data, but not seen in the X-ray data (Hilton et al. 2007). These XMM-Newton observations also confirmed that GW Lib has a very low accretion rate during quiescence.

In this paper, we present the 2007 outburst lightcurves of GW Lib in the optical (AAVSO and WASP-South), UV (Swift, UVOT) and X-ray (Swift, XRT) bands. We also present X-ray spectral analysis of the outbursts and follow-up Swift observations of GW Lib in 2008 and 2009. Previous multiwavelength observations covering outbursts of SU UMa (and WZ Sge) type systems have been obtained from e.g. VW Hya (Pringle et al. 1987, Wheatley et al. 1996b), WZ Sge (Kuulkers et al. 2002, Wheatley & Mauche 2003), and OY Car, which was observed by the EUVE (Mauche & Raymond 2000). Multiwavelength observations of dwarf novae are needed in order to enhance our knowledge of astrophysical systems with discs, e.g., X-ray binaries and AGNs. DN outbursts offer a good opportunity to study the disc physics, and compare the current theory of outbursts with the observational information. The fact that GW Lib does not show any normal outbursts and the recurrence time between the two major outbursts was over 20 years, suggests that the disc structure could be different from most other dwarf novae.

2 OBSERVATIONS AND DATA REDUCTION

GW Lib was initially observed by the Swift Gamma-ray Burst Explorer (Gehrels et al. 2004) between April 13th and May 16th, 2007, over an interval of 30 days. The data were obtained with the Ultraviolet/Optical Telescope (UVOT) (Roming et al. 2005) and with the X-ray telescope (XRT) (Burrows et al. 2003) which has an energy resolution of 140 eV at 5.9 keV (at launch) (see Capalbi et al. 2005, R ∼ 40). The XRT was operating in the Window Timing (WT) and Photon-Counting (PC) modes during the observations. The UVOT observations were obtained in the imaging mode with the UV grism in order to provide spectral information and to mitigate against coincidence losses. The resolution of the UV grism is R ∼ 150 for 11–15 magnitude range stars. The details of the 38 observations are listed in Table 1. The first two observations were obtained in imaging mode with the UVM2 filter, but these suffer from severe coincidence loss effects and were thus excluded from our analysis. The optical data were provided by the AAVSO observers and by the Wide Angle Search for Planets (WASP) (Pollacco et al. 2004).

In addition to the outburst observations, follow-up Swift observations of GW Lib were made in April-May 2008 and February-March 2009. For these observations the V and UVW1 filters were used in the UVOT instrument. The details of these observations are also given in Table 1.

2.1 UV grism data reduction

The Swift UV grism was operating in c Malked mode at the time of the outburst observations. We have used our own automated pipeline, based around UVOT Swift FTOOLS (Jimmer et al. 2006) for the spectral extraction of the UV grism data. The release version which we used (HEASoft v.6.1.2) of the Swift UVOT analysis software does not allow grism spectra to be traced, nor extracted optimally. Thus under FTOOLS, we were restricted to using a box extraction of a fixed width for both source and background regions. The extraction box must be well-centered, aligned in so far as is possible with the dispersion direction and broad enough that slight miscenterings do not preferentially exclude flux from the wings of the extracted spectra at specific wavelengths. For a well-centered box, a width of 35 pixels contains 90 percent of the integrated source counts, and this was the width chosen. Larger widths increase the source counts, but can also add in poorly subtracted background counts, and thus do not enhance the statistical quality, and further increases the likelihood of contamination by nearby sources. For the background, we used extraction widths of 25 pixels.

After having chosen our source and background regions for each observation, the images were corrected for mod-8 fixed pattern noise, and source and background spectra were extracted automatically using the FTOOL uvotimgrism. Response functions were then created with uvotrmsgen. Unfortunately, the last 39 spectra from 10 May 2007 onwards were taken at a roll-angle which placed a nearby source (TYC6766-1570-1) on a line between our source and in the same direction as the dispersion direction. These spectra were severely contaminated and we therefore exclude them from our analysis. The wavelength range of the UV data for the lightcurve was restricted to 2200–4000 Å due to contamination by other 0th order spectra in the short wavelength end.

The 2008 and 2009 observations were obtained in filter mode. We derived the V and UVW1 (X = 2600 Å) fluxes and magnitudes using the FTOOL uvotmaghist. The source counts were extracted by using circular extraction region with r_src = 5 arcsec. A circular background region with a radius of r_bg = 10 arcsec was placed on a source free region in the field of view.

2.2 X-ray data reduction

The X-ray data reduction was performed with the standard Swift pipelines retaining grades 0–12 for the PC mode and...
The Swift observations of GW Lib obtained in 2007, 2008 and 2009.

| OBSID   | T_{start}  | Roll angle | UVOT exposure (s) | XRT WT exposure (s) | XRT PC exposure (s) | Ugrism exposure (s) |
|---------|------------|------------|-------------------|---------------------|---------------------|---------------------|
| 30917001 | 2007-04-13T15:19:47 | 133 | 4914 | 2902 | 1910 | 0 |
| 30917002 | 2007-04-18T06:22:00 | 136 | 4781 | 2755 | 0 | 0 |
| 30917003 | 2007-04-20T17:53:57 | 141 | 992 | 5 | 990 | 992 |
| 30917004 | 2007-04-21T03:47:02 | 142 | 769 | 4 | 772 | 769 |
| 30917005 | 2007-04-21T14:55:01 | 142 | 904 | 2 | 910 | 904 |
| 30917006 | 2007-04-21T22:56:00 | 142 | 1442 | 4 | 1447 | 1442 |
| 30917008 | 2007-04-22T23:02:00 | 142 | 1264 | 2 | 1271 | 1264 |
| 30917009 | 2007-04-22T23:02:00 | 142 | 1264 | 2 | 1271 | 1264 |
| 30917010 | 2007-04-23T11:42:01 | 142 | 1050 | 8 | 1048 | 1050 |
| 30917011 | 2007-04-24T00:50:00 | 142 | 1352 | 13 | 1349 | 1352 |
| 30917012 | 2007-04-24T22:50:01 | 142 | 1428 | 4 | 1294 | 1288 |
| 30917013 | 2007-04-24T23:02:00 | 142 | 1264 | 2 | 1271 | 1264 |
| 30917014 | 2007-04-25T02:38:00 | 142 | 1642 | 4 | 1447 | 1442 |
| 30917015 | 2007-04-25T12:55:01 | 142 | 904 | 2 | 910 | 904 |
| 30917016 | 2007-04-25T22:15:01 | 142 | 1442 | 4 | 1447 | 1442 |
| 30917017 | 2007-04-26T00:50:00 | 142 | 769 | 4 | 772 | 769 |
| 30917018 | 2007-04-26T14:55:01 | 142 | 904 | 2 | 910 | 904 |
| 30917019 | 2007-04-26T22:56:00 | 142 | 1442 | 4 | 1447 | 1442 |
| 30917020 | 2007-04-27T00:50:00 | 142 | 1264 | 2 | 1271 | 1264 |
| 30917021 | 2007-04-27T12:55:01 | 142 | 904 | 2 | 910 | 904 |
| 30917022 | 2007-04-27T22:56:00 | 142 | 1442 | 4 | 1447 | 1442 |
| 30917023 | 2007-04-28T00:50:00 | 142 | 769 | 4 | 772 | 769 |
| 30917024 | 2007-04-28T12:55:01 | 142 | 904 | 2 | 910 | 904 |
| 30917025 | 2007-04-28T22:56:00 | 142 | 1442 | 4 | 1447 | 1442 |
| 30917026 | 2007-05-01T00:50:00 | 142 | 1264 | 2 | 1271 | 1264 |
| 30917027 | 2007-05-01T12:55:01 | 142 | 904 | 2 | 910 | 904 |
| 30917028 | 2007-05-01T22:56:00 | 142 | 1442 | 4 | 1447 | 1442 |
| 30917029 | 2007-05-02T00:50:00 | 142 | 1264 | 2 | 1271 | 1264 |
| 30917030 | 2007-05-02T12:55:01 | 142 | 904 | 2 | 910 | 904 |
| 30917031 | 2007-05-02T22:56:00 | 142 | 1442 | 4 | 1447 | 1442 |
| 30917032 | 2007-05-03T00:50:00 | 142 | 1264 | 2 | 1271 | 1264 |
| 30917033 | 2007-05-03T12:55:01 | 142 | 904 | 2 | 910 | 904 |
| 30917034 | 2007-05-03T22:56:00 | 142 | 1442 | 4 | 1447 | 1442 |
| 30917035 | 2007-05-04T00:50:00 | 142 | 1264 | 2 | 1271 | 1264 |
| 30917036 | 2007-05-04T12:55:01 | 142 | 904 | 2 | 910 | 904 |
| 30917037 | 2007-05-04T22:56:00 | 142 | 1442 | 4 | 1447 | 1442 |

0–2 for the WT mode data. The Swift X-ray data cover the energy range 0.3–10 keV, but the source is detected only up to 8.0 keV. The X-ray lightcurve was extracted from the WT and PC mode data by using the tools described in Evans et al. (2009).

The X-ray spectra were extracted with xselect. For the WT mode data, a 40 pixel (94") box for the source and an 80 pixel (189") box for the background region were used. The normal limit for pile-up in WT mode data is ~ 100 ct/s (Romano et al. 2006), thus it was not necessary to account for this when extracting the spectra. The PC mode source data were extracted using a 20 pixel (47") circle and the background data within a 60 pixel (141") circular area. The PC mode data from the first observation were not used for spectral extraction. The PSFs of the rest of the PC mode data were checked to verify that pile-up did not occur.

### 2.3 WASP data reduction

GW Lib falls into a field which was being intensively monitored by the WASP search for transiting exoplanets (Pollacco et al. 2006) at the time of the outburst. The WASP is a wide-field imaging system with each instrument having a field of view of 482 deg². The photometric accuracy of the instruments is better than 1 per cent for objects with $V$ magnitude $\sim 7.0–11.5$. The field (centred on 15h 02m, 28d 22m) was observed between February 16, 2007, and July 19, 2007, with an average of 88 images per night, each
Figure 1. The optical, UV and X-ray outburst lightcurves of GW Lib. $T_0$ is JD 2454203.1, which corresponds to the start time of the first data point in the AAVSO lightcurve. The top panel shows the AAVSO optical lightcurve (www.aavso.org) in the V band (converted to log F) in black and the WASP lightcurve in light grey (see text for details). The upper panel insert shows the rapid rise to maximum peaking one day after the onset of the outburst. The middle panel shows the UV in the wavelength range 2200–4000 Å (Swift UV grism), and the bottom panel the X-ray lightcurve in 0.3–10.0 keV (Swift XRT). The X-ray data have been binned at 600 s and the other bands are plotted per exposure.

with an exposure time of 30 s. The data were extracted and calibrated in automated fashion using the standard WASP pipeline, full details of which are given in Pollacco et al. (2006).

3 TIME SERIES ANALYSIS

3.1 Outburst lightcurves

Fig. 1 presents the April-May 2007 outburst of GW Lib. The top panel shows the AAVSO V-band lightcurve in black and the WASP lightcurve ($V+R$ bands) in light grey (scaled to match the AAVSO V band magnitude). The magnitudes have been converted to log F in order to make comparison between the optical and UV lightcurves clearer. The middle and lower panels show the UV and X-ray lightcurves respectively. The AAVSO outburst lightcurve is already rising from magnitude 13 (log F ≈ -13.6 erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$) on JD 2454203.1 which we define as $T_0$. It reaches its highest peak one day later at magnitude 7.9 (log F ≈ -11.7 erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$), and after the peak, declines steadily for 23 days. At 29 days after the beginning of the outburst the optical brightness declines sharply to magnitude ~ 14 (log F ≈ -14.2 erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$), presumably as the accretion disc returns to its quiescent state. Large variations in the WASP lightcurve around day $T_0 + 11$, resulting from poor weather conditions were excluded.

The rise of the UV emission for GW Lib was not observed, and so we are not able to quantify any UV delay, such as that previously measured by e.g. Hassall et al. (1983) in VW Hyi. However, the system is already extremely UV bright at the time of the first Swift observations, 1 d after the beginning of the outburst, when the UVM2 filter was used. Unfortunately, these two observations are far too overexposed to provide useful flux measurements and they are not shown in our lightcurve. Our UV lightcurve (from the UVOT grism data) starts 8 d after the onset of the outburst. It remains almost flat for ~ 6 days and then starts to decline.
At 24.5 days after the optical rise the UV lightcurve shows a steep decline, approximately simultaneously with the sharp optical decline. It reaches a minimum about 2 d later. The UV data after the day $T_0 + 26.0$ have been excluded due to contamination.

The X-ray observations (0.3–10.0 keV) start 1 d after the rise in the optical, approximately at the time of the optical peak. Our data do not cover the rise of the X-rays, thus we are not able to quantify any delay between the optical and X-ray rise, such as that observed e.g. by Wheatley, Mauche & Mattel (2003) in SS Cyg. In GW Lib, the X-ray flux is initially $\sim 3$ orders of magnitude above its pre-outburst quiescent level (Hilton et al. 2007), and it declines rapidly for $\sim 10$ days before continuing to decline more slowly during the remainder of the optical outburst. Around day $T_0 + 26$, the flux dips sharply from $\log F_{0.3-10.0}\text{ keV} \approx -11.6$ erg cm$^{-2}$ s$^{-1}$ to $\log F_{0.3-10.0}\text{ keV} \approx -12.0$ erg cm$^{-2}$ s$^{-1}$, lasting for less than a day. We have checked these data carefully and it is clear that this is a real dip in the brightness of the source. After the dip, the X-rays rise to the level of $\log F_{0.3-10.0}\text{ keV} \approx -11.2$ erg cm$^{-2}$ s$^{-1}$ and show a bump between days $T_0 + 26$ and $T_0 + 29$, which peaks at approximately the same time that the UV lightcurve finishes its steep decline. From $T_0 + 29$ days onwards, the X-ray flux remains approximately constant at $\sim -11.5$ erg cm$^{-2}$ s$^{-1}$.

During the two follow-up Swift observations in 2008 the count rate was consistent on days $T_0 + 378$ and $T_0 + 392$ at $0.03 \pm 0.01$ ct s$^{-1}$. In 2009, 682 and 690 days since $T_0$, it was $0.04 \pm 0.01$ ct s$^{-1}$. For comparison, Hilton et al. (2007) report a quiescence count rate of $0.02 \pm 0.01$ ct s$^{-1}$ (0.2–10.0 keV) in the XMM-Newton pn camera on August 25–26, 2005, about two years before the outburst. Assuming a thermal bremsstrahlung model of $kT = 3$ keV, this corresponds to an XRT count rate of $0.002$ ct s$^{-1}$, lasting for less than a day. We have checked these data carefully and it is clear that this is a real dip in the brightness of the source. After the dip, the X-rays rise to the level of $\log F_{0.3-10.0}\text{ keV} \approx -11.2$ erg cm$^{-2}$ s$^{-1}$ and show a bump between days $T_0 + 26$ and $T_0 + 29$, which peaks at approximately the same time that the UV lightcurve finishes its steep decline. From $T_0 + 29$ days onwards, the X-ray flux remains approximately constant at $\sim -11.5$ erg cm$^{-2}$ s$^{-1}$.

Fig. 2 shows the soft X-ray lightcurve (upper panel) in the 0.3–1.0 keV band and the hard X-ray lightcurve (middle panel) in the 1.0–10.0 keV band from the outburst observations. The lower panel shows the hardness ratio (extracted by using the tools of Evans et al. 2009). The hardness ratio gradually increases during the outburst, and shows a sharp increase at the time of the bump in the X-ray light curve, which coincides with the steep decline in the optical and UV lightcurves.

3.2 Search for oscillations in the X-ray data

Pulsations were discovered in the quiescent optical emission of GW Lib by Warner & van Zyl (1998). Pulsation periods near 230, 370 and 650 s are seen in the optical and UV wavebands (e.g. van Zyl et al. 2004; Szkody et al. 2002) and an optical 2.1 h modulation was discovered by Woudt & Warner (2002). Copperwheat et al. (2009) found that the pulsation periods were suppressed after the 2007 outburst, but that the 2.1 h modulation remained.

Hilton et al. (2007) searched for these modulations in the XMM-Newton X-ray data taken during quiescence before the outburst, but did not detect any significant periodicities. They measured an upper limit of 0.092 mag for the X-ray pulsations.

We searched for periodicities from the outburst data by using two methods. When examining shorter timescales we took power spectra of near continuous sections of data, applying the normalisation of Leahy et al. (1983) which allows the noise powers to be easily characterised so that detection limits can be set (see also Lewin, Paradijs & van der Klis 1985). For this method, the WT mode data were binned into 1 s time bins and the PC mode data into 5 s bins, which gave approximately 512 and 256 time bins per Fourier transform from individual Swift orbits, respectively. This gave 13 transforms for the WT mode and 48 for the PC mode, from which the averaged power spectrum was constructed for each mode. At the 99 per cent confidence level, no periodicities were seen in the data with a fractional amplitude upper limit of 6 per cent (WT mode) over the period range 2–512 s, and 11 per cent (PC mode) over the period range 10–640 s.

When searching for longer timescale modulations, notably at 650 s and 2.1 hr ($\sim 7560$ s), as seen previously by the authors mentioned above, we initially calculated Lomb-Scargle periodograms of the data. Unfortunately, the identification of any potentially real modulation in the WT mode data at these timescales was hindered by the window function caused by the light curve sampling. However, by folding the PC mode data at the previously seen longer periods and at the orbital period ($P_{\text{orb}} = 76.78$ min, Thorstensen 2002)
we estimated 99 per cent upper limits to the fractional amplitude of any modulation at 650 s, 76.78 min (we estimated 99 per cent upper limits to the fractional amplitude of any modulation at 650 s, 76.78 min (\(\nu/\nu = 1.11/222\)). We tested whether a third optically-thin emission component would improve the fit, and found a slightly better fit statistic of \(\chi^2/\nu = 1.08/220\). Using the F-test, we found that this provides a better description of the underlying spectrum with a confidence of 98.5 per cent. Of course, these three distinct temperature components are most likely just an approximation to an underlying continuous distribution, such as the cooling flow models used by e.g. [Wheatley et al. (1996b) and Mukai et al. (2003)].

The data and the best-fit model components for S1 with residuals are plotted in Fig. 3. The full set of fitted parameters is given in Table 3. It is worth noting that the fitted abundance is low, only 0.02\(_{-0.01}^{+0.01}\) solar. We looked at this in some detail and found that the low abundance in our fit is driven entirely by the lack of thermal iron lines at around 6.7 keV. Strong line emission is predicted also by the model around 1 keV, but the spectral resolution here is not sufficient to provide strong constraints on abundances. Nevertheless, by fitting with a black body and three optically-thin thermal emission models with variable abundances (vmekal), we found that the high oxygen abundance reported by Hilton et al. (2007) in GW Lib in quiescence (6–8 \(\times\) solar) can be ruled out for our S1 spectrum. Setting the oxygen abundance to 6 \(\times\) solar in our model resulted in an unacceptable best-fit statistic of \(\chi^2/\nu = 1.62/221\). This fit is plotted in Fig. 5.

In order to investigate the evolution of the X-ray spectra of GW Lib during the outburst, we tested the need for multi-temperature optically-thin emission components and for the black body in a similar manner for the second spectrum S2 and the subsequent spectra S3, S4 and S5. Since the abundances of the spectra S2, S3, S4 and S5 were not well-constrained, they were fixed to the best fit abundance of spectrum S1. There is no evidence for the presence of a black body component in these spectra. Thus, a black body was not employed in the spectral fitting of the subsequent outburst spectra. The best fit for spectrum S2 was found with a photoelectric absorption and three optically-thin emission components which yielded a goodness of fit of \(\chi^2/\nu = 1.25/89\). The rest of the outburst spectra S3, S4 and S5 were fitted successfully with photoelectric absorption and two optically-thin emission components. The best fit values, their 90 per cent confidence limits and the unabsorbed flux for each thermal emission component in the 0.3–10.0 keV range are described by the model around 1 keV, but the spectral resolution here is not sufficient to provide strong constraints on abundances. Nevertheless, by fitting with a black body and three optically-thin thermal emission models with variable abundances (vmekal), we found that the high oxygen abundance reported by Hilton et al. (2007) in GW Lib in quiescence (6–8 \(\times\) solar) can be ruled out for our S1 spectrum. Setting the oxygen abundance to 6 \(\times\) solar in our model resulted in an unacceptable best-fit statistic of \(\chi^2/\nu = 1.62/221\). This fit is plotted in Fig. 5.

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\[4.2\text{ Fluxes, luminosities and accretion rates}\]

The total fluxes, luminosities and accretion rates in the 0.3–10 keV range are given in Table 3. The fluxes given in the 0.3–10 keV range are absorbed fluxes. The distance was taken to be \(r = 104\) pc (Thorstensen 2003). The accretion rates were estimated by using \(\dot{M} = 2LR_{WD}/GM_{WD}\), where we adopt \(M_{WD} = 1 M_{\odot}\) and \(R_{WD} = 5.5 \times 10^8\) cm (Townsley, Arras & Bildsten 2004). The first X-ray spectrum gives a luminosity of \(2.06 \times 10^{32}\) erg s\(^{-1}\) which corre-
The XRT spectra of the GW Lib outburst

![Graph showing XRT spectra of GW Lib](image)

**Figure 3.** The X-ray spectra of GW Lib throughout the outburst.

**Table 3.** The results of the spectral fitting using photoelectric absorption, black body and three optically-thin emission components. Not all components are fitted to all spectra. The errors correspond to the 90 per cent confidence limits for one parameter of interest. The measured abundance from the S1 spectrum is $0.02^{+0.01}_{-0.01}$, and the abundances in the other fits have been fixed at this value. The unabsorbed fluxes $F_1$, $F_2$ and $F_3$ correspond to the three optically-thin emission components in the 0.3–10.0 keV band.

| Spectrum | S1 | S2 | S3 | S4 | S5 |
|----------|----|----|----|----|----|
| Model    | wa(bb+3me) | wa(3me) | wa(2me) | wa(2me) | wa(2me) |
| $n_H$ ($10^{20}$ cm$^{-2}$) | $23.83^{+0.05}_{-0.04}$ | $8.61^{+5.38}_{-3.99}$ | $8.15^{+1.23}_{-1.17}$ | $13.25^{+7.28}_{-3.34}$ | $14.63^{+6.86}_{-4.36}$ |
| $kT_{bb}$ (keV) | $0.013^{+0.001}_{-0.001}$ | – | – | – | – |
| $kT_1$ (keV) | $5.46^{+1.26}_{-0.86}$ | $4.80^{+5.07}_{-1.66}$ | $5.79^{+2.73}_{-1.54}$ | $5.19^{+5.13}_{-1.88}$ | $4.92^{+3.82}_{-1.36}$ |
| $kT_2$ (keV) | $0.71^{+0.23}_{-0.13}$ | $0.64^{+0.21}_{-0.14}$ | $0.66^{+0.06}_{-0.07}$ | $0.57^{+0.23}_{-0.24}$ | $0.48^{+0.20}_{-0.16}$ |
| $kT_3$ (keV) | $0.17^{+0.01}_{-0.01}$ | $0.17^{+0.10}_{-0.05}$ | – | – | – |
| $F_1$ ($10^{-12}$ erg/cm$^2$/s) | 120. | 6.72 | 3.05 | 3.88 | 3.62 |
| $F_2$ ($10^{-12}$ erg/cm$^2$/s) | 30.5 | 8.44 | 3.94 | 2.38 | 1.67 |
| $F_3$ ($10^{-12}$ erg/cm$^2$/s) | 271. | 4.00 | – | – | – |
| $\chi^2/\nu$ | 1.08/220 | 1.25/89 | 1.13/150 | 0.94/50 | 1.19/56 |
Figure 4. Upper panel: best-fit model components of the first outburst spectrum (S1) of GW Lib. The data are fitted with a black body and three optically-thin thermal emission components, all absorbed by the same column density. Lower panel shows the residuals.

Figure 5. Upper panel: a spectral fit (a black body and three optically-thin thermal emission models with variable abundances (\(v_{\text{mekal}}\)) to the first outburst spectrum (S1) with the oxygen abundance fixed to that found in the XMM-Newton quiescent spectrum by Hilton et al. (2007). An oxygen line of this strength (at 0.65 keV) would be detected and the fit is unacceptable with \(\chi^2/\nu = 1.62/221\). The lower panel shows clear residuals between 0.55–0.70 and above 6.5 keV.

sponds to \(\dot{M} = 1.71 \times 10^{15} \text{ g s}^{-1}\) or \(2.7 \times 10^{-11} \text{ M}_\odot \text{ yr}^{-1}\) in the 0.3–10 keV band. Since we do not see a rise in the X-rays, we are not able to say whether this is the peak luminosity of this outburst. We also derived the corresponding parameters for the bolometric luminosity by extrapolating our spectral fit over the range 0.0001–100 keV. The bolometric luminosity of the black body component in spectrum S1 is not well constrained, and the best fit value exceeds the Eddington limit of \(1.3 \times 10^{38} \text{ erg s}^{-1}\) for the assumed mass; Fig. 6 shows the 68, 90 and 99 per cent confidence levels of \(n_H\) v. \(kT_{bb}\) and the corresponding range of bolometric luminosities. It can be seen that fits are allowed with much lower absorption column densities and luminosities. There is no reason to believe that the luminosity would exceed the Eddington limit. Estimating the luminosities of supersoft X-ray sources with black body models is notoriously unreliable.
Table 4. The fluxes, luminosities and accretion rates in the 0.3–10 keV (fluxes absorbed) and 0.0001–100 keV (bolometric, fluxes unabsorbed) bands of the XRT spectra.

| Spec | Flux (erg cm$^{-2}$ s$^{-1}$) | Luminosity (erg s$^{-1}$) | $M$ (g s$^{-1}$) | Flux (erg cm$^{-2}$ s$^{-1}$) | Luminosity (erg s$^{-1}$) | $M$ (g s$^{-1}$) |
|------|------------------------------|---------------------------|-----------------|------------------------------|---------------------------|-----------------|
|      | (0.3–10 keV)                | (0.3–10 keV)              | (0.0001–100 keV) | (0.3–10 keV)                | (0.0001–100 keV)              | (0.0001–100 keV) |
| S1   | 1.60×10$^{-10}$             | 2.06×10$^{12}$            | 1.71×10$^{15}$  | –                           | 6.66×10$^{31}$              | 5.52×10$^{14}$  |
| S2   | 1.25×10$^{-11}$             | 1.63×10$^{11}$            | 1.35×10$^{14}$  | 5.10×10$^{-11}$             | 6.66×10$^{31}$              | 5.19×10$^{14}$  |
| S3   | 5.18×10$^{-12}$             | 6.66×10$^{10}$            | 5.52×10$^{13}$  | 1.12×10$^{-11}$             | 6.66×10$^{31}$              | 1.19×10$^{14}$  |
| S4   | 4.38×10$^{-12}$             | 5.63×10$^{10}$            | 4.67×10$^{13}$  | 9.53×10$^{-12}$             | 6.66×10$^{31}$              | 1.02×10$^{14}$  |
| S5   | 3.66×10$^{-12}$             | 4.71×10$^{10}$            | 3.89×10$^{13}$  | 8.12×10$^{-12}$             | 6.66×10$^{31}$              | 8.62×10$^{13}$  |

Figure 6. Black body parameters derived from the first outburst spectrum (S1) of GW Lib. The 10$^{38}$ ($L_{\text{edd}}$), 10$^{37}$ (0.1 $L_{\text{edd}}$) and 10$^{36}$ erg s$^{-1}$ (0.01 $L_{\text{edd}}$) bolometric luminosity levels of the black body component are shown as dashed lines. The contours describe the 68, 90 and 99 per cent confidence levels for $n_H$ v. $kT_{bb}$.

(e.g. Krautter et al. 1996). Consequently we do not attempt to give a bolometric luminosity for S1 in Table 4.

4.3 Later X-ray observations

We also determined the flux and luminosity for the individual integrated spectra of the 2008 and 2009 observations, and for the combined 2008+2009 spectrum. The spectra were fitted with an absorbed single-temperature optically-thin thermal emission model. For the individual 2008 and 2009 spectra, we used Cash statistics due to the low number of counts. The spectral fitting parameters with fluxes and luminosities are given in Table 5. The abundance was unconstrained by the data and we fixed the value of $Z = 0.02$ $Z_\odot$ as obtained in outburst. The values in Table 5 show that the state of GW Lib did not change much between the 2008 and 2009 observations. Compared to the luminosity obtained by Hilton et al. (2007) before the outburst ($L(0.2–10$ keV) = 9 × 10$^{28}$ erg s$^{-1}$), GW Lib is still an order of magnitude brighter in the Swift observations ∼ two years after the outburst.

4.4 Outburst UV spectra

Four background-subtracted source UV outburst spectra and one background spectrum are shown in Fig. 7. The observing dates corresponding to each spectrum are given in Table 6. They were chosen to represent the evolution of the UV data with time. The spectra show a blue continuum without strong emission or absorption lines, although weak features would be difficult to identify as the spectra suffer from modulo-8 fixed pattern noise. The top spectrum is an average of three source spectra corresponding to days $T_0 + 8$, 13 and 18 during the initial slow decline in Fig. 1. The two subsequent spectra are from days $T_0 + 23$ (before the steep decline) and $T_0 + 26$ (after the steep decline). The
penultimate spectrum averages three spectra around day $T_0 + 27$ and the bottom spectrum shows the background flux for one of the source spectra on day $T_0 + 27$. It seems the spectra become less blue after the sharp decline. All of the spectra, including the background spectrum, show a bump around $\sim 2900$ Å. This feature is most likely due to the contribution of the second order spectrum (see “Notes for observing with the UVOT UV grism” which shows that for a calibration white dwarf the second-order UV light starts $\sim 2800$ Å). In the last two source spectra, the background noise features are becoming clearer when the source itself is becoming fainter.

The July 2001 HST/STIS outburst spectrum of WZ Sge showed a Mg II absorption line at 2790–2810 Å (Kuulkers et al. 2002), Kuulkers et al. 2002) note that most of it originates from WZ Sge and part of it is due to interstellar absorption. This line is not seen in the UV spectra of GW Lib probably due to the much lower resolution of the UV grism.

The calibration of the UV grism is on-going, and consequently absolute flux measurements remain uncertain. Nevertheless, we measured monochromatic fluxes at $2200$ Å for the source spectra in Fig. 7 and obtained $\lambda F_{2200} \sim 1.49 \times 10^{-9}$, $1.14 \times 10^{-9}$, $2.13 \times 10^{-10}$, and $1.15 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$ respectively. For $L = 4 \pi r^2 F$ with $r = 104$ pc (Thorstensen 2003), the fluxes given above correspond to monochromatic luminosities $L_{2200}$ of $\sim 1.95 \times 10^{33}$, $1.49 \times 10^{33}$, $2.78 \times 10^{32}$, and $1.50 \times 10^{32}$ erg s$^{-1}$.

### Table 5. The spectral fitting parameters with fluxes and luminosities of the 2008 and 2009 (columns 2 and 3) X-ray observations of GW Lib. The fourth column shows the spectral fitting parameters for the combined 2008 and 2009 spectrum.

| Parameter | 2008 | 2009 | 2008+2009 |
|-----------|------|------|-----------|
| $n_H$ 10$^{20}$ cm$^{-2}$ | $7.23^{+5.74}_{-5.08}$ | $5.63^{+5.09}_{-4.32}$ | $0.11^{+4.45}_{-0.11}$ |
| $kT$ keV | $1.20^{+0.64}_{-0.33}$ | $2.00^{+1.09}_{-0.64}$ | $3.51^{+1.46}_{-1.16}$ |
| $F(0.3–10$ keV) erg cm$^{-2}$ s$^{-1}$ | $7.5\times 10^{-13}$ | $8.5\times 10^{-13}$ | $1.1\times 10^{-12}$ |
| $L(0.3–10$ keV) erg s$^{-1}$ | $9.8\times 10^{29}$ | $1.1\times 10^{30}$ | $1.4\times 10^{30}$ |
| $\dot{M}(0.3–10$ keV) g s$^{-1}$ | $8.2\times 10^{12}$ | $9.1\times 10^{12}$ | $1.2\times 10^{13}$ |
| $F(0.0001–100$ keV) erg cm$^{-2}$ s$^{-1}$ | $1.4\times 10^{-12}$ | $1.4\times 10^{-12}$ | $1.3\times 10^{-12}$ |
| $L(0.0001–100$ keV) erg s$^{-1}$ | $1.8\times 10^{30}$ | $1.8\times 10^{30}$ | $1.7\times 10^{30}$ |
| $\dot{M}(0.0001–100$ keV) g s$^{-1}$ | $1.5\times 10^{13}$ | $1.5\times 10^{13}$ | $1.4\times 10^{13}$ |

4.5 Later UV observations

We studied the follow-up UVOT observations from 2008 and 2009 in order to see how the UV magnitudes and fluxes have changed since the outburst. The results are given in Table 7. Since the last measurement in the outburst lightcurve, the UV flux has faded by 0.8 in log $F$.

#### Table 6. The observation dates since the onset of the outburst for the UV grism spectra in Fig. 7

| $T_0$ + ObsDate |  |
|-----------------|---|
| 8               | 2007-04-20 |
| 13              | 2007-04-25 |
| 18              | 2007-04-30 |
| 23              | 2007-05-05 |
| 26              | 2007-05-08 |
| 27              | 2007-05-09 |

#### Table 7. The average magnitudes, fluxes and their 1σ errors in the UVOT V and UVW1 ($\lambda = 2600$ Å) filters for the 2008 and 2009 observations of GW Lib. The magnitudes and fluxes are the mean values of different snapshots. Observation time corresponds to the midpoint of each observation in days since $T_0$. The exposure times are given in Table 1.

| ObsID | Obstime d | Filter | Magnitude | log Flux |
|-------|------------|--------|-----------|----------|
| 7042  | 378.25     | V      | 16.37     | -14.979  |
| 7042  | 378.25     | UVW1   | 14.69     | -14.277  |
| 7043  | 385.21     | V      | 16.40     | -14.987  |
| 7044  | 392.04     | V      | 16.39     | -14.987  |
| 7044  | 392.04     | UVW1   | 14.60     | -14.243  |
| 7045  | 682.08     | V      | 16.54     | -15.042  |
| 7045  | 682.08     | UVW1   | 14.84     | -14.339  |
| 7046  | 689.81     | V      | 16.53     | -15.039  |
| 7046  | 689.81     | UVW1   | 14.84     | -14.338  |

5 DISCUSSION

In most cases, the hard X-ray emission of dwarf novae is suppressed during an outburst. This is the case for VW Hyi (Wheatley et al. 1996a), SS Cyg (Ricketts, King, & Raine 1979; Jones & Watson 1992; Wheatley, Mauche & Mattei 2003), Z Cam (Wheatley et al. 1996a), YZ Cnc (Verbunt, Wheatley & Mattei 1999) and WZ Sge (Wheatley & Mauche 2003). In contrast, the outburst X-ray emission of GW Lib peaks at 2-3 orders of magnitude higher than its quiescent level obtained by XMM-Newton in 2005 (Hilton et al. 2007). U Gem is the only other dwarf nova seen to increase its X-ray luminosity during an outburst (Swank et al. 1978), and in this case the outburst emission is only about a factor of five above its quiescent level (Mattei, Mauche & Wheatley 2000).

The absolute luminosity of the peak X-ray emission of GW Lib is high, but not extraordinary (Table 1). It is about a factor of two less than the X-ray luminosity of SS Cyg at optical maximum (which corresponds to the second, weaker peak in the X-ray light curve of SS Cyg; Wheatley, Mauche & Mattei 2003), and it is only a

http://swift.gsfc.nasa.gov/docs/swift/analysis/uvot_ugrism.html
factor of two more luminous than RU Peg in outburst, and a factor of three brighter than SU UMa in outburst (Baskill, Wheatley & Osborne 2005). GW Lib seems to stand out due to its unusually low X-ray luminosity in quiescence, rather than an exceptional X-ray luminosity in outburst. It may be that the relatively high mass of the white dwarf (Townsley, Arras & Bildsten 2004) accounts for the high outburst X-ray luminosity, as it may do also in SS Cyg.

Very few systems have good X-ray coverage during an outburst, so it is not clear whether the steep decline in the X-ray luminosity of GW Lib during the first ten days of outburst is typical of other systems. The X-ray flux of WZ Sge itself does decline during the first half of the outburst (Wheatley & Mauche 2005), but only about a factor of three in ten days, compared with a factor of thirty in GW Lib also over ten days (although note that the first X-ray observation of WZ Sge occurred about 3 days after the optical maximum). SS Cyg also declined after the optical maximum, in this case by about a factor of six over seven days (Wheatley, Mauche & Mattei 2003). In contrast, the X-ray flux of VW Hyi was approximately constant during the outburst (Wheatley et al. 1996).

In most dwarf novae the dominant high-energy emission during an outburst is optically-thick emission from the boundary layer, which emerges in the extreme-ultraviolet (Pringle 1977). This seems also to be the case for GW Lib, with a supersoft component detected in the first Swift observation, although the luminosity of this component is poorly constrained by our observations (Fig. 7). The supersoft component is detected only in our first observation, but it is likely to be present also in the later epochs and just too soft to be detected by the Swift XRT. Only a small spectral change would be needed to move this component out of our bandpass. Indeed, the extreme-ultraviolet components of VW Hyi and WZ Sge are not detected at all with the ROSAT PSPC and the Chandra ACIS X-ray detectors respectively (Wheatley et al. 1996; Wheatley & Mauche 2005), although they are detected in the EXOSAT LE and Chandra LETG bandpasses.

In the few cases where good coverage has been achieved, the extreme-ultraviolet emission rises only after the X-ray emission has been suppressed (e.g. Wheatley et al. 1996; Jones & Watson 1992; Wheatley, Mauche & Mattei 2003), and it is assumed that this supersoft component takes over as the main source of cooling as the boundary layer becomes optically-thick to its own emission. Since the extreme-ultraviolet emission is present even in our first Swift observation, it is possible that the observed peak in X-ray emission actually represents the suppressed level, and that an even stronger X-ray peak was missed, corresponding to the peak emission of the optically-thin boundary layer. In SS Cyg this first X-ray peak is a factor of three brighter than the second, weaker peak corresponding to the optical maximum.

Figure 7. The evolution of the background-subtracted UVOT UV grism flux spectra of GW Lib throughout the outburst in descending and chronological order. The top spectrum is an average of three spectra corresponding to days $T_0 + 8, 13$ and $18$. The following three spectra correspond to days $T_0 + 23, 26$, and $27$ (the spectrum on day $T_0 + 27$ is an average of three spectra during that day). The bottom spectrum shows the background flux level for one of the spectra on day $T_0 + 27$. 
In our later Swift observations the X-rays decline, then flatten off, and at the end of the disc outburst there is a sharp dip followed by a bump in the X-ray light curve, which coincides with the rapid decline in the optical and ultraviolet lightcurves. The X-ray hardness also increases at this time. These features are shared to some extent with other systems. A dip and a bump are seen in U Gem (Mattei, Mauche & Wheatley 2000) which is the only other system where X-rays are known to be brighter in outburst than in quiescence. A bump is also seen in SS Cyg where it is thought to correspond to the boundary layer transitioning back to its optically-thin state (Wheatley, Mauche & Mattei 2003). Another feature similar to GW Lib is the increase in hardness at the end of the outburst in SS Cyg, and indeed, dwarf novae are usually harder in quiescence than in outburst (Baskill, Wheatley & Osborne 2005).

When comparing the outburst X-ray emission to quiescence it is important to distinguish between pre- and post-outburst quiescence. GW Lib was unusually faint for a dwarf nova in quiescence in the XMM–Newton observation made two years before the 2007 outburst (Hilton et al. 2007). Our Swift XRT outburst observations continued for about six days after the end of the sharp decline in the optical and ultraviolet lightcurves, which presumably defines the end of the disc outburst. Our measured X-ray luminosity after this decline (SS in Table 4) is a factor of fifty higher than the pre-outburst quiescent level (Hilton et al. 2007). Our follow-up Swift observations in 2008 and 2009 show that GW Lib declined by a factor of five after the outburst, but that it remained an order of magnitude brighter than the pre-outburst observations for at least twenty one months after the outburst. Another important difference between the XMM–Newton and Swift observations is that Hilton et al. (2007) found an oxygen abundance enhanced by at least a factor of six above the solar value, whereas we find that our first outburst spectrum is inconsistent with such a high value and that the iron abundance appears to be significantly subsolar. It is difficult to understand how observed abundances can change so much between quiescence and outburst.

It has been noted in other systems that the X-ray flux tends to decrease between outbursts. Examples include VW Hyi (van der Woerd & Heise 1987) and SS Cyg (McGowan, Priedhorsky & Tradolyuba 2004). This is in contrast to the usual predictions of the disc instability model (e.g. Lasota 2001) in which the accretion rate gradually increases during quiescence as the disc refills. The inferred decrease in the quiescent X-ray flux in GW Lib is by a much larger factor than in VW Hyi and SS Cyg, but the inter-outburst interval is also much larger in GW Lib (decades compared with weeks and months), so there is more time for this decrease to progress.

5.1 Possible disc models

The long inter-outburst intervals of GW Lib and other WZ Sge type stars mean that the opportunities to study the outbursts of these objects in detail have been very scarce. In this respect, our data represent a rare insight into these intriguing dwarf novae.

To date, the physical cause of the long inter-outburst times has remained elusive. It is not at all clear why the accretion discs in these stars should behave any differently from those in other DNe with very similar system parameters. Yet, while the majority of non-magnetic, short period DNe exhibit outbursts every few weeks or months, the WZ Sge stars outburst every few years or decades. There are two main sets of models which attempt to explain this stark difference in recurrence time. In order to suppress the onset of regular outbursts and hence lengthen the inter-outburst interval, either the quiescent viscosity must be much lower than in other systems (Smak 1993; Howell, Szekely & Cannizzo 1995) or the inner disc must be somehow truncated (Warner, Livio & Tout 1994; Matthews et al. 2007). While the low viscosity models are appealing in that they neatly explain the long recurrence times, they remain unsatisfying in requiring the viscosity in some quiescent discs to be different from others while, at the same time, being very similar during outbursts. Models which appeal to inner disc truncation, suppress regular outbursts by removing the inner region of the accretion disc where outbursts are most easily triggered. Often disc truncation is explained by the propeller action of the torque exerted on the accretion disc caused by a magnetic field anchored on a rapidly rotating primary star (Warner, Livio & Tout 1994; Matthews et al. 2007) (a white dwarf magnetic field strength of B ∼ 10^5 G was assumed for WZ Sge by Matthews et al. 2007). In this case, mass would accumulate at large radii leaving a truncated and stabilised (with respect to frequent DNe outbursts) outer disc which acts as a large reservoir of mass. If the same physical mechanism was responsible for the long inter-outburst timescales of all of the WZ Sge stars, it may be reasonable to expect their outbursts to look very similar. In this respect, the differences between the observed outburst properties of GW Lib and WZ Sge, as outlined above, are puzzling.

The detailed emission physics of the magnetic propeller models in particular is not well-understood, making theoretical predictions of multwavelength outburst lightcurves extremely difficult. However, we note that both the low viscosity and disc truncation mechanisms tend to reduce the accretion rate during quiescence and may explain the low and decreasing X-ray flux in GW Lib between outbursts. Also, in the case of GW Lib, the X-rays are quenched on a timescale of ∼ 10 days. The only plausible timescale close to this value is the viscous time of the accretion disc. Interpreting this as a viscous timescale, \( \tau_{\text{visc}} \sim R^2/\alpha H c_s H \), we obtain an associated radius of R ∼ 10^{19} cm , where we have assumed that the viscosity in the hot state \( \alpha_H = 0.1 \), sound speed \( c_s = 10 \text{ km s}^{-1} \), and disc scale height = 0.1 R. This estimate is interesting as it is close to the required values for disc truncation. Thus it is conceivable that the quenching of the X-ray flux is associated with the inward progression of the accretion disc toward the white dwarf, and the eventual development of a boundary layer, once the outburst has been triggered.

6 CONCLUSIONS

We have obtained optical, UV and X-ray observations of the 2007 outburst of the WZ Sge type dwarf nova GW Lib. GW Lib stands out as the second known dwarf nova, in addition to U Gem, where hard X-rays are not suppressed during outburst. Rather than having a remarkably high X-ray
luminosity in an outburst, GW Lib has a very low X-ray luminosity in quiescence compared to other dwarf novae. The outburst X-ray lightcurve of GW Lib shows some similarities with other dwarf novae, such as a bump seen at the end of the X-ray lightcurve and hardening of the X-rays towards the end of the outburst. These features are also seen in SS Cyg. WZ Sge and GW Lib show some differences in their outburst data: the hard X-rays in WZ Sge are suppressed and the X-rays decline with a much smaller factor in the beginning of the X-ray lightcurve compared to GW Lib.

A supersoft component, which probably originates from the optically-thick boundary layer, is detected in the first outburst spectrum. Other systems, such as VW Hya and WZ Sge also show this component in their outburst data. The spectral resolution of the Swift XRT or UVOT is not sufficient to distinguish emission or absorption lines in the spectra.

The outburst X-ray luminosity at the optical maximum was three orders of magnitude higher than during the pre-outburst quiescence level in 2005. GW Lib was still an order of a magnitude brighter during the 2008 and 2009 post-outburst observations than during the pre-outburst observations.

The long recurrence time and the lack of normal outbursts suggest that the structure of the accretion disc could be explained by models which favor very long recurrence times. The two main categories for these models are: 1) low disc viscosity in quiescence and 2) a truncated inner disc due to a magnetic propeller white dwarf. Assuming that the outbursts of all WZ Sge stars would be driven by a similar physical mechanism, the observed differences in the outburst data of GW Lib and WZ Sge are perplexing.

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REFERENCES

Baskill D. S., Wheatley P. J., Osborne J. P., 2005, MNRAS, 357, 626
Burrows D. N., Hill J. E., Nousek J. A. et al., 2005, SSRv, 120, 165
Capalbi M., Perri M., Saitta B., Tamburelli F., Angelini L., 2005, The Swift XRT Data Reduction Guide, v. 1.2
Copperwheat C. M., Marsh T. R., Dhillon V. S. et al., 2009, MNRAS, 393, 157
Evans P. A., Beardmore A. P., Page K. L. et al., 2009, in press (arXiv:0812.3662)
Duerrbeck H. W., Seitter W. C., 1987, Ap&SS, 131, 467
Gehrels N., Chincarini G., Giommi P. et al., 2004, ApJ, 611, 1005
Hassall B. J. M., Pringle J. E., Schwarzenberg-Czerny A., Wade R. A., Whelan J. A. J., Hill P. F., 1983, MNRAS, 203, 865
Hilton E. J., Szkody P., Mukadam A., Mukai K., Hellier C., van Zyl L., Homer L., 2007, AJ, 134, 1503
Hoshi R., Prog. Theor. Phys., 1979, 61, 1307
Howell S. B., Szkody P., Cannizzo J. K., 1995, ApJ, 439, 337
Immler S., Still M., Boyd P. et al., 2006, v.2.0, The SWIFT UVOT Software Guide, NASA/GSFC
Jones M. H., Watson M. G., 1992, MNRAS, 257, 633
Koester D., Chanmugam G., 1990, RPPh, 53, 837
Krautter J., Ogelman H., Starrfield S., Wichmann R., Pfeffermueller E., 1996, ApJ, 456, 788
Kuulkers E., Knigge C., Steeghs D., Wheatley P. J., Long K. S., 2002, ASP Conf. Series, Vol. 261
Lasota J.-P., 2001, NewAR, 45, 449
Leahy D. A., Darbro W., Elsner R. F., Weisskopf M. C., Kahn S., Sutherland P. G., 1983, ApJ, 266, 160
Lewin W. H. G., van Paradijs J., van den Klis M., 1988, SSR, 46, 273
Liedahl D. A., Osterheld A. L., Goldstein W. H., 1995, ApJ, 438, L115
Mattei J. A., Mauche C., Wheatley P. J., 2000, JAVSO, Vol. 28, 160
Matthews O. M., Speith R., Wynne G. A., West R. G., 2007, MNRAS, 375, 105
Mauche C. W., Raymond J. C., 2000, AJ, 541, 924
Mazumder C., Cramond J. C., 2000, AJ, 541, 924
Maza J., Gonzalez L. E., 1983, IAU Circ., 3854, 1
McGowan K. E., Friedhorsky W. C., Trudolyubov S. P., 2004, ApJ, 601, 1100
Mewe R., Lemen J. R., van den Oord G. H. J., 1986, A&AS, 65, 511
Morrison R., McCammon D., 1983, ApJ, 270, 119
Mukai K., Kinkhabwala A., Peterson J. R., Kahn S. M., Paerels F., 2003, ApJ, 586, L77
Pollacco D. et al., 2006, PASP, 118, 1407
Pringle J. E., 1977, MNRAS, 178, 195
Pringle J. E., Savonije G. J., 1979, MNRAS, 187, 777
Pringle J. E., Bateson F. M., Hassall B. J. M. et al., 1987, MNRAS, 225, 73
Ricketts M. J., King A. R., Raine D. J., 1979, MNRAS, 186, 233
Romano P., Campagna S., Chincarini G. et al., 2006, A&A, 456, 917
Roming P. W. A., Kennedy T. E., Mason K. O. et al., 2005, SSRv, 120, 95

Swift observations of GW Lib
Smak J., 1993, Acta Astron., 43, 101
Swank J. H., Boldt E. A., Holt S. S., Rothschild R. E., Serlemitsos P. J., 1978, ApJ, 226, L133
Szkody P., Gansicke B. T., Howell S. B., Sion E. M., 2002, ApJ, 575, 79
Templeton M., 2007, AAVSO Alert Notice 349
Thorstensen J. R., Patterson J., Kemp J., Vennes S., 2002, PASP, 114, 1108
Thorstensen J. R., 2003, AJ, 126, 3017
Townley D. M., Arras P., Bildsten L., 2004, ApJ, 608, L105
Verbunt F., Wheatley P. J., Mattei J. A., 1999, A&A, 346, 146
Warner B., Livio M., Tout C. A., 1996, MNRAS, 282, 735
Warner B., van Zyl L., 1998, IAUS, 185, 321
Wheatley P. J., van Teeseling A., Watson M. G., Verbunt F., Pfeffermann E., 1996a, MNRAS, 283, 101
Wheatley P. J., Verbunt F., Belloni T., Watson M. G., Naylor T., Ishida M., Duck S. R., Pfeffermann E., 1996b, A&A, 307, 137
Wheatley P. J., Mauche C. W., Mattei J. A., 2003, MNRAS, 345, 49
Wheatley P. J., Mauche C. W., 2005, ASPC, 330, 257
Whitehurst R., 1988, MNRAS, 232, 35
van der Woerd H., Heise J., 1987, MNRAS, 225, 141
Woudt P. A., Warner B., 2002, Ap&SS, 282, 433
van Zyl L., Warner B., O’Donoghue D., Sullivan D., Pritchard J., Kemp J., 2000, Baltic Astronomy, 9, 231
van Zyl L., Warner B., O’Donoghue D. et al., 2004, MNRAS, 350, 307