DIAGONISING THE BURST INFLUENCE ON ACCRETION IN THE CLOCKED BURSTER GS 1826-238

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ABSTRACT

Type I X-ray bursts on the surface of a neutron star are a unique probe into accretion in X-ray binary systems. However, we know little about the feedback of the burst emission on accretion. Hard X-ray shortages and enhancements of the persistent emission at soft X-rays have been observed. To put these findings in context with the aim of understanding the possible mechanism underneath, we investigated 68 bursts seen by the Rossi X-ray Timing Explorer from the clocked burster GS 1826-238. We diagnosed jointly the burst influence of both soft and hard X-rays, and we found that the observations can be described by the CompTT model with variable normalization, electron temperature, and optical depth. Putting these results in a scenario of coronal Compton cooling via the burst emission would lead to a shortage of cooling power, which may suggest that additional considerations, like the influence of the burst on corona formation, should be accounted for as well.

Key words: stars: coronae – stars: neutron – X-rays: binaries – X-rays: bursts

1. INTRODUCTION

A low-mass X-ray binary (LMXB) consists of a compact star (a black hole or a neutron star (NS)) and a donor. The donor usually fills its Roche lobe and thus transfers mass to the compact star by releasing the gravitational potential energy as persistent X-rays (e.g., Lewin & van der Klis 2006). Its spectrum can be described as a combination of thermal and a nonthermal (power-law-like) components. The thermal component is considered to be the emission from an optically thick accretion disk, and the power-law component is believed to originate from hot plasmas above or inside the accretion disk (White et al. 1988; Mitsuda et al. 1989), which is speculated to be the “corona” (see, e.g., Frank et al. 2002; Done et al. 2007; Zhang 2013). In the case where a neutron star is the compact object, the mass accumulated on the NS surface may end up in a violent thermonuclear explosion, in which the integrated flux could reach up to typically ∼10^{39}–10^{40} erg. These intense X-ray flares are called type I X-ray bursts (see, e.g., Lewin et al. 1993; Galloway et al. 2008).

Being a short intense shower of soft X-rays, type I X-ray bursts (XRBs) can be used as a probe of the LMXB accretion via investigating the evolution of the persistent emission along with the runway of the thermonuclear explosion. The bursts are expected to have a blackbody spectrum with slight deviations that depend on the burst luminosity (for details, see, e.g., Suleimanov et al. 2011, 2012). To extract the burst spectrum, one usually assumes that the persistent emission is unchanged during the burst, and one subtracts it off as part of the background (see, e.g., Kuulkers et al. 2003). Worpe et al. (2013), however, proposed that the persistent emission intensity is variable, thus involving a multiplicative factor f_a to the persistent emission for fitting the spectrum during the burst (assuming an unchanged spectral shape, which we shall refer to hereafter as the varying persistent flux model). They found that in photospheric radius expansion bursts the best-fit value of the f_a is significantly greater than 1, while it seems that the f_a values are ∼1 when the persistent emission is near the Eddington limit. In’t Zand et al. (2013) found spectral excesses from a blackbody spectrum at both low and high energies in SAX J1808.4-3658, which can be eliminated by using the varying persistent flux model. The value of f_a seems to be proportional to the intensity of bursts, while this correlation may reverse at higher burst luminosity in the hard state of LMXBs (Ji et al. 2014b). In addition, enhanced persistent emission was also reported during a superburst from 4U 1636-536 (Keek et al. 2014a). This shows the significant influence of the burst emission on the accretion at soft X-rays (∼2–10 keV), although the underlying mechanism is still not understood. Possible explanations may be the Poynting–Robertson effect (Walker 1992) or some other reprocessing of burst photons by the accretion disk and the corona (in’ t Zand et al. 2013). In the hard X-rays (e.g., above 30 keV), on the contrary, the persistent emission during the burst is found to have a clear shortage, indicating cooling of a corona (see, e.g., Maccarone & Coppi 2003a; Chen et al. 2012; Ji et al. 2014a) and hence dramatic changes of the persistent spectrum, because the burst emission dominates below 30 keV. This issue was partially addressed in previous work (Keek et al. 2014a). They performed a detailed time-resolved spectral analysis for this rare superburst event and found evidence in the decay phase of an enhancement of the overall persistent flux and a reduction of the corona temperature, which could be consistent with a hard X-ray shortage if the persistent spectrum continues up to tens of kiloelectronvolts. Because the superburst event is relatively rare, we explore this issue in more detail in this paper by analyzing the atoll source NS LMXB GS 1826-238, which shows more frequent X-ray bursts.

GS 1826-238 is a persistent atoll source, which did not exhibit significant spectral evolution of its persistent emission until recently (Galloway et al. 2008; Nakahira et al. 2014). Assuming a distance of 6 kpc, this source always stays in the so-called low hard state with a luminosity of 5%–9% L_{edd} (Galloway et al. 2008). Its X-ray emission in a wide energy
range of 3–200 keV can be well described by a pure thermal Comptonization model with a characteristic hot electron temperature, $T_e \sim 20$ keV (Cocchi et al. 2010). GS 1826-238 is the famous “clocked burster” because of the recurrence of the bursts being relatively stable over the span of years (Ubertini et al. 1999; Galloway et al. 2004). Also, the burst shapes remain quite constant, and the burst peak fluxes have a rather narrow distribution (see, e.g., Table 1). The mean and standard deviation of the burst peak fluxes are 24.6 and 2.8, respectively. These properties are quite helpful for reducing the possible systematic errors that result when one STACKS bursts together. The most distinguishing feature for GS 1826-238 is that it is one of a few atoll XRBs with a hard X-ray shortage being significantly detected during bursts (Ji et al. 2014a). Because for GS 1826-238 the thermal emission from either the accretion disk or the NS surface contributes little at energies above 30 keV, such a hard X-ray shortage provides the most clean probe of the change in the nonthermal emission, which likely helps to restrict the spectral model at soft X-rays with respect to the preburst emission.

In this paper we derive the evolution of the persistent emission along the burst at soft X-rays and then diagnose the burst influence on accretion in a broad energy band, using the knowledge of the previously detected hard X-ray shortage.

2. OBSERVATIONS AND DATA ANALYSIS

We analyzed all Rossi X-ray Timing Explorer (RXTE) Proportional Counter Array (PCA) pointing observations and searched for bursts. The bursts exhibiting data losses were excluded. We also ruled out several bursts for which the Standard 2 mode data were not available. Forty-three bursts were previously chosen for studying the hard X-ray shortage in the type I bursts of this source (Ji et al. 2014a). Because in this analysis the selection criteria are a bit looser, that is, bursts with incomplete persistent emission (150 s before and 250 s after the burst peak) are also considered, 25 more bursts come into the overall sample. All of the 68 bursts selected for our analysis are shown in Table 1.

In this paper we analyzed the persistent emission using Standard 2 mode data, while the Event mode data were used for studying the properties of bursts because of their high time resolution. The software environment was HEASoft ver 6.15, including the commands “saextrct” and “seeextrct” to extract light curves and spectra and “pcabackest” to estimate the background. The spectral response files were generated by the latest pcarsp v11.7.1, in which the drifting proportional counter unit (PCU) gain values over the RXTE mission lifetime have been taken into account. We have verified that the results are not sensitive to the selection of the RXTE epoch. The spectral analysis was performed by using Xspec 12.8 and its Python wrapper PyXspec. During spectral fits, the energy band used was 3–20 keV, above which the effective area of PCU drops off rapidly. To avoid the possible bias in the estimation of parameters due to the non-Gaussian distribution in some channels with small numbers of counts, a Churakov weight was used in the spectral analysis.

We performed a time-resolved analysis on each burst by adopting the same spectral fitting procedure as described in Ji et al. (2014b). In brief, we produced light curves for each burst with a time resolution of 0.25 s and took the peak of the count rate as a reference labeled as time zero. We then fitted the spectra for the interval when the count rate exceeds 25% of the burst peak. In brief, we performed a time-resolved analysis for the individual bursts around their peaks. To improve the statistics, we selected variable time intervals so that the total counts in each time bin exceeded 5000 photons. As a result, the bin size has to gradually increase toward the burst tail because of the lower count rate. The varying persistent flux model, i.e., $wabs \times (bbodyrad + f_a \times persistent flux)$, was employed to fit the spectra in the 3–20 keV band, in which the $bbodyrad$ represented the intrinsic burst component and $f_a \times persistent flux$ represented the variable persistent emission (see, e.g., Worpel et al. 2013, for details). The “wabs” component was used to describe the interstellar absorption; the hydrogen column density was fixed to $0.3 \times 10^{22}$ atoms cm$^{-2}$ (Cocchi et al. 2010). Our results are independent of the photoelectric absorption model because its major influence happens at energies below 3 keV. The varying persistent flux model was chosen because the short burst exposure does not allow the measuring of all parameters of the relatively weak persistent emission (see Table 1). Here the persistent flux was estimated by fitting the spectrum before each burst with a phenomenological model, such as $wabs \times (powerlaw + gauss)$ or $wabs \times (bbodyrad + powerlaw + gauss)$, where the Gaussian component was always set at 6.4 keV with an arbitrary width of 0.5 keV. More physical models, e.g., CompTT, would lead to a further increase of the average burst flux model. We investigated the average evolution of $f_a$ by summing up all of the bursts. In practice, we took the peak flux of each burst as a time reference ($t = 0$ s) and averaged over bins of 3 s. Figure 1 shows that at the rising phase of bursts, the $f_a$ value rapidly increases (O to A). Then, along with a further increase of the average burst flux, the $f_a$ value decreases and reaches a value of around 1 at the time of the burst flux peak (noted as point B in Figure 1). Finally, during the averaged burst decay, $f_a$ gradually returns to a value (point C) comparable to that at point A and then smoothly decreases. We note that if we divide the bursts into two groups along time and then calculate $f_a$ curves individually to check their consistency, the $\chi^2$ test leads to a reduced $\chi^2 = 51.83$ (46 dof), which indicates that the slight changes of the shape of the bursts over several years (Galloway et al. 2004; Galloway & Lampe 2012) have little influence on our results. For comparison, Figure 1 also presents the averaged hard X-ray (30–50 keV) light curve during bursts observed by RXTE/PCA.

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5. To search for the bursts, we produced 1 s light curves, then selected the observations in which the maximum count rate is 500 cts s$^{-1}$ larger than the average, and finally checked them manually.

6. See https://asd.gsfc.nasa.gov/XSPECwiki/low_count_spectra
Table 1
The Columns Denote the Observation ID, the Time When Type I Bursts Occurred, Persistent Flux, and Unabsorbed Peak Flux of Bursts at 3–20 keV.
The Persistent Flux, Peak Flux of Bursts, and Their Errors Are Obtained by Fitting Models with Xspec Command "Cflux"

| Observation ID     | Modified Julian Day | Persistent Flux \(10^{-9}\) erg s\(^{-1}\) cm\(^{-2}\) | Peak Flux \(10^{-9}\) erg s\(^{-1}\) cm\(^{-2}\) | Observation ID     | Modified Julian Day | Persistent Flux \(10^{-9}\) erg s\(^{-1}\) cm\(^{-2}\) | Peak Flux \(10^{-9}\) erg s\(^{-1}\) cm\(^{-2}\) |
|-------------------|---------------------|-----------------------------------------------|-----------------------------------------------|-------------------|---------------------|-----------------------------------------------|-----------------------------------------------|
| 50971.70          | 0.996 ± 0.010       | 28.8 ± 0.9                                    | 50971.70                                      | 1.507 ± 0.005     | 25.5 ± 0.8          |
| 50971.23          | 1.012 ± 0.004       | 27.7 ± 0.9                                    | 50971.23                                      | 1.581 ± 0.007     | 26.5 ± 0.8          |
| 50972.18          | 1.126 ± 0.007       | 28.1 ± 0.9                                    | 50972.18                                      | 1.577 ± 0.013     | 26.0 ± 0.8          |
| 50976.42          | 1.014 ± 0.004       | 27.5 ± 0.7                                    | 50976.42                                      | 1.617 ± 0.009     | 24.7 ± 0.9          |
| 50988.83          | 0.991 ± 0.006       | 27.1 ± 0.7                                    | 50988.83                                      | 1.578 ± 0.026     | 25.6 ± 0.9          |
| 51724.88          | 1.309 ± 0.007       | 24.6 ± 0.7                                    | 51724.88                                      | 1.578 ± 0.026     | 24.2 ± 0.8          |
| 51725.71          | 1.176 ± 0.019       | 27.3 ± 0.7                                    | 51725.71                                      | 1.636 ± 0.007     | 24.7 ± 0.8          |
| 51725.88          | 1.176 ± 0.019       | 26.8 ± 0.7                                    | 51725.88                                      | 1.636 ± 0.007     | 25.1 ± 0.8          |
| 51726.72          | 1.364 ± 0.009       | 26.0 ± 0.7                                    | 51726.72                                      | 1.620 ± 0.021     | 26.5 ± 0.8          |
| 51728.77          | 1.359 ± 0.014       | 26.0 ± 0.7                                    | 51728.77                                      | 1.551 ± 0.011     | 25.7 ± 0.8          |
| 51811.75          | 1.324 ± 0.016       | 26.5 ± 0.8                                    | 51811.75                                      | 1.551 ± 0.011     | 24.7 ± 0.8          |
| 51813.49          | 1.361 ± 0.012       | 24.9 ± 0.7                                    | 51813.49                                      | 1.537 ± 0.028     | 23.5 ± 0.8          |
| 51814.01          | 1.417 ± 0.017       | 26.4 ± 0.8                                    | 51814.01                                      | 1.600 ± 0.015     | 25.7 ± 0.8          |
| 51814.35          | 1.397 ± 0.007       | 26.0 ± 0.8                                    | 51814.35                                      | 1.580 ± 0.011     | 23.8 ± 0.8          |
| 51813.15          | 1.368 ± 0.011       | 26.1 ± 0.7                                    | 51813.15                                      | 1.543 ± 0.006     | 25.9 ± 0.8          |
| 52484.57          | 1.578 ± 0.017       | 27.6 ± 0.8                                    | 52484.57                                      | 1.543 ± 0.006     | 24.8 ± 0.8          |
| 52484.42          | 1.717 ± 0.038       | 24.7 ± 0.8                                    | 52484.42                                      | 1.587 ± 0.009     | 26.6 ± 0.8          |
| 52485.01          | 1.615 ± 0.024       | 26.4 ± 0.7                                    | 52485.01                                      | 1.583 ± 0.015     | 25.7 ± 0.8          |
| 53205.20          | 1.580 ± 0.013       | 24.3 ± 0.8                                    | 53205.20                                      | 1.557 ± 0.045     | 25.2 ± 0.8          |
| 53206.06          | 1.514 ± 0.012       | 26.3 ± 0.8                                    | 53206.06                                      | 1.257 ± 0.008     | 20.2 ± 0.6          |
| 53966.37          | 1.654 ± 0.010       | 24.5 ± 0.8                                    | 53966.37                                      | 1.257 ± 0.008     | 20.8 ± 0.7          |
| 52736.53          | 1.417 ± 0.009       | 23.6 ± 0.7                                    | 52736.53                                      | 1.227 ± 0.014     | 17.8 ± 0.6          |
| 52736.67          | 1.410 ± 0.006       | 24.4 ± 0.8                                    | 52736.67                                      | 1.251 ± 0.005     | 17.9 ± 0.5          |
| 52736.80          | 1.410 ± 0.006       | 24.0 ± 0.6                                    | 52736.80                                      | 1.251 ± 0.005     | 18.7 ± 0.5          |
| 52736.48          | 1.348 ± 0.007       | 24.5 ± 0.7                                    | 52736.48                                      | 1.283 ± 0.024     | 20.5 ± 0.7          |
| 52738.61          | 1.397 ± 0.014       | 23.6 ± 0.7                                    | 52738.61                                      | 1.283 ± 0.024     | 19.3 ± 0.7          |
| 52738.75          | 1.397 ± 0.014       | 32.4 ± 0.9                                    | 52738.75                                      | 1.283 ± 0.024     | 20.2 ± 0.7          |
| 52820.56          | 1.507 ± 0.009       | 24.1 ± 0.5                                    | 52820.56                                      | 1.282 ± 0.013     | 20.2 ± 0.6          |
| 52944.40          | 1.425 ± 0.010       | 26.4 ± 0.8                                    | 52944.40                                      | 1.231 ± 0.007     | 19.8 ± 0.7          |
| 52834.39          | 1.515 ± 0.010       | 25.1 ± 0.8                                    | 52834.39                                      | 1.231 ± 0.007     | 19.6 ± 0.6          |
| 52835.31          | 1.523 ± 0.013       | 26.9 ± 0.7                                    | 52835.31                                      | 1.561 ± 0.009     | 24.4 ± 0.8          |
using the Event mode data (Ji et al. 2014a). The hard X-ray shortage is significant around the burst peak and gradually recovers to its initial level.

To illustrate the \( f_a \) evolution against flux, we present these data also in Figure 2. The correlation is significantly different between the cases when the burst flux is larger and smaller than \( \sim 10^{-8} \text{ erg s}^{-1} \text{ cm}^{-2} \). The turnover is smooth instead of a sharp peak. The Pearson correlation coefficient is 0.87 with a \( p \) value of 2.4 \( \times \) 10\(^{-15} \) for the former, but \( \sim 0.95 \) with a \( p \) value of 2.6 \( \times \) 10\(^{-7} \) for the latter. This result strongly confirms what was reported previously: \( f_a \) is highly dependent on the burst luminosity (in’t Zand et al. 2013; Worpel et al. 2013; Keek et al. 2014a). Although a quite similar \( f_a \) trend was reported previously in the hard state of 4U 1608-522 (Ji et al. 2014b), the fact that no significant shortage of the persistent hard X-ray emission is observed in this source (Ji et al. 2014c) prevents us from a joint diagnosis of the \( f_a \) evolution over a broad energy band.

As shown in Ji et al. (2014a) for GS 1826-238, the hard X-ray shortages for the persistent emission are still significant around points A and C of the bursts, suggesting a cooled corona. However, at that time, the \( f_a \) curve at soft X-rays shows large enhancements of the persistent emission (\( f_a \sim 1.8 \)). Around the burst peak, both the hard X-ray flux and the \( f_a \) present a similar trend of anticorrelation with the burst flux, which likely suggests a common cause. An enhancement in \( f_a \) can be the result of, for example, the intrinsic spectrum that deviates from a blackbody slightly (Suleimanov et al. 2011, 2012) or the reflection components (Ballantyne & Strohmayer 2004; Ballantyne & Everett 2005; Keek et al. 2014b), which might lead to a biased estimate of \( f_a \) when the “\( \text{bbodyrad} \)” model is used.

In what follows we diagnose these possible mechanisms in light of the possible burst influence on the persistent emission, using the results of \( f_a \) as derived at soft X-rays in this paper and

\[ \text{of the persistent emission shortage reported previously at hard X-rays (Ji et al. 2014a).} \]

3.2. Diagnosing the Burst Influence

Here we adopt the "\( \text{burstatmo} \)" model to describe the intrinsic spectra of bursts instead of the simple \( \text{bbodyrad} \) (see Suleimanov et al. 2011, 2012). The "\( \text{burstatmo} \)" model represents the atmospheres of NS and emergent spectra in a plane-parallel, hydrostatic, and LTE approximation. Hence, we performed again the above-described analysis, but now using a slightly different model: \( \text{wabs} \times (\text{burstatmo} + f_a \times \text{persistent flux}) \). There are three parameters in the \( \text{burstatmo} \) model: the radius and luminosity of the NS and a normalization. We cannot simultaneously constrain these parameters because of the large error bars, and we chose to fix the less impacting parameter—the radius of the NS—at 10 km. If the increasing value of \( f_a \) up to \( \sim 1.8 \) originates from the deviation of the intrinsic burst spectrum from a blackbody, after using the "\( \text{burstatmo} \)" model, \( f_a \) should be around 1. However, we found that the resulting \( f_a \) is very similar to the case when the \( \text{bbodyrad} \) model was used (i.e., similar to Figure 1 but with slightly bigger error bars). In addition, the "\( \text{burstatmo} \)" model does not improve the goodness of fit. The reduced \( \chi^2 \) is 1.10 (18 dof), which is comparable to 1.08/18 (do) using the model \( \text{wabs} \times (\text{bbodyrad} + f_a \times \text{persistent flux}) \). In order to further rule out the possibility that the \( f_a \) originates from the bias of fitting due to the spectral subtle deviations between the intrinsic spectra (i.e., \( \text{burstatmo} \)) and the phenomenological \( \text{bbodyrad} \) model, we used the \( \text{burstatmo} \) model to produce faked spectra with assumed burst luminosities of 0.5 and 1, respectively, and then we fitted them by the varying persistent flux model using the \( \text{bbodyrad} \) model. The resulting best-fit values of \( f_a \) are 1.31 and \(-4.01 \), respectively, which are inconsistent with the observed values (1.6 and 1.1 with error bars of \(-0.1\)) shown in Figure 1.

Alternatively, the reflection during bursts produced by the accretion disk represents viable possibilities for influencing the persistent flux (Ballantyne & Strohmayer 2004; Ballantyne &
Everett 2005; Keek et al. 2014b). These were detected during superbursts (in’t Zand & Weinberg 2010; Keek et al. 2014a) or hinted at in normal bursts (Galloway et al. 2008). For individual bursts, the statistics are not good enough to search for possible reflection components. Therefore, we stacked the residuals derived from the spectral analysis using the varying persistent flux model. If the reflection component does exist, one would expect some structure in the residuals. The analyses were performed at three instances \((t = 0, 20, 60 \text s)\) with a time bin of \(\sim 1 \text s\) for the different phases of the (average) burst. We found, however, no additional structures suggestive of emission lines or edges. The excess around 6.4 keV is hardly visible with a significance level below 2\(\sigma\).

The hard X-ray shortage during bursts in GS 1826-238 (and other LMXBs) is indicative of cooling of the corona (Maccarone & Coppi 2003a; Ji et al. 2014a). The result reported from a superburst in 4U 1636-536 also showed evidence in the burst tail for changes of the electron temperature \(T_e\) in the corona when the blackbody normalization was fixed (Keek et al. 2014a). We investigated whether the \(f_a\) variability shown in Figure 1 corresponds to any corona cooling by performing simulations. We set free the electron temperature \(T_e\) and produced some faked spectra, and we fitted them using the varying persistent flux model to look into a possible influence on the \(f_a\) factor. We used the model CompTT to describe the persistent flux; the model parameters \((T_0 = 1.02, T_e = 21.5 \text keV, \text{ and } \tau = 3.81)\) were adopted from the report of Cocchi et al. (2010). We note that a slightly different model, for example, cutoffpl or comptb, barely affects our analysis. Assuming that the spectrum during the bursts is \(wabs \times (bbbodyrad + CompTT)\) with variable \(T_e\), we produced faked spectra by using the Xspec command fakeit, where the \(bbbodyrad\) components are set at typical values of \(T = 2 \text keV\) and norm = 100. Then we used the varying persistent flux model to fit these faked spectra, i.e., assuming the spectrum remains constant in shape but varies in normalization. The resulting value \(f_a\), as illustrated in Figure 3, clearly indicates that a lower temperature \(T_e\) tends to result in a smaller \(f_a\).

Considering that the three additional independent variables in the coronal model CompTT, that is, the normalization \((N)\), the optical depth \((\tau)\), and the temperature of the seed photons \((T_0)\), are also expected to vary under the shower of soft X-rays from bursts, we further investigated if the \(f_a\) evolution can be connected to variations in these parameters. For simplicity, we first kept \(\tau\) and \(T_0\) unchanged during bursts, but we set free the variables \(N\) and \(T_e\); see below for a discussion of variations in the other parameters. We performed simulations by producing faked spectra based on the model \(wabs \times (bbbodyrad + N \times CompTT(T_e))\), in which there are two free variables: \(N\) and \(T_e\). We again used the varying persistent flux model to fit these faked spectra, like done before. The normalization of \(CompTT\) is fixed to \(4.78 \times 10^{-3}\), for which the inferred count rate is consistent with the hard X-ray \((30-50 \text keV}\) observations, that is, \(1.69 \text{cts s}^{-1} \text pcu}^{-1}\). The assumed temperature and normalization in the \(bbbodyrad\) model are 2 keV and 100, respectively, which corresponds to the values around the burst peaks; note that the simulations are insensitive to the assumed blackbody parameters. The result is illustrated in the left panel of Figure 4. The color bar in that figure shows the value of \(f_a\), whereas the black lines show the contours where \(f_a\) equals 0, 1, and 2, respectively. We note that in Figure 4 the \(f_a\) is just a result of using the varying persistent flux model and does not reveal physical meanings, that is, the enhanced (suppressed) accretion rate when the \(f_a\) is larger (smaller) than 1. The result suggests that larger \(N\) and \(T_e\) lead to a larger \(f_a\) value. This is not surprising because both the \(N\) and \(f_a\) are normalizations; \(T_e\) will affect the efficiency of the up-Compton scattering. Thus, the scenario of corona cooling via bursts can be sketched as follows. At the beginning of the burst, the normalization \((x\ text axis, N)\) increases rapidly, which phenomenologically accounts for the \(f_a > 1\) (O\text{--}A, point O represents the initial values before the bursts, i.e., \(T_e = 21.5 \text keV\) and \(N = 1\)). This process may be accompanied by a moderate decrease of the \(T_e\). Then, \(T_e\) drops sharply and dominates the burst influence by largely reducing \(f_a\) (A\text{--}B and B\text{--}C). In the cooling tails the process might be a rough inverse of the O\text{--}A process, but with a dominance of corona heating over cooling.\(^8\) We note that the burst flux and the \(f_a\) value at point A are comparable with these at point C, whereas its hard X-rays seems to be slightly stronger, which may imply a little larger \(T_e\) at point A.

As mentioned above, the hard X-ray shortage in the bursts of GS 1826-238 is observed to be rather robust (Ji et al. 2014a). This provides a unique opportunity to test the cooling scenario speculated upon above, by checking if the observed hard X-ray shortage is consistent with the persistent spectral model derived from the varying persistent flux model. For a given persistent model and assumed parameters, one can deduce the hard X-ray count rates by convolving it with PCA’s response matrix and then compare to the results using observations directly. Therefore, the observed hard X-ray shortage can impose a strong constraint in the parameter space of the persistent spectral model. The hard X-ray count rate at 30–50 keV before the bursts is \(\sim 1.69 \pm 0.1 \text{cts s}^{-1} \text pcu}^{-1}\) and is reduced to a minimum \(\sim 0.8 \pm 0.1 \text{cts s}^{-1} \text pcu}^{-1}\) around the burst peak. Assuming that the coronal spectrum is \(N \times CompTT(T_e)\),\(^8\) Note that Figure 4 is just a schematic diagram and the positions of the points (A/C, B) are not precise; they only represent the values of \(f_a \sim 1.8\), and \(\sim 1\), respectively.

\[^8\]Note that Figure 4 is just a schematic diagram and the positions of the points (A/C, B) are not precise; they only represent the values of \(f_a \sim 1.8\), and \(\sim 1\) respectively.
there are high color temperature or the lack of significant nonthermal emission. For details, see Ji et al. (2014c).}

Following Worpel et al. (2013), we employed the varying persistent flux model to fit the spectra in the energy band 3–20 keV during bursts. The $f_a$ is correlated with the burst flux up to $\sim10^{-8}$ erg s$^{-1}$ cm$^{-2}$ (which corresponds to $\sim0.8 \times 10^{38}$ erg s$^{-1}$ assuming a distance of 6 kpc and a gravitational redshift of 1.3), whereas above this value it is anticorrelated. This confirms the previous report using the hard state of 4U 1608-522 (Worpel et al. 2013; Ji et al. 2014b). In 4U 1608-522, however, no hard X-ray shortages were found (Ji et al. 2014c).

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Figure 4. $f_a$ resulting by assuming the $\tau = 3.81$ and 2 for the left and right panel, respectively. The color bar shows the intensity of the $f_a$, and the black lines show the contours where the $f_a$ equals 0, 1, and 2, respectively. The two cross hatches enclose the possible region of $N$ and $T_e$, which are deduced from the hard X-ray shortages in Figure 2 in Ji et al. (2014a). The green lines show the initial state before bursts, $f_a = 1$ and $T_e = 21.5$ keV.

4. DISCUSSION AND SUMMARY

Feedback of type I X-ray bursts onto the accretion material surrounding the compact star in LMXBs was predicted earlier (Walker & Meszaros 1989; Walker 1992; Inogamov & Sunyaev 1999, 2010; Ballantyne & Strohmayer 2004; Ballantyne & Everett 2005; Kluźniak 2013). However, because of the generally short exposure of bursts, it is hard to test them in individual events. Using RXTE observations of GS 1826-238 spanning 17 years, we were able to study in detail the overall changes of the persistent emission while bursting. This study can be done because of its constant burst shape (e.g., Thompson et al. 2005) and dominance of the coronal emission in the hard state, and, therefore, significant nonthermal radiation above $\sim$30 keV (e.g., Galloway et al. 2004).
Around the point B in Figure 1, $f_\alpha$ has a trend similar to that of the strength of the hard X-ray shortage. This hints at a sufficiently cooled corona when the burst emission is intense. Figure 4 shows that the electron temperature $T_e$ may account for the $f_\alpha$ valley observed around the burst peak. Such a $T_e$ reduction/recovery feature was observed as well in the decay phase of the superburst from 4U 1636-536 (Keek et al. 2014a), which also points to corona cooling under a shower of soft X-rays. We find, however, that to reconcile the hard X-ray shortage with the $f_\alpha$ evolution at soft X-rays, one has to take into account a smaller optical depth $\tau$. The Comptonized spectrum can be used to estimate the cooling power, that is, the power of losing energy of the corona under the shower of burst photons. Here we estimated the cooling power as the difference between the incident flux and the emergent flux after the Compton process. The emergent flux is estimated by using the *Xspec* command “flux” with the parameters specified below.¹⁰ and the incident flux is inferred by analytic estimation; the emergent energy of photons is $\sim \frac{4\pi}{6} \frac{D^2}{6 \text{kpc}^2}$ erg $\text{s}^{-1}$ in the energy band 1–100 keV, which is only $\sim 8\%$ of the cooling power before bursts. The uncertainties of the cooling power are difficult to constrain. If we artificially assume that the error bars of $T_e$ and $\tau$ are $\sim 3$ keV and 1 at the 90% confidence levels, respectively, and they are independent, the 5% lower and upper boundaries of the inferred distribution of the cooling power are 1.5% and 24.0% of the cooling power before bursts, respectively. This cooling power turns out to be not sufficient to account for the decreased temperature of electrons in the corona (Keek et al. 2014a). Thus we speculate that a possible solution might be to take into account an additional mechanism, that is, corona formation, which may be influenced as well by the burst. This may be reminiscent of the XRB outbursts in their spectral transition from hard state to soft state, where the corona is eventually diminished along with the increasing accretion rate. If one assumes that the changes of the electron temperature are the result of the balance between the Compton cooling and heating mechanisms, a suppressed heating process might be a solution to the above contradiction. However, the heating mechanism currently is still poorly known. In evaporation models, both the disk and corona are individually powered by the release of gravitational energy associated with the accretion of matter affected by viscous stresses, which depends strongly on the viscosity parameter ($\alpha$) (Meyer & Meyer-Hofmeister 1994; Liu & Taam 2013). Alternatively, in magnetic reconnection models, the heating power is $\sim \frac{B^2}{4\pi} V_A$, where $V_A$ is the Alfvén speed (Liu et al. 2002). Therefore, if at any point in time the system is in approximate equilibrium, where the heating power equals the cooling power, the viscosity parameter $\alpha$ or the Alfvén speed $V_A$ is expected to change dramatically during bursts. We caution that this scenario might be oversimplified. In outburst transitions, which are also attributed to the cooling and reheating of the corona, the low-state to high-state spectral transition at the initial rise of outbursts occurs at a luminosity five times greater than that of the transition from high state to low state at the declining stage (Maccarone & Coppi 2003b), which is known as the “hysteresis effect.” This means that the flux of the seed photons might not be the only factor that can influence the cooling and reheating of the corona, and some other unknown processes should be taken into account (Begelman 2014).

We speculate that during transitions from the hard state to the soft state in outbursts of LMXBs, the corona is cooled by the increasing number of soft seed photons emitted from the accretion disk, which in general leads to an increased value of $\tau$ (for details, see, e.g., Narayan & Yi 1995; Esin et al. 1997). This seems inconsistent with what we infer for GS 1826-23. As shown in the left panel of Figure 4, the main inconsistency that results from $f_\alpha$ and the hard X-ray shortage is at the points A and C. A smaller optical depth of the corona has to be introduced to account for the difference of the persistent emission modifications between the soft and the hard X-rays. We speculate that this “discrepancy” might arise from the different optical depths of the corona for the seed photons having different origins. Considering that the corona is geometrically thick above the accretion disk, but exists only within a small radial radius, the optical depth for the seed photons from the accretion disk would be larger for these photons from type I X-ray bursts. In addition, the seed photons from type I bursts would lead to a significant Poynting–Robertson drag (Walker 1992). This may imply that during bursts the inner part of the corona vanishes and becomes thinner in the radial direction (Walker 1992), leading to a smaller optical depth.

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