X-ray/Optical Bursts from GS 1826–24

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\textbf{ABSTRACT}

We report results from the first simultaneous X-ray (\textit{RXTE}) and optical (SAAO) observations of the low-mass X-ray binary GS 1826–24 in June 1998. A type-I burst was detected in both X-ray and optical wavelengths. Its energy-dependent profile, energetics and spectral evolution provide evidence for an increase in the X-ray burning area but not for photospheric radius expansion. However, we may still derive an upper limit for its distance of 7.5 \pm 0.5 kpc, assuming a peak flux of \( \sim 2.8 \times 10^{-8} \) erg cm\(^{-2}\) s\(^{-1}\). A \( \sim 3\) s optical delay with respect to the X-ray burst is also observed and we infer that this is related to the X-ray reprocessing in the accretion disk into the optical. This provides support for the recently proposed orbital period of \( \sim 2\) h. We also present an \textit{ASCA} observation from March 1998, during which two X-ray bursts were detected.

\textbf{Key words:} accretion, accretion disks – binaries: close – stars: individual (GS 1826–24) – X-rays: bursts

\section{INTRODUCTION}

GS 1826–24 was discovered serendipitously in 1988 by the \textit{Ginga} satellite (Makino et al. 1988) at an average flux of 26 mCrab (1–40 keV) and was fitted by a single power law spectrum with \( \alpha \sim 1.7\). Whilst showing some evidence for variability during 1988–89 (Tanaka \& Lewin 1995; In’t Zand 1992), \textit{ROSAT} PSPC observations in 1990 and 1992 (Barret et al. 1995) found comparable flux levels and no X-ray bursts were detected during 8 hours exposure on the source. The spectrum was well fitted by a single power law with \( \alpha \sim 1.5 – 1.8\) and an absorption column, \( N_H \sim 5 \times 10^{21} \) cm\(^{-2}\). Temporal analysis of both the \textit{Ginga} and \textit{ROSAT} data yielded a featureless \( f^{-1}\) power spectrum extending from \( 10^{-4} – 500\) Hz (Tanaka \& Lewin 1995; Barret et al. 1995), with neither quasi-periodic oscillations (QPOs) nor pulsations being detected.

Since there was no detection prior to \textit{Ginga}, the source was catalogued as an X-ray transient. Its similarities to Cyg X–1 and GX 339–4 in the low state, both in spectrum and temporal behaviour (hard X-ray spectrum and strong flickering), led to an early suggestion by Tanaka (1989) that it was a soft X-ray transient with a possible black-hole primary. Following its detection by \textit{CGRO} OSSE in the 60–200 keV energy range, Strickman et al. (1996) doubted the suggestion of a black-hole primary after examining the combined spectrum from both \textit{Ginga} and OSSE. They found that this required a model with an exponentially cut-off power law plus reflection term. The observed cut-off energy around 58 keV is typical of the cooler neutron star hard X-ray spectra. The suggestion that GS 1826–24 contains a neutron star was also discussed in detail by Barret et al. (1996), where they compared the luminosity of the source with other X-ray bursters. The recent report of 70 X-ray bursts in 2.5 years by \textit{BeppoSAX} WFC (Ubertini et al. 1999) and an optical burst by Homer et al. (1998) confirms the presence of a neutron star accretor.

Following the first \textit{ROSAT} PSPC all-sky survey observations in September 1990, and the determination of a preliminary X-ray position, a search for the counterpart yielded a time variable, UV-excess, emission line star (Motch et al. 1994; Barret et al. 1995). The source had \( B = 19.7\), and an uncertain V magnitude (\( \sim 19.3\)), due to contamination by a nearby star. Subsequent high-speed CCD photometry by Homer et al. (1998) yielded a \( \sim 2\) hr optical modulation, but confirmation of its stability requires observation over a longer time interval. We therefore carried out an \textit{ASCA} observation and simultaneous \textit{RXTE}/optical observations of GS 1826–24 in order to study its spectral behaviour and very short timescale variability, as well as the 2.1 hr optical modulation. In Table 1, we summarize the \textit{ASCA}, \textit{RXTE} and SAAO observations used in this work.

This paper is structured as follows. An outline of all the X-ray and optical observations is given in section 2. In sec-
Table 1. A Journal of the X-ray/optical observations of GS 1826–24

| Observatory | Detector     | Date       | Time (UT) | Start | End   |
|-------------|--------------|------------|-----------|-------|-------|
| ASCA        | SIS+GIS      | 31.03.98   | 10:52     | 20:54 |       |
| RXTE        | PCA          | 23.06.98   | 19:20     | 21:59 |       |
|             |              | 24.06.98   | 19:20     | 21:58 |       |
|             |              | 25.06.98   | 19:21     | 21:57 |       |
|             |              | 28.07.98   | 08:12     | 14:22 |       |
|             |              | 29.07.98   | 13:05     | 15:51 |       |
| SAAO        | 1.9m+UCT CCD | 23.06.98   | 19:08     | 04:57 |       |
|             |              | 24.06.98   | 19:07     | 03:17 |       |
|             |              | 25.06.98   | 18:36     | 04:11 |       |

2 OBSERVATIONS AND DATA REDUCTION

2.1 ASCA

The ASCA satellite consists of four co-aligned telescopes, each of which is a conical foil mirror that focuses X-rays onto two Solid State Imaging Spectrometers (SIS) and two Gas Imaging Spectrometers (GIS) (Tanaka, Inoue & Holt 1994). The SIS detectors are sensitive to photons in the 0.4–10.0 keV energy band with nominal spectral resolution of 2% at 6 keV. The GIS detectors provide imaging in the 0.7–10 keV energy range and have a relatively modest spectral resolution of 8% at 6 keV, in comparison to the SIS, but with a larger effective area at higher energies.

For our observation of GS 1826–24 on 1998 March 31 (see Table 1), one CCD was activated for each SIS, giving an 11′ × 11′ field of field and temporal resolution of 4 s. The GIS detectors were set to MPC mode (i.e. no image could be extracted) so that the temporal resolution would be improved to 0.5 s.

The data were filtered with standard criteria including the rejection of hot and flickering pixels and event grade selection. We extracted the SIS source spectra from circular regions of 3′ radius, yielding 11.2 ks total exposure. The background spectra were extracted from source-free regions of the instruments during the same observation. For GIS, after the standard selection procedure, the net on-source time was 18.9 ks.

2.2 RXTE

We also observed GS 1826–24 with the Proportional Counter Array (PCA) instrument on RXTE (Bradt, Rothschild & Swank 1993) between 1998 June 23 and July 29 (see Table 1). The PCA consists of five nearly identical Proportional Counter Units (PCUs) sensitive to X-rays with energy range between 2–60 keV and a total effective area of ~6500 cm². The PCUs each have a multi-anode xenon-filled volume, with a front propane volume which is primarily used for background rejection. For the entire PCA and across the complete energy band, the Crab Nebula produces a count rate of 13,000 counts s⁻¹. The PCA spectral resolution at 6 keV is approximately 18% and the maximum timing resolution available was 1 µs. However, in order to maximize our timing and spectral resolution, we adopted a 125 µs time resolution, 64 spectral energy channel mode over 2–60 keV in addition to the standard mode configuration. All light curves and spectra presented here have been corrected for background and dead-time. For most of the time, at least four PCUs were turned on, and so we utilized only data from these PCUs in order to minimize systematic uncertainties.

2.3 Optical

Observations of a small (50 × 33 arcsecs) region surrounding the optical counterpart of GS 1826–24 were made using the UCT-CCD fast photometer (O’Donoghue 1995), at the Cassegrain focus of the 1.9m telescope at SAAO, Sutherland from 1998 June 23 to 26. The UCT-CCD fast photometer is a Wright Camera 576 × 420 coated GEC CCD which was used here half-masked so as to operate in frame transfer mode, allowing exposures of as short as 2 s with no dead-time. The conditions were generally good with typical seeing ~1.5–2.5 arcsec and the timing resolution for the source was 5 s. An observing log is presented in Table 1. We performed data reduction using IRAF, including photometry with the implementation of DAOPHOT II (Stetson 1987). Due to moderate crowding of the counterpart with a nearby but fainter neighbour and the variable seeing, point spread function (PSF) fitting was employed in order to obtain good photometry. The details of this procedure are given in Homer et al. (1998).

3 ANALYSIS AND RESULTS

3.1 ASCA Observations

Given the better spectral resolution and higher sensitivity below 2 keV of the SIS detectors, we use those data to study the persistent emission of GS 1826–24. The spectrum (excluding the burst intervals, see below) was fitted with a blackbody plus a power law component. The fit quality was good, with $\chi^2 = 1.14$ for 307 degrees of freedom (d.o.f.) and these results are summarized in Table 2 and Fig. 1 (whenever an error for a spectral parameter is quoted throughout this paper, it refers to the single parameter 1σ error).

Our results are consistent with those obtained by In’t Zand et al. (1999) using the BeppoSAX NFI, taken six days later. Moreover, their 2–10 keV flux of $5.41 \times 10^{-10}$ erg cm⁻² s⁻¹ which is only ~9% smaller than our determination, is consistent with the ~10% fall in count rate seen by the RXTE ASM during that interval.

Two X-ray bursts were detected by the ASCA GIS and one of them was caught by SIS. The time interval between the two bursts was ~5.4 hr and is consistent with the 5.76±0.6 hr quasi-periodicity of the burst recurrence as found by BeppoSAX WFC observations (Ubertini et al. 1999). Figure
2 shows the time profiles of the two bursts in the 0.7–10 keV range with 4 s binning. Their rise times (difference between time of the peak and time of the start of the burst using a linear-rise exponential-decay model) and e-folding times are comparable, see Table 3.

Since the GIS was set to MPC mode, which has no positional information, the lack of background estimation limits the usefulness of the spectra. We therefore here analyse the first burst which was detected with SIS.

Table 3. Timing parameters of the two bursts by fitting linear-rise exponential-decay model.

|          | burst 1       | burst 2       |
|----------|---------------|---------------|
| Peak time (MJD) | 50903.628    | 50903.853     |
| Rise time (s)   | 6.7 ± 0.2     | 8.8 ± 0.02    |
| e-folding time (s) | 55 ± 1.8     | 50.8 ± 1.9    |
| Peak flux (0.7–10 keV; Crab units) | 0.22         | 0.23         |

We extracted a series of spectral slices through the burst with 4 s time resolution in the rising phase and 20 s resolution during decay. Spectral analyses of these slices were performed over the 0.5–10 keV range using a variety of approaches. The most straightforward ‘standard’ approach was to choose a 300 s section of data immediately prior to the burst and use this as our ‘background’ for spectral fits to the individual spectra through the burst. The net (burst – ‘background’) emission was well fitted (χ² ∼ 0.6 – 1.2) with a simple blackbody. Figure 3 (left) shows the time variation of the bolometric flux, blackbody temperature and radius assuming a distance of 8 kpc (In’t Zand et al. 1999). The radii are rather low (∼ 4 km) and show an anti-correlation with temperature.

However, the analysis of X-ray burst data can be complicated in cases where the persistent emission contains a blackbody contribution from the outer layers of the neutron star. Failing to account for this component may lead to errors in the temperature determination and severe underestimates in the derived blackbody radius during the later stages of the burst (van Paradijs & Lewin 1985). We thus repeated our analysis, fitting the above two-component model to each gross (continuum + burst) spectrum, rather than a single blackbody component to the net burst spectrum. The power-law component was held constant at its continuum value while the blackbody component was permitted to vary. The results of our two-component spectral fits are shown in Figure 3 (right), once again for an assumed distance of 8 kpc. The most important difference with the results of the ‘standard’ approach is that the blackbody radius is now in the range for a typical neutron star (∼ 10 km). The blackbody radii show moderate variations, which appear to be anti-correlated with temperature. This indicates that the blackbody radiation from the neutron star contributes significantly to the persistent emission. The blackbody temperatures are higher during the beginning of the burst and then decline as expected for a type I burst (see Figure 3).

The change of the apparent blackbody radius may be affected by the non-Planckian shape of the spectrum of a hot neutron star (see Sztajno et al. 1986 and references therein). As a result, the temperature fitted using a blackbody is sim-
A.K.H. Kong, L. Homer, E. Kuulkers, P.A. Charles and A.P. Smale

Figure 3. Results of the spectral analysis of net burst (left) and gross burst (right) emission from ASCA. Plotted are the variation of the flux (top), blackbody temperature (middle) and blackbody radius (bottom).

Figure 4. Variation of the blackbody radius of the gross burst emission (burst plus persistent) after correction for the deviation of the spectrum of a hot neutron star from a pure blackbody spectrum (see text for explanation). The dashed line is the mean blackbody radius.

3.2 Simultaneous RXTE/Optical Burst Analysis

During simultaneous X-ray/optical observations on 24 June 1998, both RXTE PCA and the SAAO 1.9m + UCT CCD detected a burst (see Figure 5). The burst lasted for ∼150 s and the time profiles of the burst in both X-ray and optical are of the fast-rise exponential-decay form with the e-folding times in the different energy bands given in Table 5. The optical and X-ray bursts started almost at the same time but a delay is present between the peaks. The optical burst resembles the low energy (2–3.5 and 3.5–6.4 keV) X-ray light curves in which they all have a flat peak and a shoulder during the decay phase. At higher energies (> 6.4 keV), the peak is much sharper and the decay is faster during the initial decay phase.
Figure 5. The optical (SAAO) and X-ray (RXTE) burst profiles in various energy bands. The timing resolution is 5 s (optical) and 0.5 s (RXTE/PCA). The decay times strongly depend on photon energy with decays being shorter at higher energies.

Table 4. Burst parameters for the ASCA and RXTE bursts

| Burst | $F_{\text{max}}$ | $E_{\text{burst}}$ | $E_{\text{pers}}$ | $L_{\text{pers}}/L_{\text{burst}}$ | $L_{\text{pers}}/L_{\text{max}}$ | $\gamma$ | $\tau$ |
|-------|-----------------|------------------|-----------------|---------------------------------|---------------------------------|---------|------|
| ASCA  | 3.0             | 0.13             | 7.1             | 54.6                            | 0.12                            | 43.3 s  |      |
| RXTE  | 2.77            | 0.11             | 5.1             | 50                              | 0.1                             | 39.7 s  |      |

- $a$ Unabsorbed bolometric peak flux
- $b$ Total burst fluence
- $c$ Persistent emission fluence
- $d$ Assuming 5.4 hr burst separation
- $e$ Assuming 5.76 hr burst separation

X-ray spectral analysis is performed in the same way as for the ASCA data. The persistent emission is fitted with a single power-law spectrum with $N_H = (7.3 \pm 1.5) \times 10^{21}$ cm$^{-2}$ and photon index, $\alpha = 1.7 \pm 0.01$ ($\chi^2 = 1.11$ for 23 d.o.f.) which reveals an absorbed flux of $(1.2 \pm 0.01) \times 10^{-9}$ erg cm$^{-2}$ s$^{-1}$ in the 2–20 keV range. The photon index, $\alpha$ is much higher than that seen by ASCA and suggests a softer spectrum during the RXTE observations. We also perform spectral fitting with a power-law plus blackbody model but the fit does not improve and leads to a large error in $N_H$. Both the ‘standard’ method (net burst spectrum) and gross spectrum were almost indistinguishable from those presented in Figure 5, presumably because the blackbody provides such a small contribution to the continuum emission. We also undertook the non-Planckian analysis as mentioned in the previous section, with results very similar to Figure 6, indicating that the effect due to the non-Planckian shape of the neutron star spectrum is very small. Once again the neutron star shows the spectral cooling during the burst typical of a type-I burst. The unabsorbed bolometric peak flux of the blackbody radiation and other burst parameters are listed in Table 4. The ratio $L_{\text{pers}}/L_{\text{burst}} = 50 \pm 4$ if we assume that the separation of two bursts is 5.76 hr (Ubertini et al. 1999).

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The blackbody radius increases to a maximum as the burst rises, but does not show the simultaneous drop in \( kT_{bb} \) and increase in \( R_{bb} \) that is the overt signature of photospheric radius expansion (see Lewin, van Paradijs \\& Taam 1995). However, when we plot the flux \( F_{bol} \) versus \( F_{bol}^{1/4}/kT_{bb} \propto (R/d)^{1/2} \) we do find evidence for an increase in the X-ray burning area on the star (Strohmayer, Zhang \\& Swank 1997). This is shown in Figure 7 where the burst begins in the lower left and evolves diagonally to the upper right and then across to the left at an essentially constant value until near the end of the burst. This is an indication that indeed the X-ray burning area is not a constant but increases with time during the rising phase. \( F_{bol}^{1/4}/kT_{bb} \) eventually reaches a nearly constant value and the neutron star surface simply cools during the decay phase.

Kilohertz QPOs between 200 and 1200 Hz were not detected during the burst with an upper limit of 1\% (at 99\% confidence). We also set upper limits on the presence of any coherent pulsations during the burst: < 1\% between 100–500 Hz and 600–1200 Hz, and < 3\% between 1000–4000 Hz (the Nyquist limit). A detailed timing analysis of the remaining simultaneous X-ray/optical data will be presented in paper II.

### 3.2.1 X-ray/optical time delay

Figure 5 shows the simultaneous optical/X-ray burst in different energy bands where there is a few seconds delay at the peak of the burst. In order to quantify this delay, we performed: (i) cross-correlation analysis, (ii) modelled the optical burst by convolving the X-ray light curve with a Gaussian transfer function.

#### 3.2.1.1 Cross-correlation

We cross-correlated the optical data with X-ray data from different energy bands as well as the total (2–60 keV) X-ray light curve. This allows us to determine the correlation and estimate any time lag between X-ray and optical variability. The measurement of the cross-correlation function provides a characteristic delay which does not depend on particular model fitting. The results show that the optical burst lags the X-ray burst by \( \sim 4 \) s, which is marginally larger than expected in this system. The separation of the compact object and companion star is 2–3 light-s if we assume an orbital period of \( \sim 2.1 \) hr (Homer et al. 1998), a neutron star mass of 1.4 \( M_\odot \) and a companion star mass of 0.1–1.1 \( M_\odot \). However, in using a cross-correlation method we are essentially limited to the 5 s time resolution of the optical data (the PCA data have a much higher time resolution). Moreover, the delay appears to vary, from almost nothing at the start of the burst to a few seconds at the peak. This suggests that the delay might be a function of flux. Therefore a cross correlation analysis cannot provide a full picture of the delay between the X-ray and optical fluxes and instead we model the optical burst by convolving the X-ray light curve with a transfer function.

#### 3.2.1.2 Transfer function

In order to model the time delay between the optical and X-ray bursts, we convolve a Gaussian transfer function with the X-ray light curve and use \( \chi^2 \) fitting to model the remaining simultaneous X-ray/optical fluxes and instead we model the optical burst by convolving the X-ray light curve with a transfer function.

The blackbody radius increases to a maximum as the burst rises, but does not show the simultaneous drop in \( kT_{bb} \) and increase in \( R_{bb} \) that is the overt signature of photospheric radius expansion (see Lewin, van Paradijs \\& Taam 1995). However, when we plot the flux \( F_{bol} \) versus \( F_{bol}^{1/4}/kT_{bb} \propto (R/d)^{1/2} \) we do find evidence for an increase in the X-ray burning area on the star (Strohmayer, Zhang \\& Swank 1997). This is shown in Figure 7 where the burst begins in the lower left and evolves diagonally to the upper right and then crosses to the left at nearly constant \( F_{bol}^{1/4}/kT_{bb} \). It is evidence for an increasing X-ray burning area during the burst rise while the stellar surface cools off during the decay stage, see text.

**Figure 6.** The variation of the flux, blackbody temperature and radius during the burst detected by RXTE. See text for explanation.

**Figure 7.** Plot of bolometric flux \( F_{bol} \) vs. \( F_{bol}^{1/4}/kT_{bb} \) for the RXTE burst. The burst evolves from the lower left to upper right and then crosses to the left at nearly constant \( F_{bol}^{1/4}/kT_{bb} \). It is evidence for an increasing X-ray burning area during the burst rise while the stellar surface cools off during the decay stage, see text.
Table 5. Timing parameters of the simultaneous X-ray/optical burst by fitting linear-rise exponential-decay model.

| Energy Band   | Peak time (MJD) | Rise time (s) | e-folding time (s) |
|---------------|----------------|---------------|-------------------|
| 2–3.5 keV     | 50988.82510    | 7.2 ± 0.2     | 59 ± 2            |
| 3.5–6.4 keV   | 50988.82511    | 7.3 ± 0.2     | 54.3 ± 0.9        |
| 6.4–9.7 keV   | 50988.82512    | 7.81 ± 0.07   | 35.6 ± 0.8        |
| 9.7–16 keV    | 50988.82512    | 8.52 ± 0.05   | 20.5 ± 0.7        |
| Optical       | 50988.82516    | 10.7 ± 0.1    | 55 ± 4            |

Figure 8. Best-fitting predicted light curves using a Gaussian transfer function on the four X-ray energy bands. The resulting curves are superimposed on the optical data points.

Figure 9. Contour plot of the convolution with the RXTE light curves and Gaussian transfer function where the contour is defined as the 1σ confidence region.

4 DISCUSSION

X-ray and optical bursts from GS 1826–24 were previously reported by Ubertini et al. (1999), In’t Zand et al. (1999) and Homer et al. (1998). Our X-ray/optical observations of GS 1826–24 showed three X-ray bursts, of which two were observed by ASCA, whereas one was observed by RXTE simultaneously with the optical. On the basis of their spectral properties and time profiles, all the bursts have a cooling trend during their decays and exhibit blackbody spectra with temperatures of a few keV. The time profiles show fast rise times of 7–9 s and long decay times ranging from 20–60 s depending on the energy band. We therefore interpret the three bursts detected from GS 1826–24 as type I bursts (Hoffmann et al. 1978). The relatively long rise time (∼7–9 s), as compared to bursts in other systems, indicates that the burst front may have enough time to spread over the whole neutron star surface during the rise to burst and suggests that the burning is homogeneous over the surface of the neutron star. This is consistent with the fact that we see no evidence for pulsations during the burst. We note that X-ray burst rise times in other sources have been observed to be smaller than ∼6 sec (see e.g. Sztajno et al. 1986; Lewin et al. 1987), making this system rather unique. The burst rise times derived by In’t Zand et al. (1999) range from 5–8 s which are also consistent with our observations.

For the simultaneous burst we may compare the ratio of the persistent to peak fluxes, in both the X-ray and optical, using the results of Lawrence et al. (1983). They derived a simple power law relation between the changes in U, B and V band fluxes and the corresponding X-ray flux variations during a well-studied burst of X1636–536, with \( \frac{F_{X,max}}{F_{X,pers}} = \left( \frac{F_{opt,max}}{F_{opt,pers}} \right)^{\beta} \), where \( \beta \) varies with passband. Our burst shows that \( \beta \approx 4 \) which is comparable to the value \( \beta \sim 3 \) found for X1636–536 in the V band, which is the closest approximation to our white light passband. Hence, we may imply that the reprocessed emission from the GS 1826–24 burst is also approximately that from a blackbody (with a temperature set by the degree of X-ray irradiation), where the optical passband is on the Rayleigh-Jeans tail (Lawrence et al. 1983).

The X-ray burst observed by RXTE shows evidence
for an increase in the burning area during the early rise phase, but no evidence for photospheric radius expansion. Note that this is consistent with the fact that most X-ray bursts showing photospheric radius expansion have rise times less than ~1 sec (see Lewin et al. 1995). However, by assuming that our observed peak luminosity of \( F_{\text{max}} = (2.8 \pm 0.4) \times 10^{38} \text{ergs s}^{-1} \) is near the Eddington limit of \( \sim 1.8 \times 10^{38} \text{ergs s}^{-1} \) for a 1.4 \( M_\odot \) neutron star, we can set an upper limit to the distance to GS 1826–24. We derive a maximum distance of \( d = 7.5 \pm 0.5 \) kpc. This estimate is consistent with the upper limit from BeppoSAX NFI observations (7.4 ± 0.7 kpc; In’t Zand et al. 1999) and the optical lower limit of 4 kpc (Barret et al. 1995). The luminosity ratios are \( L_{\text{pers}}/L_{\text{burst}} \sim 55 \) and ~50 for the bursts observed with ASCA and RXTE, respectively. This is comparable with that found by BeppoSAX WFC (60 ± 7; Ubertini et al. 1999). Coupling this value with an estimated stable accretion rate of \( \sim 1.5 \times 10^{-9} \text{M}_\odot \text{yr}^{-1} \) (Ubertini et al. 1999), the burst must involve a combined hydrogen-helium burning phase (Lewin, van Paradijs & Taam 1995). This relatively long burst also resembles the theoretical results of X-ray bursts driven by rapid proton capture process, or rp-process (see Hanawa & Fujimoto 1984; Taam 1981; Bildsten 1999; Schatz et al. 1998).

Pedersen et al. (1982) have shown that the optical burst mainly reflects the geometry of the system and that the contribution of intrinsic radiative processes is small. Hence the correlated optical and X-ray bursts discussed above are useful as probes of the structure and geometry of the compact object surroundings. Within the framework of the low-mass X-ray binary system, the reprocessing can occur in the accretion disk and the companion star. Based on our observed mean delay of 3 ± 1 s for the optical burst with respect to low energy X-rays, we can then constrain the orbital period of the system. By Kepler’s law, the light travel time of 2–4 s corresponds to an orbital period of 1.6–5.5 hr if we assume a 1.4\( M_\odot \) neutron star and a companion star mass of 0.1–1.1\( M_\odot \) (i.e. for a low-mass main sequence star and stable mass transfer). Hence, this range of periods provides support for the 2.1 ± 0.1 hr orbital period proposed by Homer et al. (1998). Lastly, from only one simultaneous optical/X-ray burst, we cannot draw a firm conclusion as to whether the optical burst is due to reprocessing in the disk or on the surface of the companion star. However, given that the source is a low inclination system (< 70°; Homer et al. 1998) and the ratio of smearing to delay is ~1, the reprocessing is expected to be dominated by the accretion disc.

It is important in future studies to search for the possibly variable delays if the reprocessing occurs on the surface of the companion star (Matsuoka et al. 1984) or the ‘thick spot’ in the disk proposed by Pedersen et al. (1981). Whether the dominant reprocessor is the companion star or the ‘thick spot’, one expects the ratio of optical to X-ray flux in a burst to vary periodically. Moreover, the optical delay would vary as a function of orbital phase as suggested by Pedersen, van Paradijs & Lewin (1981). Ubertini et al. (1999) recently proposed a 5.76-hr quasi-periodicity in the occurrence of X-ray bursts in GS 1826–24, which makes this problem difficult to resolve with current low-Earth-orbit satellites. However, with upcoming missions such as Chandra and XMM, much longer continuous X-ray coverage will be possible, and together with ground-based telescopes will enable us to probe the structure of this source in much greater detail.

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Table 6. Summary of results from convolution of a Gaussian transfer function to the four different X-ray energy bands light curves

| Energy Band (keV) | \( \tau_0 \) (s) | \( \Delta \tau \) (s) | \( \Psi(10^{-3}) \) | \( \chi^2_\nu \) (51 d.o.f.) |
|------------------|-----------------|-----------------|------------------|------------------|
| 2.3–3.5 keV      | 2.8 ± 0.7       | 3.1 ± 1.3       | 13.8 ± 6.2       | 0.49             |
| 3.5–6.4 keV      | 2.8 ± 0.6       | 2.7±1.2         | 13.7±1.3         | 0.42             |
| 6.4–9.7 keV      | 3.7 ± 0.7       | 4 ± 1           | 7.0 ± 1.2        | 1.5              |
| 9.7–16 keV       | 5.6 ± 0.9       | 6.1±1.2         | 4.5±0.7          | 2.1              |

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