CHANDRA AND RXTE SPECTRA OF THE BURSTER GS 1826–238

THOMAS W. J. THOMPSON, RICHARD E. ROTHSCCHILD, JOHN A. TOMSICK, HERMAN L. MARSHALL

ABSTRACT

Using simultaneous observations from the Chandra X-Ray Observatory and the Rossi X-Ray Timing Explorer, we investigated the low-mass X-ray binary (LMXB) and “clocked burster” GS 1826–238 with the goal of studying its spectral and timing properties. The uninterrupted Chandra observation captured 6 bursts (RXTE saw 3 of the 6), yielding a recurrence time of 3.54 ± 0.03 hr. Using the proportional counter array onboard RXTE, we made a probable detection of 611 Hz burst oscillations in the decaying phases of the bursts with an average rms signal amplitude of 4.8%. The integrated persistent emission spectrum can be described as the dual Comptonization of ∼ 0.3 keV soft photons by a plasma with kT_e ∼ 20 keV and τ ∼ 2.6 (interpreted as emission from the accretion disk corona), plus the Comptonization of hotter ∼ 0.8 keV seed photons by a ∼ 6.8 keV plasma (interpreted as emission from or near the boundary layer). We discovered evidence for a neutral Fe Kα emission line, and we found interstellar Fe L II and Fe L III absorption features. The burst spectrum can be fit by fixing the disk Comptonization parameters to the persistent emission best-fit values, and adding a blackbody. The temperature of the boundary layer seed photons was tied to the blackbody temperature. The blackbody/seed photon temperature at the peak of the burst is ∼ 1.8 keV and returns to ∼ 0.8 keV over 200 s. The blackbody radius is consistent with R_bb ≈ 10.3–11.7 km assuming a distance of 6 kpc, though this value cannot be interpreted as the physical size of the neutron star due to partial covering of the stellar surface by the accretion disk. By accounting for the fraction of the surface that is obscured by the disk as a function of binary inclination, we determined the source distance must actually be near 5 kpc in order for the stellar radius to lie within the commonly assumed range of 10–12 km. The order of magnitude increase in flux at burst peak is seen to cause Compton cooling of the electron plasma surrounding the disk, as the plasma temperature decreases to ∼ 3 keV at burst onset, and then slowly returns to the persistent emission value after about 150 s.

1. INTRODUCTION

The low-mass X-ray binary (LMXB) GS 1826–238 was discovered with Ginga in 1988 (Makino et al. 1988). Due to its temporal and spectral similarities to Cyg X–1 and GX 339–4, the source was originally tentatively classified as a black hole candidate (BHC) (Tanaka 1989). Later optical studies lead to the identification of a V = 19.3 mag (and therefore low-mass) optical counterpart (Barret et al. 1995). The companion was subsequently found to have a 2.1 hr modulation (and implied orbital period) and a refined position of α = 18h29m28.2s and δ = −23°47′49.6″ (J2000) (Homer et al. 1998).

The spectral and temporal characteristics that Tanaka (1989) initially used to associate GS 1826–238 with a black hole system were later found to be present in other X-ray bursters (e.g., 4U 1608–522, Yoshida et al. 1993). Moreover, the photon index of its energy spectrum was measured to have a relatively low cut-off energy (∼ 58 keV) for a BHC, and was perhaps more indicative of the typically cooler neutron star (NS) hard X-ray spectra (Strickman et al. 1996). X-ray bursts from this source were first conclusively observed with BeppoSAX by Ubertini et al. (1997), firmly establishing the source as a NS and strongly suggesting it to be weakly magnetized (B < 10^{10} G).

The periodicity of the type I bursts from GS 1826–238 has been remarkably stable over the span of years (Ubertini et al. 1999). Although quasi-periodic bursting is not unique among LMXBs, such consistency over long durations is indeed unusual. The regular intervals between bursts suggest that the accretion rate is stable, that the accreted matter is completely consumed during the bursts, and that the fraction of the stellar surface covered prior to each burst is approximately constant. Investigations of burst recurrence rates and energetics have lead to convincing arguments that type I bursts stem from unstable thermonuclear burning of accreted hydrogen and helium (e.g., Strohmayer & Bildsten 2003). As freshly accreted material falls onto the NS surface, it is hydrostatically compressed by new material at a rate per unit area m ∼ 10^4 g cm^{-2} s^{-1}, assuming isotropic accretion and a NS radius of 10 km.

The thermal energy deposited by the infalling matter causes temperatures in most of the thin NS “atmosphere” to exceed 10^7 K, so that during the accumulation phase hydrogen burns via the hot CNO cycle at a rate that is limited only by the mass fraction Z_{CNO} and not the temperature (Bildsten 2000). Within hours to days, the extreme gravity on the NS surface (∼ 10^{14} cm s^{-2}) compresses the accumulated matter to densities high enough to trigger unstable thermonuclear ignition. GS 1826–238, in particular, has near limit-cycle behavior with stable hydrogen burning during the accumulation phase followed by mixed hydrogen and helium burning triggered by thermally unstable helium ignition (Bildsten 2000).

The α-parameter – the ratio of the integrated persistent fluence between bursts to the burst fluence – and the long burst duration (∼ 150 s), imply that after thermonuclear ignition the hydrogen burns via the rapid-proton (rp) process where energy is released through successive proton captures and β decays (Wallace & Woosley 1981). The measured α-value for GS 1826–238 of ∼ 42 (Galloway et al. 2004; hereafter G04) is remarkably consistent with theoretical predictions: The gravitational energy released during accretion onto a 1.4 M_{⊙} NS is about

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200 MeV per nucleon, while the energy released through thermonuclear fusion is about 5 MeV per nucleon for a solar mix going to iron group elements, giving an expected value of 40. Moreover, the variation in $\alpha$ with the global accretion rate $\dot{M}$ implies solar metallicity in the accreted layer (G04), although recent work using an adaptive nuclear reaction network shows that the critical mass required for a burst is independent of the composition of the accreted material (Woosley et al. 2004), and so attempts to infer the metallicity of the fuel from burst composition of the accreted material (Woosley et al. 2004), implies solar metallicity in the accreted layer (G04), although attempting to infer the metallicity of the fuel from burst emission, assuming there is an optical path through which the disk or surrounding accretion disk corona (ADC) (Church et al. 1997, 1998; Balucińska-Ciesla plus Comptonized emission from an extended accretion disk, and corona by the bulge in the outer disk where persistent emission at various levels of decreased flux results—a Comptonization region plus blackbody emission from the inner accretion disk plus blackbody emission from the NS which is Comptonized in the local region of the star. More recently, the dipping class of LMXBs has constrained the types of emission models that are most likely. The constraints are provided by the fact that the models must fit the persistent emission at various levels of decreased flux resulting from partial occultation and absorption of the NS, accretion disk, and corona by the bulge in the outer disk where accretion flow from the companion star impacts. The evolution of these spectra at various levels of flux are well-described by a model consisting of point-like blackbody emission plus Comptonized emission from an extended accretion disk corona (e.g., Church et al. 1997, 1998; Balucińska-Church et al. 2001; Smale et al. 2001). During dipping, the blackbody component is observed to disappear rapidly, indicating that the emission comes from a point and not from an extended region. As expected, the Comptonized component is observed to gradually decrease. By measuring the ingress times of the dip, Church (2001) was able to estimate the size of the Comptonizing region for several sources and found the radius of the region to be typically $\sim 50,000$ km. This measurement is consistent with the value obtained much earlier by Canizares (1976) for 3U 1820–30. The large extent of the emission region is evidence for a Comptonized component that is emitted from an ACCD and not the disk itself. Moreover, Smale et al. (2001) observed complete covering of this region in many sources, suggesting that the corona must be geometrically thin, as it would be unlikely that a corona with spherical geometry would be completely occulted. On the contrary, studies of emission and absorption features in dipping sources by Boirin et al. (2005) show that the spectra are also consistent with a less strongly ionized absorber along the line of sight rather than a simple increase in absorption. Progressive covering of the Comptonized component in their models is not required.

The persistent emission spectrum of GS 1826–238 has been discussed by previous authors (e.g., Barret et al. 1995, Ubertini et al. 1999, Del Sordo et al. 1999, in ‘t Zand et al. 1999a, Barret et al. 2000, Kong et al. 2000). The spectral model that has consistently produced an acceptable fit is a blackbody plus Comptonized emission, the latter being modeled in $\text{XSPEC}$ with either a cut-off power law ($\text{cutoffpl}$) or the more explicit $\text{comptt}$. Broadband $\text{BeppoSAX}$ spectra in the 0.1–200 keV range found the spectrum to be consistent with the Comptonization of a 0.6 keV Wien spectrum by a plasma with $kT_e \sim 20.7$ keV, plus a 3.8 keV blackbody (in ‘t Zand et al. 1999a). Del Sordo et al. (1999) found the spectrum to be well-fitted with a blackbody plus cut-off power law, with $kT_{\text{bb}} \sim 0.9$ keV, $\Gamma \sim 1.3$, and cut-off energy $\sim 50$ keV. Strickman et al. (1996) and in ‘t Zand et al. (1999a) also obtained a fit with this model and the results of each group are fairly consistent. Kong et al. (2000) fit the persistent emission spectrum from 0.5–10 keV with a blackbody ($\sim 0.7$ keV) plus power law ($\Gamma \sim 1.1$).

The burst emission spectrum has been studied a few times previously. in ‘t Zand et al. (1999a) studied burst spectra and found significant flux up to 60 keV, indicating that the burst emission may be Comptonized in a similar manner as the persistent emission. The peak blackbody temperature was measured to be $\sim 2$ keV, which cooled to about 1.3 keV over 100 s. Ubertini et al. (1999) studied the spectrum for two bursts, though with only two separate integration bins of 13 s at burst peak and 43 s through the decay. The peak spectrum was fit with a blackbody temperature of $\sim 2.1–2.3$ keV and the decay with temperature $\sim 1.6–1.9$ keV. Kong et al. (2000) fit the burst spectrum by fixing the power law component to its persistent value and adding a blackbody; the peak temperature was $\sim 2.6$ keV. Marshall et al. (2003) searched the present data for absorption features during the burst peak and decay to search for evidence for the gravitational redshift to the surface of the NS. No features were observed.

We begin in § 2 by presenting the observations of GS 1826–238 that were used in this study, and we specifically discuss the data preparation prior to spectral analysis. In § 3 we measure the burst periodicity and compare to previous measurements. We use the burst recurrence time and energetics to discuss the type of burning occurring on the NS surface. We conclude the section by discussing a probable detection of burst oscillations during the decaying phases of the burst. In § 4 we examine the evolution of the broadband persistent emission spectrum between bursts to see whether or not any significant changes in the parameters occur during the accumulation phase. We find that the persistent emission data from 0.5–200 keV are best fit with a model characterized by absorbed emission from two distinct Comptonizing regions, plus iron line emission. We also report the detection of interstellar absorption features. We study the evolution of the burst spectrum in § 5 by adding a blackbody to the persistent emission spectrum. The disk Comptonization parameters are fixed at their persistent emission best-fit values, and the temperature of the boundary layer seed photons is tied to the blackbody temperature. From the blackbody parameters we derive a blackbody plus Comptonized emission, the latter being modeled in $\text{XSPEC}$ with either a cut-off power law ($\text{cutoffpl}$) or the more explicit $\text{comptt}$. Broadband $\text{BeppoSAX}$ spectra in the 0.1–200 keV range found the spectrum to be consistent with the Comptonization of a 0.6 keV Wien spectrum by a plasma with $kT_e \sim 20.7$ keV, plus a 3.8 keV blackbody (in ‘t Zand et al. 1999a). Del Sordo et al. (1999) found the spectrum to be well-fitted with a blackbody plus cut-off power law, with $kT_{\text{bb}} \sim 0.9$ keV, $\Gamma \sim 1.3$, and cut-off energy $\sim 50$ keV. Strickman et al. (1996) and in ‘t Zand et al. (1999a) also obtained a fit with this model and the results of each group are fairly consistent. Kong et al. (2000) fit the persistent emission spectrum from 0.5–10 keV with a blackbody ($\sim 0.7$ keV) plus power law ($\Gamma \sim 1.1$).

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TABLE 1
CHANDRA AND RXTE OBSERVATIONS OF GS 1826–238

<table>
<thead>
<tr>
<th>Obs. ID</th>
<th>Telescope/Instrument</th>
<th>Energy Band (keV)</th>
<th>Exp. (ks)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2739</td>
<td>Chandra/ACIS-S</td>
<td>0.5–8.3</td>
<td>68.2</td>
</tr>
<tr>
<td>01,02,000a</td>
<td>RXTE/PCA</td>
<td>3–23</td>
<td>24.6b</td>
</tr>
<tr>
<td>01,02,000a</td>
<td>RXTE/HEXTE</td>
<td>17–200</td>
<td>19.4b</td>
</tr>
</tbody>
</table>

NOTE. — All observations are from 2002 July 29.

aThe RXTE observation IDs are each preceded by 70044-01:-

bDue to earth occultation and the satellite’s passage through the

South Atlantic Anomaly, there are time gaps of 15–30 min in cov-

erage; the times listed represents the sum of 9 separate observation

intervals.

2. OBSERVATIONS AND ANALYSIS

In this paper we utilize two simultaneous observations from

2002 July 29, taken with Chandra and Rossi X-Ray Timing

Explorer (RXTE). The 68.2 ks Chandra observation was

made using the Advanced CCD Imaging Spectrometer (ACIS;

Garmire et al. 2003) and is sensitive to photons from 0.3–10

keV. The source was focused onto one of the back-illuminated

ACIS chips (S3). To minimize the adverse effects due to pile-

up, and to gain better time resolution on the rise of the bursts,

we used half-frame readout on the inner 4 ACIS chips with

1.74 s frame-time. We use the “level 2” event lists from the

standard data processing, and apply a standard correction to

produce re-

out. To obtain high resolution spectra, we had the High En-

ergy Transmission Grating (HETG; Canizares et al. 1992)

inserted into the optical path.

The 36 ks RXTE observation uses the Proportional Counter

Array (PCA; Jahoda et al. 1996), and the High Energy X-Ray

Timing Experiment (HEXTE; Rothschild et al. 1998). The

PCA is made up of five proportional counter units (PCUs) and

is sensitive to photons from 2–60 keV. The HEXTE in-

strument comprises two clusters, each of which contains four

NaI/CsI scintillation detectors, and is sensitive to photons from

15–250 keV. Both instruments have large effective areas (≈ 6000 cm² and 1400 cm², respectively) and microsecond

timing. Table 1 provides a summary of the GS 1826–238

observations used in the spectral analysis.

2.1. Data Preparation for Spectral Analysis

The Chandra HETG Spectrometer is composed of the Medium Energy Grating (MEG) and the High Energy Grating

(HEG). The two gratings are slightly offset and appear as “whiskers” traversing all ACIS chips. The MEG is cal-

ibrated from 0.3–5.0 keV and the HEG is calibrated from

1.0–8.3 keV. In this analysis, we only made use of the 1st

order MEG/HEG data. All of the Chandra analysis made

extensive use of the Chandra Interactive Analysis of Observ-

ations (CIAO) version 3.01 with software calibration ver-

sion (CALDB) 2.26. We used the CIAO routine textract for the extraction of grating spectra, mkgrmf to produce re-

sponse matrices, and fullarf to create the auxiliary response

matrices. We added the positive and negative diffraction or-

ders and their corresponding auxiliary response files using the

script add_grating_orders. Systematic errors of 10% were

derived from calibration observations of the Crab pulsar and

Mrk 421, and were added to both the persistent and burst

emission fits.3 We binned the persistent and burst emission
data in the largest possible bins to obtain maximum statisti-

cal quality, while maintaining sufficient resolution to observe

prominent absorption or emission lines. For the persistent

emission analysis we bin the data in 1000 count PHA bins, and

in the burst analysis we use 500 count bins. This gener-

ally led to bins with width ∼ 50–100 eV. We excluded the

MEG 1st order data from 0.8–0.9 keV because these data fall

on a gap between the ACIS chips. After preliminary anal-

ysis, we concluded that the data near 2.1 keV are affected by

a residual calibration uncertainty in the response due to an irid-

ium M-edge. To correct for this, we included an inverse edge

effect, and in the burst analysis we use 500 count bins. This gen-

eral data treatment did not include any counts from the zeroth order source region as these data are affected by severe pile-up. Not only is the burst recurrence time approximately constant, but the light curve of any particular burst is virtually indistinguishable from any other (see Fig. 1 (c)). Although the time between sequential

bursts has been rather constant, the average burst recurrence
time has been observed to be steadily decreasing over long

time scales (Cocchi et al. 2000, G04). Using a total of 44

RXTE observations from 1997 November to 2002 July, G04

measured the burst interval to be 5.74 ± 0.13 hr initially, 4.10

± 0.08 hr in 2000, and 3.56 ± 0.03 hr in 2002. We mea-

sured the average burst recurrence time of the five complete

Chandra intervals to be 3.54 ± 0.03 hr (12750 ± 102 s; also

in 2002). The individual intervals were measured from burst

peak to peak and are listed in Table 2. The 2002 recurrence
time measurement by G04 was measured using the same PCA
data that we use in this paper, while our measurement is based

3 see http://space.mit.edu/ASC/calib/hetgcal.html
on the Chandra data. The 40% decrease in the burst recurrence time from 1997 to 2002 has been coupled with a 66% increase in the mean persistent flux (G04). Such behavior is expected since the increase in persistent luminosity is assumed to be due to an increase in the global accretion rate, and therefore less time is required to reach the critical amount of fuel. While the observations of G04 are consistent with this trend, Bildsten (2000) found exactly the opposite behavior in many low accretion rate LMXBs. For example, bursts from 4U 1705–44 became less frequent as $M$ increased. To explain the conundrum, Bildsten (2000) suggested that a greater fraction of the stellar surface of 4U 1705–44 may be covered prior to ignition, so that the accretion rate per unit area actually decreased. This may also be the case for GS 1826–238: If the relation between the rise in the persistent flux and the decrease in the burst recurrence time were linear, we would expect an even greater decrease in burst recurrence time than has been observed by G04. Another possible explanation for the longer-than-expected recurrence time regards the fact that at smaller recurrence times, less helium will be made prior to ignition, and so the column depth required to produce the instability will increase (Cumming & Bildsten 2000).

The location of the burning during bursts is not assumed to be spherically symmetrical. It is likely that ignition begins near the stellar equator since matter is preferentially deposited there during accretion (Spitkovsky et al. 2002). The anisotropic burning caused by the hot spot at the point of ignition may be revealed through the observation of burst oscillations, the frequencies of which correspond to the NS rotation frequencies (e.g., Muno 2004).

We searched for burst oscillations by computing and averaging the power spectra for the 3 bursts observed with 125 $\mu$s resolution event mode PCA data using a sampling rate of 2048 Hz (Nyquist frequency: 1024 Hz). To improve statistics, we averaged power spectra for sequential 0.25, 0.5 and 1 s sections of the light curve (4, 2, and 1 Hz resolution), with total segment lengths varying from 3 to 30 s. We searched in the $\sim 10$ s rise, around the burst peak, and at different times during the burst decay until 65 s from the burst peak. PCA deadtime effects cause a $\sim 1\%$ decrease in the mean value of the Poisson noise to 1.98 (from 2.0) in the Leahy normalization (see Leahy et al. 1983). We initially included the entire 2–60 keV energy band and made no significant detections at any point during the burst. We then tried varying

<table>
<thead>
<tr>
<th>Burst Interval</th>
<th>$\Delta T$ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1→2</td>
<td>12861</td>
</tr>
<tr>
<td>2→3</td>
<td>12884</td>
</tr>
<tr>
<td>3→4</td>
<td>12510</td>
</tr>
<tr>
<td>4→5</td>
<td>12994</td>
</tr>
<tr>
<td>5→6</td>
<td>12502</td>
</tr>
</tbody>
</table>

**NOTE.** — The individual burst intervals were measured from the peak of one burst to the next. There is a small uncertainty in these measurements since the Chandra data have a frame time (and time resolution) of 1.74 s.

4. Persistent Emission Spectrum

4.1. Evolution Between Bursts

Along with burst energetics and timing, we can learn much from GS 1826–238 through its energy spectra. We began our investigation by creating spectra for 1 ks intervals following the onset of a burst in order to see if there were significant changes in the best-fit parameters between bursts. Since the average burst recurrence time for the five complete burst intervals in the 68 ks Chandra observation was measured to be 12750 ± 102 s, we were able to create 1 ks intervals up to 11–12 ks after the burst. To improve statistics we stacked the datasets from all five Chandra burst intervals. We also constructed nearly two complete burst intervals using the simultaneously acquired RXTE data. Although these data have time gaps, we determined the time since the previous burst for any individual RXTE dataset by comparing it to the Chandra burst times. With the benefit of the simultaneous observations we obtained statistically significant measurements from 0.5–200 keV for each 1 ks interval (except 9–10 ks). To each dataset, we fit a model composed of Comptonized emission plus a broken power law. This preliminary model was only used to examine whether or not there were significant changes to the spectrum with time, and ultimately, a different model was determined to be more physically plausible (see below).

Nevertheless, this exercise showed us that the best-fit parameters remain approximately constant after 1 ks, although with slightly elevated soft X-ray flux through 3 ks from the peak of the burst. In the following fits, we therefore define the persistent spectrum to be for $T > 3$ ks. In the integrated persistent emission analysis below, we found that the inclusion of data from 1–3 ks only minimally distorted most spectral parameters, however the inferred $N_H$ was underestimated by $\sim 50\%$ due to the excess of soft photons.

We are fortunate to have Chandra data along with RXTE since observations of bursters with low-Earth orbit telescopes may miss some bursts if they occur during a gap in coverage when the source is occulted by the Earth or the telescope is passing through the South Atlantic Anomoly. Fig. 1 (b) provides an illustration of the potential ambiguity involved with the selection of persistent emission datasets. For example, it is clear that any persistent emission analysis would be slightly distorted if the first 3 ks of the second Chandra observation (corresponding to the decay of the first burst observed
FIG. 1.— Light curves for the Chandra HETG and RXTE PCA instruments. The top two light curves (a and b) show the intervals when each telescope was taking data. The Chandra light curve includes the HETG data from 0.3–8 keV and has time resolution of 3.48 s, as does the data in plot (c). The PCA light curve includes data from 3–8 keV and uses 16 s time bins. The time axis of the top three plots begins at MJD 52484.2039. The lower plots show the individual (c) and average (d) of the 6 Chandra bursts. We used the smallest possible binning of 1.74 s, and the curves were aligned using the rises of the bursts. The zero point reference time for plot (d) also corresponds to the peak of the burst. The curve can be approximated by a decaying exponential with scale time 60 s, however this value cannot be interpreted physically since it includes all instrumental effects resulting from differences in the detector response with energy.

FIG. 2.— Averaged Leahy-normalized power spectrum for the 3 bursts (15–30 s from burst peak) observed with PCA (top and bottom left), and a histogram of the distribution of the powers scaled to zero mean (bottom right). The frequency bins are 4 Hz. The vertical dashed lines in the bottom right sub-figure represent 1σ and 4σ standard deviations from the mean. The power at 611.2 Hz deviates from the Poisson level by 4.7σ.
with *Chandra* were included.

### 4.2. Integrated Spectrum

By summing all PHA datasets that fall within the 3–12 ks interval, we further constrain the statistics and explore standard models for LMXBs in addition to other models. LMXBs are typically modeled with a blackbody or disk blackbody to represent the NS surface or the inner accretion disk, plus Comptonized emission which can be modeled in *Xspec* with *compTT* or a cut-off power law (*cutoffpl*). Although these models have similar profiles, they are not necessarily interchangeable. While Comptonized emission can be empirically described with a cut-off power law, the model of Titarchuk (1994) is derived from analytical equations that are founded on the real analytical theory of Comptonization of soft photons, and the output parameters are physically explicit which allow direct interpretation. On the contrary, the index of a cut-off power law cannot be interpreted in physical terms, while in *compTT* it is related to the combination of the optical depth and plasma temperature. Albeit, the cut-off energy of *cutoffpl* is related to the plasma temperature as $E_{\text{cut}} \sim 2kT_{\text{e}}$. For these reasons we chose the Titarchuk (1994) model to represent Comptonized emission. With this description, the spectrum is governed entirely by the plasma temperature and the parameter, which characterizes the distribution law of the number of scatterings (i.e., $P(n) \propto \exp(-\beta n)$ is the probability that a seed photon undergoes $n$ scatterings before escaping the plasma). The optical depth of the plasma is calculated from the parameter and depends on the input geometry: disk or spherical. Generally, for a given parameter, a larger optical depth is inferred from a spherical geometry than a disk geometry. This is because the final spectral shape is determined by photons which undergo many more scatterings than the mean, and the longest dimension of a spherical plasma cloud is clearly shorter than that of a disk (Titarchuk 1994).

We initially tried to fit the data by employing a single *compTT* component, but the resulting fit was unacceptable due to excesses above 70 keV and below 1.5 keV. The addition of a blackbody component reduced the soft excess, and allowed the plasma temperature and thus the up-scattering efficiency to increase (since $(E_i) \sim (E_i)e^{-\tau}$, where $y \equiv kT_{\text{e}}/m_{\text{e}}c^2$ is the Comptonization parameter) to try to match the hard excess. Although the fit was better ($\chi^2 = 1.30$), it was still unacceptable. This is contrary to the results of Inogamov & Sunyaev (1999), the spreading of accretion flow from the equator to the poles leads to two bright rings of enhanced emission that are symmetric about the equator. The latitude of these rings increases with accretion rate, and in the accretion regime of GS 1826–238, i.e. $\sim 10^{37} \text{ g s}^{-1}$ (inferred from the total flux), these rings lie $\sim 0.5$–1.5 km from the equator. Therefore, assuming the blackbody emission comes from these rings, the secondary Comptonized emission region only has to be large enough to cover the inner $\pm 1.5$ km above and below the equator. Following in 't Zand et al. (1999b), an approximate effective radius for the spherical emission area of the Wien seed photons is given by $3 \times 10^4 d \sqrt{F_{\mu}/(kT_{\text{e}})^2} \text{ km}$, where $d$ is in kpc, the flux is measured in erg s$^{-1}$ cm$^{-2}$, and the seed photons are measured in keV. This approach yielded a soft photon emitting region with radius $R_{\text{s}} \sim 4d_{68}$ km, which is only consistent with the seed photons being generated at the boundary layer if the region is confined to a half-thickness of $\sim 2.5$ km, depending on the inclination of the system, and assuming that any emission from “below” the accretion disk is not observable. Finally, since the flux of photons passing through the boundary layer relative to the disk is larger per unit area, we expect Compton cooling to maintain a lower plasma temperature for the secondary Comptonized emission region. This is indeed what is observed (see Table 3).

In addition to a dual Comptonization model, we also modeled the spectrum with a single *compTT* plus a broken power law in order to give an estimate of its shape for possible non-thermal interpretation. If the secondary emission is indeed non-thermal, perhaps it stems from an ADC generated by magnetohydrodynamic turbulence, analogous to what is observed in the solar corona (Croston et al. 1998). Alternatively, the emission may be synchrotron radiation from a relativistic jet escaping the system. Such jets have been found to be rather common among LMXBs and link these systems to active galactic nuclei (AGNs) (e.g., Fender 2002). Clearly, these possibilities are highly speculative.
4.3. Iron Line Detection

After obtaining a fit with the two component models, the residuals revealed a line feature around 6.5 keV, which prompted the addition of a Gaussian to the models. The best-fit value for the line was measured to be approximately 6.45 keV, with a flux which corresponds to an equivalent width (EW) of $\sim 37.2$ eV. We interpret this feature as a neutral Fe K$\alpha$ line. An F-test showed that the probability for an improvement to the fit occurring by chance is $5.3 \times 10^{-5}$ for the dual Comptonization model, and $6.8 \times 10^{-3}$ for the Comptonization plus broken power law model. However, it should be noted that the use of an F-test to measure the significance of lines may not be valid (Protassov et al. 2002). We present the best-fit parameters for these models in Table 3. We also present the results of a blackbody plus cut-off power law model, which is described below. To account for the uncertainties in the soft component parameters due to less precise uncertainties in the relative instrumental flux calibrations, we introduced a multiplicative constant into the spectral models. For tainties in the relative instrumental flux calibrations, we introduced a multiplicative constant into the spectral models. For tainties in the relative instrumental flux calibrations, we introduced a multiplicative constant into the spectral models. For tainties in the relative instrumental flux calibrations, we introduced a multiplicative constant into the spectral models. For tunities in the soft component parameters due to less precise uncertainties in the relative instrumental flux calibrations, we introduced a multiplicative constant into the spectral models. For.

4.4. Comparison to Previous Fits

To facilitate comparison to the results of previous work, we also fitted the spectrum of GS 1826–238 with a blackbody plus cut-off power law model (model 3), and a blackbody plus power law from 0.5–10 keV (not included in the table). These models have been used by others to provide acceptable fits to ASCA observations of X-ray halos around 29 sources (cf. Predehl & Schmitt 1995, Fig. 7). The hydrogen column density that we obtained in this fashion is consistent with the best-fit value of models 1 and 2. By freezing $N_\text{H}$ in model 3 to the common lower value, the model fits the data poorly. We therefore conclude that the common LMXB model of a blackbody plus Comptonized emission described by comptt or cutoffpl is not appropriate for the persistent emission spectrum of GS 1826–238.

4.5. Interstellar Absorption Features

The persistent emission spectrum was searched for interstellar absorption features. This effort turned up a good candidate at about 17.15 Å. The feature is broad (0.102 ± 0.027 Å FWHM) with an optical depth at line center of 0.63 ± 0.09, when fitted with a Gaussian. The formal significance is about 3.8$\sigma$; based on about 800 bins searched at 0.03 Å binning, there is about a 6% chance that one would find such a feature due to random fluctuations. Including a narrower feature at about 17.5 Å with a significance of 2.9$\sigma$, we modeled both features with structure in the Fe L edge due to the interstellar medium (ISM). The wavelengths of these features are a match to those of Fe L III at 17.51 Å and Fe L II at 17.19 Å. The match is not perfect. Figure 4 shows the near edge extended absorption fine structure (NEXAFS) of the Fe L edge as measured by Kortright and Kim (2000) and the edge structure of butadiene iron tricarbonyl($C_2FeH_5O_3$) from the Corex data base maintained by A. P. Hitchcock. Neither model matches the data without a slight energy shift to match the L III feature. Furthermore, the 17.15 Å line is somewhat broader than expected and may have an excess of absorption at the short wavelength side. Schulz et al. (2002) identified

4 see http://unicorn.mcmaster.ca/corex
the Fe L features in the spectrum of Cyg X-1 and suspected that there is a mix of Fe molecules, citing, in particular, a feature near 17.15 Å that might be due to a more pure form of Fe. Without the corresponding L III feature in our spectrum, however, we suspect that the extra broadening might result from statistical fluctuation. The models use a cosmic abundance of Fe ($4 \times 10^{-5}$ relative to H) and the observed ISM column density of 2.0 $\times 10^{21}$ cm$^{-2}$. Thus, these absorption features are consistent with Fe in the ISM.

5. BURST SPECTRUM AND EVOLUTION

We also studied the evolution of the spectrum throughout the burst and its decay by subdividing the first 1 ks from burst peak into 8 datasets with progressively larger integration times (Table 4). Those data above 40 keV were ignored as too few counts were obtained for significance. All of the datasets were fit with the XSPEC model phabs*edge(comptt + compton + bbody) (d: disk, s: sphere), with the hydrogen column density frozen at the common value of 1.85 $\times 10^{21}$ cm$^{-2}$. We initially allowed the disk Comptonization parameters to vary, but the best-fit values for each dataset, including the normalizations, changed by $\lesssim 5\%$, so they were frozen at the persistent emission values. Since the blackbody emission during a burst provides a large influx of seed photons in the inner boundary layer, the spherical seed photon temperature was fixed to the blackbody temperature, which is justified since most Comptonized emission is emitted within $\sim 20$ km of the surface of the NS (Frank et al. 1985). Table I shows the evolution of the spectral parameters.

Using the results from Table 4, we can place an upper limit to the source distance assuming the blackbody luminosity is Eddington-limited, which it is not since the bursts are significantly sub-Eddington. During the first 10 s following the peak of the burst, the average flux from 0.5–40.0 keV was measured to be $1.96 \times 10^{-8}$ erg cm$^{-2}$ s$^{-1}$. We corrected the peak flux by assuming an approximately constant spectrum for this interval (i.e. constant spectral parameters), and by measuring the burst decay scale time ($\sim 35$ s over the energy band). The peak flux was found to be $\sim 12\%$ larger than the 0–10 s mean, or $2.2 \times 10^{-8}$ erg cm$^{-2}$ s$^{-1}$. Moreover, we must account for radiation that is absorbed or scattered out of the line-of-sight on its way to the telescope. The hydrogen column density toward the source was assumed to be about $2 \times 10^{21}$ cm$^{-2}$, which corresponds to a scattering optical depth of 0.02 (Predehl & Schmitt 1995). Thus scattering and absorption along the line of sight reduce the observed flux by $(1 - e^{-0.02}) \approx 0.02$. If we assume that the blackbody normalization is also $\sim 12\%$ larger than the 0–10 s mean, and that the unabsorbed normalization is $\sim 2\%$ larger still, we arrive at a maximum source distance of 9.2 kpc for the bursts being at the Eddington limit. This upper limit on the distance is consistent with the 8 kpc upper limit derived by in ‘t Zand et al. (1999a).

The thermal nature of the burst spectrum with a blackbody temperature of $\sim 1.8$ keV, accompanied by the cooling, is typical for a type I X-ray burst (Lewin et al. 1995). While the blackbody temperature decreases by a factor of about 2.2 dur-

<table>
<thead>
<tr>
<th>TABLE 3</th>
<th>PERSISTENT EMISSION SPECTRAL PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model:</td>
<td>1. Two Comptonized plus Bkn. PL b</td>
</tr>
<tr>
<td></td>
<td>2. Comptonized plus Bkn. PL b</td>
</tr>
<tr>
<td></td>
<td>3. Blackbody plus CPL c</td>
</tr>
<tr>
<td>N$_{\text{H}}$ ($\times 10^{21}$ cm$^{-2}$)</td>
<td>1.60$^{+0.32}_{-0.66}$</td>
</tr>
<tr>
<td>kT$<em>{d}$/kT$</em>{s}$ (seed: K$_{\text{bb}}$ (keV))</td>
<td>0.42$^{+0.05}_{-0.03}$</td>
</tr>
<tr>
<td>R$<em>{d}$/R$</em>{s}$ (km)</td>
<td>4.02$^{+0.04}_{-0.04}$</td>
</tr>
<tr>
<td>N$_{\text{H}}$ (cm$^{-2}$)</td>
<td>20.79$^{+0.38}_{-0.33}$</td>
</tr>
<tr>
<td>$\tau_{d}$/R$_{d}$</td>
<td>2.56$^{+0.04}_{-0.03}$</td>
</tr>
<tr>
<td>$y_{d}$/N$_{d}$</td>
<td>1.07$^{+0.17}_{-0.27}$</td>
</tr>
<tr>
<td>$\Gamma_1$</td>
<td>$\ldots$</td>
</tr>
<tr>
<td>$\Gamma_2$</td>
<td>$\ldots$</td>
</tr>
<tr>
<td>$E_{\text{break}} - E_{\text{cut}}$ (keV)</td>
<td>$\ldots$</td>
</tr>
<tr>
<td>$E_{\text{peak}}$ (keV)</td>
<td>6.44$^{+0.03}_{-0.02}$</td>
</tr>
<tr>
<td>EW$_{\text{line}}$ (eV)</td>
<td>37.2$^{+0.1}_{-0.84}$</td>
</tr>
<tr>
<td>$\chi^2$/d.o.f.</td>
<td>0.70 (521)</td>
</tr>
</tbody>
</table>

Note. — All errors are quoted at the 90% confidence level for a single parameter.

a XSPEC: phabs*edge (comptt + compton + gauss)
b XSPEC: phabs*edge (comptt + bknpower + gauss)
c XSPEC: phabs*edge (bbody + cutoffpl + gauss)

The parameters for spherical and disk geometries are listed as “disk/spherical”, or “primary/secondary” for models 1 and 2. The two geometries are fit together in model 1, and separately in model 2.

The spectral Wien emission radius and the blackbody radius. The derivation of the Wien radius is described in § 4.2. The blackbody radius is defined by the relation $L_{\text{bb}} = 4\pi R_{\text{bb}}^2 S_{\text{bb}}$, where $S$ is the Stefan-Boltzmann constant. The blackbody normalization in XSPEC is defined to be $L_{\text{bb}}/D_{10}$, where $L_{\text{bb}}$ is the blackbody luminosity in units of $10^{37}$ erg s$^{-1}$ and $D_{10}$ is the distance to the source in units of 10 kpc. The derivation $R_{\text{bb}}$ uses a ratio $R_{\text{bb}}/D_{10} = 1.4$ (Ebisuzaki et al. 1984, also see [1]).

This equivalent width is an upper limit.
Fig. 3.— Persistent emission spectrum and residuals of the dual Comptonization model (1), and the residuals of models 2 and 3. For each model, the upper residuals are for the MEG and PCA, and the lower residuals are for the HEG and HEXTE. The range 0.8–0.9 keV is ignored since these MEG counts fall on a gap between ACIS CCDs. To provide clarity, we have only plotted every third (second) MEG (HEG).

### Table 4: Spectral Evolution During Burst Decay

<table>
<thead>
<tr>
<th>Interval (s)</th>
<th>kT$_{bb}$ (keV)</th>
<th>Norm. ($\times 10^{-2}$)</th>
<th>$R_{bb}$ (km)</th>
<th>kT$_e$ (keV)</th>
<th>$\tau$</th>
<th>$F_X$: 0.5–10.0 keV ($\times 10^{-9}$ erg s$^{-1}$ cm$^{-2}$)</th>
<th>5.5–40.0 keV ($\times 10^{-9}$ erg s$^{-1}$ cm$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–10</td>
<td>1.76$^{+0.06}_{-0.11}$</td>
<td>12.0$^{+0.6}_{-1.5}$</td>
<td>11.6$^{+0.8}_{-1.6}$</td>
<td>3.1$^{+0.6}_{-0.2}$</td>
<td>9.9$^{+2.1}_{-3.0}$</td>
<td>13.5</td>
<td>19.6</td>
</tr>
<tr>
<td>10–30</td>
<td>1.75$^{+0.09}_{-0.01}$</td>
<td>10.8$^{+0.5}_{-0.6}$</td>
<td>11.5$^{+1.2}_{-0.5}$</td>
<td>3.8$^{+0.5}_{-0.6}$</td>
<td>7.8$^{+3.4}_{-4.8}$</td>
<td>10.4</td>
<td>14.9</td>
</tr>
<tr>
<td>30–65</td>
<td>1.50$^{+0.03}_{-0.08}$</td>
<td>5.1$^{+0.2}_{-0.2}$</td>
<td>10.4$^{+1.3}_{-1.1}$</td>
<td>3.3$^{+0.4}_{-0.5}$</td>
<td>8.0$^{+1.6}_{-3.2}$</td>
<td>7.1</td>
<td>10.4</td>
</tr>
<tr>
<td>65–100</td>
<td>1.24$^{+0.03}_{-0.05}$</td>
<td>3.1$^{+1.3}_{-0.9}$</td>
<td>7.9$^{+0.7}_{-0.7}$</td>
<td>5.0$^{+0.4}_{-0.5}$</td>
<td>11.8$^{+0.5}_{-0.4}$</td>
<td>3.8</td>
<td>6.6</td>
</tr>
<tr>
<td>100–150</td>
<td>1.04$^{+0.03}_{-0.04}$</td>
<td>0.6$^{+0.6}_{-0.6}$</td>
<td>7.9$^{+0.7}_{-0.7}$</td>
<td>5.0$^{+0.4}_{-0.6}$</td>
<td>11.8$^{+0.5}_{-0.4}$</td>
<td>2.0</td>
<td>3.6</td>
</tr>
<tr>
<td>150–200</td>
<td>0.86$^{+0.09}_{-0.06}$</td>
<td>0.6$^{+0.6}_{-0.6}$</td>
<td>7.9$^{+0.7}_{-0.7}$</td>
<td>5.0$^{+0.4}_{-0.6}$</td>
<td>11.8$^{+0.5}_{-0.4}$</td>
<td>2.0</td>
<td>3.6</td>
</tr>
<tr>
<td>200–500</td>
<td>0.83$^{+0.05}_{-0.04}$</td>
<td>0.6$^{+0.6}_{-0.6}$</td>
<td>7.9$^{+0.7}_{-0.7}$</td>
<td>5.0$^{+0.4}_{-0.6}$</td>
<td>11.8$^{+0.5}_{-0.4}$</td>
<td>2.0</td>
<td>3.6</td>
</tr>
<tr>
<td>500–1000</td>
<td>0.81$^{+0.03}_{-0.03}$</td>
<td>0.6$^{+0.6}_{-0.6}$</td>
<td>7.9$^{+0.7}_{-0.7}$</td>
<td>5.0$^{+0.4}_{-0.6}$</td>
<td>11.8$^{+0.5}_{-0.4}$</td>
<td>2.0</td>
<td>3.6</td>
</tr>
</tbody>
</table>

**Note.** All errors are quoted at the 90% confidence level for a single parameter. The XSPEC model used in this analysis was phabs*edge(comptt$_d$ + comptt$_s$ + bbody). Only the last two components had free parameters. The column density was set to $1.85 \times 10^{21}$ cm$^{-2}$, and the parameters describing disk Comptonization were fixed to the persistent emission best-fit values. The seed photon temperature of the spherical Comptonizing region was tied to the blackbody temperature. Good fits were obtained with $\chi^2_\nu$ consistently $\sim 0.9$.

*The peak of the burst is defined to take place at $t = 0$. 

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Fig. 4.— Spectrum of the persistent emission of GS 1826–238 near 17.5 Å. A global model of the continuum is shown for several models of the Fe L edge complex due to the ISM. Dashed curve: The ISM opacity model provided in the \texttt{tbabs} model of \texttt{XSPEC}, using the prescription provided by Wilms et al. (2000). Thin curve: The Fe L edge opacity model based on measurements by Kortright & Kim (2000). Dotted curve: The Fe L edge structure is based on the transmission of butadiene iron tricarbonyl (C$_7$FeH$_6$O$_3$) from the Corex data base maintained by A. P. Hitchcock. Thick curve: The model based on the Hitchcock data but shifted by 3 eV to match the data better. The 17.15 Å line is somewhat broader than expected and may have an excess of absorption at the short wavelength side but these absorption features are generally consistent with a cosmic abundance of Fe.
ing burst decay, the normalization decreases by more than a factor of 30. Nevertheless, the derived blackbody radius remains approximately constant as long as blackbody emission is observable. Figure 5 shows the derived blackbody radius and the fraction of blackbody flux \( F_{\text{bb}} / F_{\text{total}} \) from 2–10 keV during the first 150 s after burst ignition. Clearly these data are consistent with a blackbody radius of \( \sim 10.3–11.7 \) km, assuming a source distance of 6 kpc and a ratio \( F_{\text{bb}} / F_{\text{total}} \) (spectral hardening factor) of 1.4. Such a correction must be applied since NSs do not radiate as perfect blackbodies during X-ray bursts because the thermalization of photons occurs at scattering optical depths greater than unity, where the temperature is higher than the effective temperature. Rather, the photons are thermalized at optical depths of \( \sim 4–5 \) (e.g., Ebisuzaki et al. 1984, London et al. 1986, Madej et al. 2004). Assuming that the entire stellar surface is involved when blackbody emission is observable, i.e. the burning does not cease in one area sooner than another, the slight decrease in the inferred blackbody radius for the 100–150 s interval (see Fig. 5) could be explained by a \( \sim 10\% \) increase in the spectral hardening factor. This is a possibility since at lower effective temperatures \( (T_{\text{eff}} < 1.5 \) keV) the spectral hardening factor increases with decreasing temperature, as the relative contribution of electron scattering to the total opacity decreases (London et al. 1986). However, within the error limits, the blackbody radius for this interval is still consistent with the measured values during the first 100 s of the burst.

The derived blackbody radius cannot be interpreted as the physical size of the NS since LMXBs do not have isotropic radiation fields. Due to the presence of an optically thick accretion disk, any blackbody emission from the surface of the NS that is in the “shadow” of the accretion disk would not be directly observed but would possibly emerge as Comptonized emission. The only geometrical arrangement for which we can naively interpret the blackbody radius as the stellar radius is when the accretion disk is perpendicular to the line of sight \( (i = 0^\circ) \). In all other cases the inferred blackbody radii underestimate the stellar radius, and so one must account for the covered region in order to extract a stellar radius from a measured blackbody temperature and flux.

The area of the covered region increases nonlinearly with increasing binary inclination, moving from 0% of the projected area when \( i = 0^\circ \) to 50% when \( i = 90^\circ \). Furthermore, since accretion disks are not infinitesimally thin there will also be some portion of the surface covered by the disk. The amount of covering by the disk can be parametrized by the disk half-height \( h \). In spite of the nonlinear relation between the amount of covering and the inclination and disk half-height, the fraction of the stellar surface that is covered can be calculated using straightforward geometrical principles. With these issues in mind we interpreted \( \pi R^2_{\text{bb}} \) as the observable projected area of the star, and by calculating the fraction of surface covered we derived an effective stellar radius \( R_{\text{eff}} \) as a function of inclination and disk half-height for source distances of 6 kpc and 5 kpc, which is presented in Fig. 6. Using optical observations of the counterpart of GS 1826–238, Mescheryakov et al. (2004) were able to derive an approximate inclination of \( i \sim 40^\circ–70^\circ \), and so we only include this range in the figure.

From photometric measurements of the optical counterpart, Barret et al. (1995) derived an approximate lower limit to the distance to GS 1826–238 of 4 kpc. Assuming the range of possible binary inclinations used above is correct, it is apparent that a source distance near 5 kpc gives a NS radius within the commonly assumed range of \( \sim 10–12 \) km (see the right axis of Fig. 6). On the contrary, a distance of 6 kpc does not give a NS radius within the common range. Even with an infinitely thin accretion disk and an inclination at the lower bound \( (i = 40^\circ) \) of Mescheryakov et al. (2004), the smallest possible stellar radius at this distance within the error limits is \( \sim 11 \) km.

From the results of the Table 4, it is clear that the burst photons immediately cool the Comptonizing plasma to \( \sim 3.4 \) keV. Over the next 150 s, the plasma temperature recovers the persistent emission value of \( \sim 6.8 \) keV. This type of plasma cooling during a burst may be an example of Compton cooling. The same inverse Compton scattering process that transfers energy to the persistent emission photons also transfers energy to the photons emitted during a burst. The difference is that during the burst the flux of photons increases by more than an order of magnitude (for the 0–10 s interval), so that the balance between heating and radiative cooling is disturbed. It is also evident that the optical depth of the plasma is weakly constrained in the burst spectral analysis. Although the best-fit values for the first few intervals seem to indicate a larger optical depth, the range of uncertainty still includes the persistent emission value.

6. EMISSION REGION GEOMETRIES

Since blackbody emission is observable during the bursts but not during the quiescent phase, we can speculate as to the geometries of the corresponding emission regions. To begin, GS 1826–238 has a weak magnetic field so infalling matter probably impacts the NS along the equator rather than at the poles. The release of gravitational binding energy through thermalization of the accreted material may result in a strip of blackbody emission along the equator (Church & Balucińska-Church 2001), or the accumulation and spreading of accretion flow from the equator toward the poles may cause two bright emission rings that are symmetric about the equator (Inogamov & Sunyaev 1999). The inability to see blackbody emission in the interval between bursts suggests that the equatorial strip or enhanced bright rings must be covered by an optically thick layer. This is explained naturally by the persistent emission dual Comptonization model.

At the onset of a burst, ignition likely starts near the equator and then rapidly spreads to cover the entire stellar surface in a couple seconds or less (Spitkovsky et al. 2002). Once the entire accumulated layer is burning, the subsequent blackbody emission indicates that there is an optical path for the radiation outside of the equatorial strip. It could be argued that the accretion flow is disrupted during a burst, or that a spherical corona surrounding the NS is temporarily blown away, and that this provides a path for the blackbody emission. However, the flux provided by the inner Comptonizing region also increases substantially during a burst, so the boundary layer plasma must still be present to up-scatter the seed photons. Moreover, our measurement of the Wien emission radius \( (\sim 4 \) km) is too small for the corona to completely surround the star. Instead, we assume that this emission region is likely confined to the equatorial region. This explanation supports theories where the Comptonizing plasma or ADC is geometrically thin.

7. SUMMARY

Our investigation of the LMXB GS 1826–238 using simultaneous RXTE and Chandra observations has led us to the following conclusions. From the observation of five uninterrupted burst intervals with Chandra in July 2002, we mea-
Fig. 5.— Blackbody radius and fraction of blackbody flux ($F_{bb}/F_{\text{total}}$) from 2–10 keV during the first 150 s after burst ignition. The bottom curve is fit “by eye” with a cosine. Beyond 150 s, the XSPEC blackbody normalization decays to zero. These data are consistent with a blackbody radius between 10.3 and 11.7 km for an assumed distance of 6 kpc.

Fig. 6.— Effective stellar radius as a function of binary inclination and disk half-height ($h$) for source distances of 6 kpc (left axis) and 5 kpc (right axis). The shaded region represents the uncertainty and corresponds to the same range of blackbody radii as in Fig. 5. While the uncertainty is only plotted for $h = 0$, the magnitude of the uncertainties for the other values of $h$ are approximately the same and have been omitted for clarity.

measured a burst recurrence time of $3.54 \pm 0.03$ hr, which is consistent with G04’s measurement. G04’s measured decrease in the burst recurrence time between 1997 and 2002 has been coupled with an even larger percentage increase in the mean persistent flux, possibly indicating that a greater fraction (as compared to 1997) of the stellar surface may be covered prior to ignition. We detected 611.2 Hz burst oscillations with a 0.033% chance that the signal resulted from random fluctuations. The average rms amplitude of the peak is 4.8%.

The RXTE/Chandra 0.5–200 keV integrated persistent emission spectrum is best fit with a dual Comptonization model, whereby two distinct Comptonizing regions exist and are characterized by a different set of parameters. The extended energy range of RXTE is essential to constraining the photon index or Comptonization parameter, and eliminates the need for a blackbody component. This result is contrary to most spectral models of LMXBs that include a visible blackbody component. The spectrum also requires a neutral Fe Kα emission line at 6.45 keV with EW $\sim 37.2$ eV. In addition, we find strong evidence of interstellar Fe L absorption features at the about 17.15 Å and 17.5 Å, with significance $3.8\sigma$ and $2.9\sigma$, respectively.
During a burst, blackbody emission accounts for the majority of the flux though it quickly disappears after ~150 s. Throughout this period, the data are consistent with a blackbody radius between 10.3 km and 11.7 km for a distance of 6 kpc if one assumes the blackbody flux comes from the full 4\pi R^2 of the neutron star surface. By accounting for the fraction of the surface that is obscured by the accretion disk, however, the source distance must be nearer to 5 kpc to be consistent with a neutron star radius of 10–12 km. We also see Compton cooling during the bursts, as the plasma temperature immediately decreases to ~3 keV and then slowly returns to the persistent emission value of ~6.8 keV after about 150 s. Since blackbody emission is not observed in the persistent spectrum yet dominates the burst spectrum, we conclude that the emission from those regions of the stellar surface along the equator are covered in the persistent phase. During the burst the entire surface is radiating as a blackbody, and so this emission can be seen outside of the covered region.

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