EVIDENCE FOR ACCRETION RATE CHANGE DURING TYPE I X-RAY BURSTS

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ABSTRACT

The standard approach for time-resolved X-ray spectral analysis of thermonuclear bursts involves subtraction of the pre-burst emission as background. This approach implicitly assumes that the persistent flux remains constant throughout the burst. We reanalyzed 332 photospheric radius expansion bursts observed from 40 sources by the Rossi X-Ray Timing Explorer, introducing a multiplicative factor \( f_a \) to the persistent emission contribution in our spectral fits. We found that for the majority of spectra the best-fit value of \( f_a \) is significantly greater than 1, suggesting that the persistent emission typically increases during a burst. Elevated \( f_a \) values were not found solely during the radius expansion interval of the burst, but were also measured in the cooling tail. The modified model results in a lower average value of the \( \chi^2 \) fit statistic, indicating superior spectral fits, but not yet to the level of formal statistical consistency for all the spectra. We interpret the elevated \( f_a \) values as an increase of the mass accretion rate onto the neutron star during the burst, likely arising from the effects of Poynting–Robertson drag on the disk material. We measured an inverse correlation of \( f_a \) with the persistent flux, consistent with theoretical models of the disk response. We suggest that this modified approach may provide more accurate burst spectral parameters, as well as offering a probe of the accretion disk structure.

Key words: accretion, accretion disks – stars: neutron – X-rays: bursts

Online-only material: color figures

1. INTRODUCTION

Thermonuclear (type I) X-ray bursts arise from the unstable ignition of accreted H/He near the surface of an accreting neutron star in a low-mass X-ray binary (LMXB) (e.g., Fujimoto et al. 1981; Strohmayer & Bildsten 2006). Gas accreted from a low-mass stellar companion accumulates on the surface of the neutron star, where it is compressed and heated hydrostatically. When the temperature and pressure are high enough, a thermonuclear explosion is triggered. These events are observed as a sudden increase in X-ray luminosity to many times the persistent level (e.g., Lewin et al. 1993; Strohmayer & Bildsten 2006). Type I bursts have been detected from over 100 sources in our Galaxy.4 Typical bursts exhibit rise times of 1–10 s, durations of a few tens of seconds to a few minutes, and have total energy outputs of \( 10^{39} \)–\( 10^{40} \) erg.

Analyses of type I bursts typically make a number of implicit assumptions, namely:

1. The total source spectrum comprises two additive components: one (the “burst component”) arising from nuclear burning and the other (“persistent emission”) arising from accretion.
2. The burst component has the same spectral shape for all bursts from all sources.
3. That shape is a blackbody, with variable temperature and normalization.
4. The persistent emission’s spectral shape does not change during a burst and is identical to its pre-burst shape.
5. The persistent emission’s intensity does not change during a burst and is identical to its pre-burst intensity.

Making the last two of these assumptions allows the subtraction of the pre-burst emission of the neutron star from the burst spectra as background (e.g., van Paradijs & Lewin 1986; Lewin et al. 1993; Kuulkers et al. 2003; Galloway et al. 2008, hereafter G08). This approach (hereafter referred to as the “standard approach”) implicitly assumes that the accretion rate remains constant throughout a burst, but it is not obvious that this assumption is reasonable. For instance, when the flux reaches the Eddington limit, in the so-called photospheric radius expansion (PRE) bursts, one would naively expect, assuming isotropic emission, accretion to cease entirely because the outward radiation force exceeds the gravitational force. Lamb & Miller (1995) argue that accretion ought to be shut off if the luminosity exceeds Eddington anywhere in the accretion flow, not necessarily just at the stellar surface. The effect of radiation halting accretion flow has apparently been observed for a number of the very brightest and most vigorous bursts (e.g., in’t Zand & Weinberg 2010), during which, for a few seconds, no X-ray flux (beyond instrumental background) is observed from the star—though this may also be due to the atmosphere expanding so far that it obscures the emitting regions of the accretion disk. On the other hand, increased luminosity during a burst might enhance the accretion rate, via Poynting–Robertson drag acting upon the accretion disk (Walker & Meszaros 1989; Miller & Lamb 1996; Walker 1992, hereafter W92). At luminosities greater than \( 0.01 L_{\text{Edd}} \), radiation forces have more of an effect on the accretion flow than general relativistic effects (Miller & Lamb 1993). Since there are questions about the isotropy of the burst emission (e.g., Boutloukos et al. 2010), it is not obvious which of outward pressure and radiation drag will dominate. It is therefore of importance to determine if a varying accretion rate is detectable during a PRE burst, and to quantify any variation that is detected. In this paper, we attempt to measure a change in the accretion rate by performing spectral fits where the pre-burst (persistent) emission is allowed to vary during a burst, but holding all the other assumptions of the standard approach fixed.

See http://www.sron.nl/~jeanz/bursterlist.html.
Some of the implicit assumptions of the standard analysis approach have been tested in previous studies: van Paradijs & Lewin (1986) pointed out that, if the total spectrum and persistent spectrum are both treated as blackbodies, subtracting the former from the latter will not leave a net burst spectrum that can be fit with a blackbody. This idea was followed up by Kuulkers et al. (2002) in a study of the rapidly accreting GX 17+2. They did not find that accounting for this effect improved the spectral fits and concluded that the persistent emission does not originate from the same location as the burst emission on that neutron star. Muno et al. (2000) and Strohmayer & Brown (2002) allowed for the accretion to shut off entirely, by subtracting the instrumental background only, and Strohmayer & Brown (2002) allowed for the accretion to shut off entirely, by subtracting the instrumental background only, but did not find that the spectral fits were improved by doing so. Recently, in’t Zand et al. (2013) studied a PRE burst from SAX J1808.4—3658 using combined Chandra and Rossi X-Ray Timing Explorer (RXTE) data and found that an observed excess of photons at both low and high energies can be well described by allowing a 20-fold increase of the pre-burst persistent emission. It also may be that the persistent emission is composed of separate contributions arising from different sites. These include a boundary layer at the inner edge of the accretion disk (e.g., Kuulkers et al. 2002), the inner regions of the accretion disk proper (e.g., Christian & Swank 1997; Cackett et al. 2010), emission from the neutron star itself or its photosphere (van Paradijs & Lewin 1986), and Compton scattering in an accretion disk corona (White & Holt 1982). However, disentangling these contributions is likely to be difficult because they are probably correlated and spectrally indistinct.

Deviations of the burst component of the spectrum from a blackbody spectrum could also be present. Such spectral changes have been theoretically predicted at both the high-energy (e.g., London et al. 1984, 1986) and low-energy (e.g., Madej 1991; Madej et al. 2004) ends of the X-ray spectrum. However, the literature is divided as to whether these are actually present in observations. Excess photons at high energy have been reported in bursts from 4U 2129+11 (van Paradijs et al. 1990) and GX 17+2 (Kuulkers et al. 2002). On the other hand, pure blackbodies have been found to give generally good results up to the present time (e.g., Güver et al. 2012), and some authors argue that they are consistent with blackbodies to extremely high confidence (Boutloukos et al. 2010). One might further divide the burst emission into contributions from a continuum and discrete spectral features superimposed upon it such as emission lines and absorption edges. Continuum changes are likely to be present throughout all stages of a burst (e.g., Suleimanov et al. 2011). Changes in the spectral features are thought to be largely confined to the Eddington-limited radius expansion period as these are thought to be due to ashes from nuclear burning being mixed into the expanding envelope (Weinberg et al. 2006), and have been detected in the so-called superexpansion bursts (in’t Zand & Weinberg 2010). However, the non-detection of spectral features in a PRE burst from SAX J1808.4—3658 by in’t Zand et al. (2013) suggests that such features may be too weak to be detected by currently available instruments: this source is the brightest PRE burster (see Table 4), and the burst in question was observed by two X-ray observatories. Galloway et al. (2010b) previously used Chandra spectra to search for spectral features in PRE bursts from 4U 1728—34, without success. Either the sought-after features are too weak to be detected, or they are not present in every burst.

If the accretion rate varies for any bursts, we expect it to be for the PRE bursts, although there is obviously a possibility that outward radiation pressure and radiation drag will partially negate each other; this makes them the most stringent tests of the idea that accretion rate might increase. They are the most luminous bursts for any given source and therefore should produce the largest radiation forces. They will also have the best signal-to-noise ratio of bursts from any given source. These bursts are of interest because they can be used to probe the structure of LMXB systems. Since they reach the Eddington luminosity of the neutron star, the atmosphere is no longer bound to the surface of the star and expands. The luminosity is thought to remain within a few percent of the local Eddington luminosity throughout the radius expansion (e.g., Hanawa & Sugimoto 1982; Ebisuzaki et al. 1983; Titarchuk 1994b). Thus, radius expansion bursts can in principle be used to measure the surface gravitational redshift of the neutron star and thereby its compactness (e.g., Damen et al. 1990; Özel et al. 2009; Güver et al. 2010; Stein et al. 2010), giving insights into the neutron star equation of state (Lattimer & Prakash 2007). Radius expansion bursts can also be used to determine the distance to the bursting star (Basinska et al. 1984), making them potentially useful as standard candles (e.g., Kuulkers et al. 2003).

The structure of this paper is as follows. In Section 2, we describe the data and its collection. In Section 3, we develop and implement a modified spectral analysis method, and apply it to a single burst to demonstrate its feasibility. In Section 4, we apply the method to all the PRE bursts in our sample to build a statistical picture of the phenomenon. In Section 5, we investigate the effect of allowing non-thermal burst emission of fixed shape. In Section 6, we compare our results to theoretical predictions made by Walker (1992). In Section 7, we discuss our results and place them in the context of previous work.

### 2. DATA COLLECTION AND REDUCTION

We used observational data from the RXTE, publicly available through the High-Energy Astrophysics Science Archive Research Centre (HEASARC),5 dating from shortly after the satellite’s launch on 1995 December 30 to the end of the RXTE mission on 2012 January 3. RXTE carries three instruments for detecting X-rays. The All-Sky Monitoring (ASM) camera consists of three Scanning Shadow Cameras sensitive to photons with energies between 1.5 and 12 keV with a field of view of approximately 2 deg, and performed 90 s step-stare observations of most of the sky every 96 minutes (Levine et al. 1996). The Proportional Counter Array (PCA) consists of five Proportional Counter Units (PCUs) sensitive to photons with energies between 2 and 60 keV and has a field of view of approximately 1 deg (Jahoda et al. 2006). RXTE also carries the High Energy X-Ray Timing Experiment (HEXTE), a collection of scintillation counters with a 1 deg field of view (Rothschild et al. 1998), but we do not use data from HEXTE in this work.

We took as the basis for our sample the G08 catalog of bursts. The G08 sample identifies PRE bursts according to the criteria set out in G08 (their Section 2.3). Briefly, these criteria define a PRE burst as one that (1) reaches a local maximum blackbody normalization $K_{bb}$ at or near the moment of peak flux, (2) has declining values of $K_{bb}$ after this time, and (3) attains its lowest blackbody temperature at the maximum $K_{bb}$. At the time of publication of G08, the catalog contained 254 PRE bursts; since then, a further 118 PRE bursts have been observed, giving a total of 372.6

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5 See http://heasarc.gsfc.nasa.gov.
6 See burst.sci.monash.edu/minbar.
Unless otherwise stated, the data analysis procedures are as in G08. For those bursts for which suitable data modes were available, time-resolved spectra in the range 2–60 keV covering the burst duration were extracted on intervals beginning at 0.25 s during the burst rise and peak. The bin size was gradually increased into the burst tail to maintain roughly the same signal-to-noise level. The RXTE PCUs are subject to a short (≈10 μs) interval of inactivity following the detection of each X-ray photon. This “dead time” reduces the detected count rate below what is incident on the detector (by approximately 3% for an incident rate of 400 counts s⁻¹ PCU⁻¹). We calculated for each measured spectrum an effective exposure, taking into account the fraction of events lost during dead time, following the approach recommended by the instrument team. Contributions to the dead-time fraction arise from coincidence and particle events as well as source and background photons.

We re-fit the spectra over the energy range 2.5–20 keV using the revised PCA response matrices, version 11.7, and adopted the recommended systematic error of 0.5%. The fitting was undertaken using XSPEC version 12. In order to accommodate spectral bins with low count rates, we adopted Churazov weighting.

We modeled the effects of interstellar absorption, using a multiplicative model component (wabs in XSPEC), with the column density $N_H$ frozen. The $N_H$ values are drawn from the literature, preferentially from studies of neutron stars using instruments sensitive at lower X-ray energies than RXTE. They are listed in the Appendix. In the original analysis carried out by G08, the neutral absorption was determined separately for each burst, from the mean value obtained for spectral fits carried out with the $N_H$ value free to vary. This has a negligible effect on the burst flux, but can introduce spurious burst-to-burst variations in the blackbody normalization.

3. METHOD

Our revised analysis is to fit the burst spectra with a two-component model consisting of a blackbody, representing the burst emission, and a model of the pre-burst persistent emission, representing the emission due to accretion of material onto the neutron star, with a prefactor $f_b$ left free in the fits. As we cannot distinguish contributions to the persistent emission arising from different locations in the neutron star system, we simply assume that the persistent emission is indivisible and results entirely from accretion onto the neutron star. As PRE bursts are likely to be the most stringent tests of changes in accretion onto the star, we select these events for our analysis.

It is also possible that the burst emission is non-Planckian, but fitting a non-blackbody spectrum requires the existence of theoretical models that can describe the data. The most recent model atmospheres of bursting neutron stars are those of Suleimanov et al. (2011), but even these have been only partially successful (Zamfir et al. 2012) and are not intended for radius expansion spectra. In the absence of models that are demonstrably better than blackbodies, and no consensus that blackbody fits really are unsuitable, we keep the assumption of thermal burst emission for the majority of our analysis. We discuss this issue further in Section 5. Similarly, we do not draw a distinction between deviations from a blackbody due to continuum or features in this paper, since spectral features are either not present in every burst or are too weak to be detected.

In order to demonstrate our approach, we select a burst from the well-studied PRE burster 4U 1636–536 (Swank et al. 1976). This source is an attractive candidate for several reasons. It is a prolific burster, with 75 PRE bursts recorded by RXTE. At a distance of approximately 6 kpc (G08) it is relatively nearby. Its average peak burst flux of $(6.9 \pm 6) \times 10^{-9}$ erg cm⁻² s⁻¹ is among the brightest sources and ensures good signal to noise. The hydrogen column density of $0.25 \times 10^{22}$ cm⁻² (Asai et al. 2000) is low compared to most other sources in the catalog, minimizing the absorption corrections that have to be performed on the spectra. There are no other known LMXBs in the same field of view as 4U 1636–536, so confusion with the persistent emission of other sources is not an issue (see Section 4.1 for further discussion of this problem). Finally, 4U 1636–536 accretes mixed H/He (Galloway et al. 2006) and is therefore representative of the majority of neutron stars in our sample (G08).

The burst we chose was detected on 2001 June 15 (burst ID 34 in G08). The data for this burst consist of 122 spectra recorded by RXTE with an integration time of typically 0.25 s. Of these spectra, 37 are after the beginning of the burst, which we take to be the first time that the flux exceeds 25% of the maximum burst flux. Recording continued up to 176.75 s after the burst start, but the flux had declined to the pre-burst level by 24.75 s. Two of the RXTE’s PCUs, numbers 3 and 4, were active for this burst.

3.1. Characterizing the Persistent Emission

We adopted the integrated X-ray flux for a 16 s interval prior to the start of each burst as the persistent emission. This spectrum also includes a time-dependent contribution from instrumental (non-source) background; to estimate this contribution we used the full-mission, “bright” source (>40 counts s⁻¹) models released 2006 August 6 with the pcre backlash tool. Subsequent model fits to each persistent (and burst) spectrum used the corresponding model spectrum estimated for that burst as background. We then generated a model for the persistent emission consisting of a blackbody plus a power law, both corrected for interstellar absorption. The fits were performed with XSPEC (Arnaud 1996; Dorman & Arnaud 2001) using wabs*(bbodyrad+powerlaw) as the model. The hydrogen column density was kept fixed at $0.25 \times 10^{22}$ cm⁻², the value determined in Asai et al. (2000).

For the persistent emission model, we obtained a blackbody temperature of $(1.9^{+0.1}_{-0.1})$ keV and a normalization of $(6.0^{+1.2}_{-1.0}) \times 10^{51}$ km²/(10 kpc)². The power-law component had index $(+3.0^{+0.2}_{-0.3})$ and normalization $(2.2^{+0.8}_{-0.5})\times10^{-8}$ cm⁻² s⁻¹ at 1 keV. Errors given are the 1σ confidence level. The reduced $\chi^2$ for this fit was 0.699 for 21 degrees of freedom, indicating that the model adequately describes the data. Figure 1 shows the fit to the data and the residuals.

3.2. Modeling the Burst Spectrum

We initially fit the burst spectra with the standard approach: a blackbody spectrum, corrected for interstellar absorption using the same hydrogen column density as above, i.e., wabs*bbodyrad in XSPEC. We subtracted the measured pre-burst emission, which includes a component that does not arise from the source (the instrumental background), and fit the resulting burst spectrum. This is the same implementation of the

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5 See http://heasarc.gsfc.nasa.gov/docs/xte/recipes/pca_deadtime.html.
6 See http://www.universe.nasa.gov/xrays/programs/rxte/pca/doc/rmf/pcarmf-11.7.
standard approach as in G08. These initial fits provide standard approach fits to which we can compare ours, as well as sensible spectral parameters to seed the variable persistent emission fits.

Now we introduce the dimensionless quantity $f_a$, the persistent emission multiplicative factor, as a third variable parameter. The burst spectra are fitted again, replacing the recorded pre-burst emission subtraction with just the instrumental background, with the model

$$S(E) = A(E) \times B(E; T_{bb}, K_{bb}) + f_a \times P(E) - b(E)_{inst},$$

where $S(E)$ is the fitted spectrum as a function of energy $E$, $A$ is the absorption correction, $B$ is the blackbody function with temperature $T_{bb}$ and normalization $K_{bb}$, $P$ is the persistent model described in Section 3.1, and $b_{inst}$ is the instrumental background. Note that the persistent model already contains an absorption factor. The parameter $f_a$ is allowed to vary between $-100$ and $100$. This allows us to track changes in the accretion rate through the factor $f_a$. Because of the 0.25 s integration time of the burst spectra, our measured peak $f_a$ values may be slight underestimates.

Figure 2 shows the time evolution of burst bolometric flux (top panel), the $f_a$ factor (middle panel), and the reduced $\chi^2$ for both treatments (lower panel) for our selected burst. We found that the $f_a$ increases to many times the pre-burst level, peaking at $17.8 \pm 4.7$ at 0.25 s after the burst start. The errors are $1\sigma$ significance limits determined by XSPEC. The burst bolometric flux is calculated from the blackbody parameters

$$F = \sigma T_{bb}^4 (R/d)^2$$

$$= 1.076 \times 10^{-11} \left( \frac{kT_{bb}}{1\text{keV}} \right)^4 K_{bb} \text{ erg cm}^{-2} \text{ s}^{-1},$$

where $T_{bb}$ is the blackbody temperature, $R$ is the effective radius of the emitting surface, $d$ is the distance to the source, and $K_{bb}$ is the normalization of the blackbody assuming isotropic emission. The calculated flux does not include the contribution to the total flux due to the scaled persistent emission. The burst component flux for the variable $f_a$ fits is therefore consistently lower than the standard approach fits for the peak of the burst, where $f_a > 1$. We also find that, after the beginning of the burst, the $\chi^2$ for the variable $f_a$ fits is consistently lower than for the standard approach fit, with means of $1.26 \pm 0.59$ and $1.50 \pm 0.60$, respectively. A Kolmogorov–Smirnov test shows that the two sets of $\chi^2$ values have a 4.0% probability of being consistent with one another. Figure 3 shows the flux–temperature curve for this burst.

The pre-burst persistent emission is very much fainter than the peak of the burst emission, by a factor of 35. It is possible that counting statistics in the burst spectrum could induce a spurious response in $f_a$. To investigate this possibility, we examined the spectrum with the highest $f_a$, which was $17.8 \pm 4.7$ recorded 0.25 s after the burst start. We took the blackbody parameters for that spectrum, $kT = 1.572$ keV and normalization $1034 \text{ km}^2/(10 \text{ kpc})^2$, and generated $10^3$ simulated spectra consisting of an absorbed blackbody with those parameters plus the persistent model times unity. The simulated spectra also incorporated counting statistics typical of the detector.

Figure 1. Measured persistent spectrum for the 2001 June 15 burst from 4U 1636–536 and the fitted spectral model (top panel), and residuals to the data (bottom panel). The reduced $\chi^2$ is 0.699, indicating a good fit to the data.
These represent a burst spectrum for which $f_a$ does not change and for which any measured deviation from $f_a = 1$ must be due to noise or the fitting procedure.

We fit each of the simulated spectra with our variable $f_a$ model. The mean parameters for these were $kT = 1.569 \pm 0.011$ keV, $K_{bb} = 1061 \pm 49$ km$^2$/s (10 kpc)$^2$, and $f_a = 0.36 \pm 1.18$. The mean parameters are therefore consistent with those that seeded the simulated fits. Adopting the standard deviation of the simulation values as the error on the fitted $f_a$, we found our measured $f_a$ for the real burst spectrum was 14.6 standard deviations higher than the simulated mean. We therefore conclude that the high $f_a$ values do not arise from counting statistics alone. Figure 4 shows a histogram of the measured $f_a$ for the simulated spectra compared with the value measured from the real burst spectrum.

Thus, for one burst we have found evidence for a spectral effect which can be described by varying the level of the persistent emission. This change is statistically significant for at least some of the spectra; 20 of the 37 of the spectra after the beginning of the burst had $f_a$ above unity with more than 4$\sigma$ significance (using the above procedure; see also Figure 4). The associated improvement in $\chi^2$ is of greater than 3$\sigma$ significance using $f$-tests. We apply the new method to all the PRE bursts in our sample in the next section.

4. STATISTICS OF MANY BURSTS

4.1. Burst Selection

We restrict our sample of PRE bursts to exclude events that are unsuitable for analysis. Three bursts were excluded for which the Standard-2 data were missing, preventing estimation of the instrumental background via pcabackest.

Some burst sources, such as 4U 1728–34, AQL X–1, and GRS 1747–312, lie in crowded fields containing other LMXBs. If the other source(s) were active at the time of observation, then their persistent emission could be confused with the source under observation and it would not be possible to scale only the persistent flux from the burst source. These sources need to be excluded from consideration.

We used ASM data to quantify this effect.9 For each burst, we found every source within the PCA’s field of view and took the ASM counts at the time record nearest the burst start time. Since the PCA’s response drops off approximately linearly with distance from the field-of-view’s center, we multiplied the ASM counts by $1−s$, where $s$ is the angular distance of the source from the center of the field of view, in degrees. We compared all the other sources to the burst source, and if the total contribution is more than 10% of the pre-burst flux of the burst source, we excluded this burst from consideration. We found source confusion in 36 bursts. The majority of these are from 4U 1728–34, which lies very near ($\Delta\theta = 0.56$) in the sky to the Rapid Burster, and which was frequently observed to burst during targeted observations of the Rapid Burster (Fox et al. 2001).

4.2. Modeling the Persistent Emission

In order to measure a change in the level of persistent emission for every burst spectrum, we need to construct a model for the persistent emission for each burst that can then be incorporated into the burst fits. It is not possible to simply use the detected photon counts for each energy bin because these include instrumental background.

We found that the blackbody-plus-power-law model used in Section 3 does not give adequate fits for every burst, so we considered a set of alternative spectral models. We fit each persistent spectrum with a range of different models. These

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9 See xte.mit.edu.
are summarized in Table 1, and retained the fit that gave the best (i.e., lowest) $\chi^2_{\nu}$. We found that the six models listed in Table 1 are sufficient to describe the persistent emission of all but one burst (see Figure 5). We are not overly concerned with theoretical interpretations of these models—the main objective is to get a function that matches the data—but the literature does provide some commonly used functions. White (1986) points out the importance of scattering, mentioning that this can be modeled with a Compton spectrum or a blackbody with an added power law, and we include both in our selection of alternatives. The inclusion of a Gaussian at 6.4 keV was motivated by the detection of fluorescent Fe emission for some sources at this energy (G08). The combination of thermal bremsstrahlung with a Gaussian was found by experimenting in XSPEC with persistent spectra that could not be properly fit with any of the other five models. For models containing a Gaussian, the lower limit on the line width is set to 0.1 keV to avoid the Gaussian simply approximating a delta function that removes the error on a single energy bin. In models where the hydrogen column densities are held constant, these are given in the Appendix. The $N_H$ values are mostly taken from the literature, and references are given in the Appendix. In persistent emission models where the hydrogen column densities are allowed to vary, the quantity $A(E)$ (see Equation (1)) is to be thought of as the product of the true interstellar absorption and a multiplicative factor that corrects the shape of the persistent emission model. As $A(E)$ is a multiplicative factor, it is unaffected by changes in $f_a$ and so this treatment does not introduce any systematic effects. One persistent emission spectrum, preceding a burst from Cyg X–2 observed at 14:29, 1996 March 27 (burst ID 2 in G08), could not be fit adequately by any of the six models, so this burst was excluded from the analysis.

The reduced $\chi^2$ for the spectral fits to the remaining 332 persistent spectra had a mean of 1.03 and a standard deviation of 0.35, with an average of $\nu = 21$ degrees of freedom. The skewness was 1.00 and the kurtosis was 2.8. This distribution is therefore somewhat more skewed and significantly more peaked compared to expected theoretical values of $\sqrt{8/\nu} = 0.62$ and $12/\nu = 0.57$ for the skewness and kurtosis, respectively. However, a Kolmogorov–Smirnov test gave a value of $D = 0.069$ and an 8.8% probability that the measured distribution is consistent with that expected assuming a good fit. We therefore consider these persistent emission models adequate for use in the subsequent generation of burst fits. The distribution of $\chi^2_{\nu}$ for the fitted persistent emission spectra is shown in Figure 5.

### 4.3. Fitting Burst Spectra

As in Section 3, initially we fit the burst spectra via the standard approach using an absorbed blackbody, by subtracting the recorded pre-burst emission, i.e., \texttt{wabs*bbbodyrad} in XSPEC. This is the same implementation of the standard approach as the one outlined in G08.

We then replace the detected pre-burst emission with just the instrumental background and fit the same spectra with a blackbody corrected by the adopted interstellar extinction value plus a multiple of the persistent emission model for that burst. We fix the hydrogen column density to the values given in the Appendix. The multiple of the persistent emission $f_a$ is allowed to vary as a free parameter, along with the temperature and normalization of the blackbody, as we did in Section 3.

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Table 1: XSPEC Models for Fitting the Persistent Emission

| XSPEC Model                      | Number of Spectra | Notes                                      |
|----------------------------------|-------------------|--------------------------------------------|
| wabs*(bbbodyrad+pol)             | 127               | N\text{H} fixed to values in the Appendix |
| wabs*(bbbodyrad+pol+gauss)       | 62                | N\text{H} fixed, Gaussian energy set to 6.4 keV |
| wabs*(compTT)                    | 37                | N\text{H} fixed                           |
| wabs*(gauss*bremss)              | 18                | N\text{H} allowed to vary                 |
| wabs*(bbbodyrad+diskbb\text{\textsuperscript{a}}) | 31 | All parameters variable\text{\textsuperscript{b}} |
|                                  | 57                | All parameters variable\text{\textsuperscript{b}} |
| Total usable spectra             | 332               |                                            |
| Rejected due to source confusion | 36                | Other active sources in field              |
| No background data               | 3                 |                                            |
| No good persistent model fit     | 1                 | Minimum $\chi^2_{\nu} > 5$                 |

Notes.

\text{\textsuperscript{a}} See Titarchuk (1994a).

\text{\textsuperscript{b}} All parameters are variable for the generation of persistent emission models. Their values are subsequently frozen for the burst spectral fits in Section 4.3.

\text{\textsuperscript{c}} See XSPEC manual (http://heasarc.gsfc.nasa.gov/xanadu/xspec/manual/manual.html) and references therein.

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![Figure 5](image-url) Distribution of $\chi^2_{\nu}$ for the fits to the persistent emission spectra for the 332 PRE bursts (blue stepped line) and the theoretical distribution (dashed curve) for $\nu = 20$. A Kolmogorov–Smirnov test showed a 8.8% probability that the measured distribution is consistent with that expected assuming a good fit, indicating that our model fits of pre-burst spectra are adequate. (A color version of this figure is available in the online journal.)
The Levengood–Marquardt algorithm used by XSPEC can become trapped in local $\chi^2$ minima, returning obviously unphysical results such as extremely high temperatures or normalizations. This problem can be mitigated if sensible initial values for the parameters are given rather than the XSPEC defaults, which are not appropriate in every case. We use the blackbody temperature and normalization of the blackbody obtained from the standard model, and $f_a = 1$, to seed these fits.

Generating and fitting to 1000 simulated spectra, as was done in Section 3.2, for each of the tens of thousands of burst spectra would be computationally prohibitive. To avoid needless work, we excluded spectra for which the variable $f_a$ fit was spurious. Only spectra with blackbody temperatures between 0.1 and 5.0 keV, normalizations of less than $10^6$ km$^2$ s$^{-1}$, and bolometric fluxes less than $10^{-6}$ erg cm$^{-2}$ s$^{-1}$ were retained. We also excluded $f_a$ determinations for which XSPEC encountered fitting errors such as non-monotonicity or reaching the parameter limits. This left 26,113 burst spectra out of the original 41,282. Almost all (>99%) of the discarded spectra were recorded before the beginning of the burst or very late in the cooling tail (i.e., stages 0 or 4 in Table 2; see also Section 4.4), and the failure to obtain spectral fits can be attributed to very low photon counts for these spectra. We also reduced the number of simulated spectra for each measured spectrum from 1000 to 320.

As a further check that $f_a$ is measuring a real spectral effect, we took the highest $f_a$ spectrum for each burst and performed an $f$-test on it, comparing the $\chi^2$ statistic from the standard approach and variable $f_a$ fits. Because $f_a \times P(E)$ is an additive component (see Equation (1)), $f$-tests are a suitable test (e.g., Orlandini et al. 2012). We found that, of these, 165 had detections of greater than $3\sigma$ significance and 65 had detections of better than $4\sigma$ significance.

We define the burst stage: the pre-burst stage consists of all times before the beginning of the burst, the expansion stage occurs from the beginning of the burst to the time of maximum normalization, the contraction stage is from the time of the maximum normalization up to and including the touchdown time, and the cooling tail stage is at all times after the touchdown time but before the bolometric flux drops back below one-quarter of the maximum flux. We neglect spectra after this time. We define the cooling tail as the stages 0 or 4 in Table 2; see also Section 4.4.

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### Table 2

| Stage Number | Stage Name | Description |
|--------------|------------|-------------|
| 0            | Pre-burst  | Flux has not yet reached 1/4 of the maximum |
| 1            | Expansion  | Normalization has not yet reached maximum |
| 2            | Contraction| Radius has reached maximum, $kT$ has not yet reached maximum |
| 3            | Cooling tail| Flux still above 1/4 maximum |
| 4            | Post-burst | Flux has dropped below 1/4 maximum |

There are 451 spectra with $f_a$ less than zero, for which the $f_a$ measurement is significant to more than $3\sigma$ (via the procedure detailed in Figure 4), and which occur in the Eddington-limited phase, out of 26,113. Of these, 333 spectra come from just six bursts. These six events are summarized in Table 3. By inspection of the flux–temperature curves, we identified that four of the six are examples of superexpansion bursts (in’t Zand & Weinberg 2010), particularly powerful PRE events for which the atmosphere is expanded to much larger radii than usual. In these events, the temperature of the photosphere drops out of the detection band of RXTE, resulting in zero observed flux from the star. The other two are bursts with highly unusual flux–temperature curves and appear to consist of two consecutive expansions separated by a few seconds, followed by a cooling tail with larger blackbody radius than the maximum radius reached during expansion.

### 4.4. $f_a$ as a Function of Burst Stage

Figure 6 shows the distribution of persistent flux factor $f_a$ for every burst spectrum (i.e., spectra from the Eddington-limited and cooling tail stages). The distribution of $f_a$ has a wider spread for the Eddington-limited spectra, so that there is a larger fraction of high $f_a$ spectra during radius expansion than for the cooling tail. However, the population of high $f_a$ spectra in the cooling tail is not negligible. This suggests that elevated $f_a$ is not only a result of the burst being Eddington-limited.
in Figure 7. However, none of the Kolmogorov–Smirnov tests were consistent with the null hypothesis; even our variable $f_a$ fits do not adequately fit the data, though they are an improvement on the old method. Some other systematic error must yet contribute to the discrepant spectral fits, perhaps deviations in the intrinsic burst spectrum from the assumed blackbody shape. Kolmogorov–Smirnov tests on the variable $f_a$ method against the standard approach likewise indicate that the two methods are not consistent with each other, for either the cooling tail or Eddington-limited spectra.

We also investigated whether the degree of radius expansion correlates with the increase in persistent emission. We define the reduced radius for an individual burst as the photospheric radius divided by the radius at touchdown point, which corrects for the distance of the source, assuming that the isotropy factor does not change. We compared the maximum reduced radius with the maximum $f_a$ for each burst; see Figure 8. These two maxima do not necessarily occur at the same moment. We found only a slight relationship between maximum $f_a$ and maximum expansion, nor is there a decrease in $f_a$ outside the accretion disk radius, suggesting that obscuration of the disk by the expanding atmosphere does not significantly affect the observed accretion emission.

One possible contribution to the elevated persistent flux during contraction is the fallback of the extended atmosphere. During the expansion phase, the atmosphere can be driven off the accretion disk boundary layer at $R = 1.18 R_\ast$ (Popham & Sunyaev 2001). The majority of photospheric expansion events exceed this radius. There is no obvious relationship between maximum $f_a$ and maximum expansion, nor is there a decrease in $f_a$ outside the accretion disk radius, suggesting that obscuration of the disk by the expanding atmosphere does not significantly affect the observed accretion emission.

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![Figure 7](image1.png)

**Figure 7.** Distribution of reduced $\chi^2$ for the variable $f_a$ vs. standard approach spectral fits, for both cooling tail and Eddington-limited spectra. Also plotted is the theoretical distribution for 23 degrees of freedom, which is the mean for the standard approach fits (blue line). Allowing the persistent emission to vary significantly improves the fits, but there are still significant deviations from the expected distribution for a perfect model. The variable $f_a$ and standard approaches are not consistent with being drawn from the same distribution using a Kolmogorov–Smirnov test.

(A color version of this figure is available in the online journal.)

**Table 3**

| Source          | Date and Time       | G08 Burst ID | Description          |
|-----------------|---------------------|--------------|----------------------|
| 4U 1722−30      | 1996 Nov 8, 07:00   | 1            | Superexpansion burst a |
| 4U 2129+12      | 2000 Sep 22, 13:47  | 1            | Superexpansion burst  |
| 2S 0918−549     | 2008 Feb 8, 03:02   | 5b           | Superexpansion burst a |
| 4U 1722−30      | 2008 Mar 1, 16:18   | 4b           | Superexpansion burst a |
| XB 1832−330     | 1998 Nov 27, 05:45  | 1            | Atypical burst profile|
| HETE J1900.1−2455 | 2010 Sep 20, 05:29 | 7b           | Atypical burst profile|

**Notes.**

a This burst was also studied by in’t Zand & Weinberg (2010).
b This burst postdates G08; a consistent burst ID numbering scheme is assumed.
c This burst was also studied by in’t Zand et al. (2011).

during contraction is the fallback of the extended atmosphere. During the expansion phase, the atmosphere can be driven off at about $10^{18} \, \text{g} \, \text{s}^{-1}$ (Weinberg et al. 2006). This is, naturally, around the order of $M_{\text{Edd}}$, the Eddington accretion rate. As an order-of-magnitude estimate, we make the assumption that half the expanded mass is driven off permanently. In a burst that is Eddington-limited for 5 s, the mass that is not expelled is about $2.5 \times 10^{18} \, \text{g}$. There are approximately 40% more contraction spectra than expansion spectra. All the spectra at these high fluxes are taken at 0.25 s intervals, so the atmosphere must generally contract more slowly than it expanded, by a factor of about 40%. It follows that the accretion rate due to the atmosphere falling back could be as much as $M_{\text{Edd}}/3$. CEOs.
There are bursters for which the pre-burst accretion rate is only 1% of $M_{\text{Edd}}$, so for these sources there should be a noticeable excess of contraction stage spectra with $f_a$ around 20–30. We have not detected any such excess (see Figure 6), so we conclude that atmosphere fallback does not contribute significantly to the accretion luminosity. A careful comparison with non-PRE bursts would clarify this issue further, as by definition atmosphere fallback cannot occur in these events, and this will be investigated in a subsequent paper.

5. SPECTRAL SHAPE CHANGES

Deviations of the burst component (that is, everything except persistent emission) from a blackbody could also be reflected by a changing $f_a$, especially if these deviations manifest as an excess of photons at high energy. Such spectral changes have been theoretically predicted at both the high-energy (e.g., London et al. 1984, 1986) and low-energy (e.g., Madej 1991; Madej et al. 2004) ends of the X-ray spectrum. Deviations from a pure blackbody are frequently inferred during radius expansion bursts (see, e.g., Kuulkers et al. 2002, 2003). The influence of these deviations on $f_a$ measurements must be investigated, but this is difficult because the nature of the deviations is not known. Here, we attempt to test the alternative hypothesis that the poor fit of the burst component from a blackbody.

We take the approach of assuming that the burst component retains a consistent spectral shape, which we model as a blackbody plus power law. We returned to our “prototype” burst (see Section 3) and fit the Eddington-limited and cooling tail spectra (stages 1–3 in Table 2) with an absorbed blackbody plus power law, with all parameters except $N_H$ variable. The mean power-law index of these fits was 1.93 ± 0.68. We then fit the spectra again, this time holding the power-law index fixed at this value but allowing the normalization to still vary. As we are here assuming that the power law is intrinsic to the burst emission, rather than being a separately varying component, we must specify the power-law normalization so that it contributes a fixed proportion of the total flux. Using a linear fit, we found that the normalization of the power law was best described by

$$\text{Power-law norm} \approx \frac{K_{bb} \times kT^4}{3212},$$

(3)

where $kT$ is the blackbody temperature in keV and $K_{bb}$ is the normalization of the blackbody in km$^2$/100 kpc$^2$. We fit the spectra a third time, this time tying the power-law normalization to the blackbody parameters with the relation given by Equation (3), which fixes the shape of the burst emission.

We found the mean $\chi^2$ was 1.27 ± 0.43 for the spectra of the 2001 June 15 burst from 4U 1636–536 using this fitting method, compared with 1.69 ± 0.58 and 1.21 ± 0.37 for the standard and variable persistent methods, respectively. Thus, for this burst, the phenomenological model fits the data nearly as well as the variable persistent model. We then used the same model, with the same power-law index and normalization relation, to fit every stage 1–3 spectrum from all radius expansion bursts in our catalog. Restricting these to spectra where XSPEC did not encounter fitting errors for any of the three methods, we found that our phenomenological model gave a mean $\chi^2$ of 1.43 ± 1.10, compared with 1.45 ± 0.82 and 1.21 ± 0.60 for the standard and variable persistent methods, respectively. The phenomenological model is thus globally no better than the standard approach. If there is a non-blackbody contribution to the burst component, it must differ between sources and change from burst to burst. Furthermore, it would also have to resemble the persistent emission for every burst, at least superficially, or the variable $f_a$ method would not be able to consistently improve the reduced $\chi^2$; and this itself hints at a relationship with the persistent emission. Clearly, any further investigation into such deviations must be physically motivated rather than phenomenological.

We then tested whether introducing a phenomenological change to the burst spectrum removes the need for a variable persistent emission. We fit the spectra of the 2001 June 15 burst from 4U 1636–536 using the variable persistent model, but replacing the blackbody burst component with the phenomenological spectrum. If our initial detection of a variable $f_a$ merely reflected the non-blackbody character of the burst component, then we would expect the detection to disappear. We still detect $f_a$ to vary significantly, though the values are consistently lower by roughly 20% than for the original fits. Furthermore, the mean $\chi^2$ for these fits was 1.17 ± 0.35, suggesting that allowing the persistent emission to vary improves the fits even when a non-blackbody model for the burst component is assumed. These results suggest very strongly that our detection of $f_a$ cannot be attributed to a confounding spectral effect intrinsic to the burst component.

If our variable $f_a$ fits are measuring a non-blackbody contribution to the burst spectrum, then we should expect $f_a$ to increase with burst flux. Suppose that a non-Planckian part of the burst component contributes a fixed fraction of the burst component flux and that our variable $f_a$ fits are trying to remove it. Then if the burst flux doubles, we would require $f_a$ to double also in order to fit out the non-Planckian part. We investigated this by comparing $f_a$ against $F/F_{\text{Edd}}$, where $F_{\text{Edd}}$ is the source’s Eddington flux (see the Appendix) for all Eddington-limited and cooling tail spectra. It is clear from Figure 9 that there is no relationship between the quantities. To test whether plotting all the points together obscures a relationship present in individual bursts, we selected the Eddington-limited and cooling tail spectra from our prototype burst and three randomly selected other bursts, and performed Kendall rank correlation tests on their $f_a$ against their blackbody fluxes. No statistically significant correlation was present in any of these bursts. If the hypothesized non-blackbody contribution is present at the high-energy tail, then we would expect an inverse correlation between blackbody temperature and $f_a$ because at low temperatures the blackbody drops out of the band detectable by RXTE, leaving only the hard tail to be fit. However, we find a slight positive correlation of $\tau = 0.031$ at 4.2$\sigma$ significance using a Kendall rank correlation test.

Our new fitting model holds the shape of the persistent emission fixed. Since the persistent emission of LMXBs changes shape according to whether it is in a high or low state (Hasinger & van der Klis 1989), it is reasonable to think it may change shape temporarily if the accretion rate changes during a burst. It is possible that spectral shape changes in the persistent spectrum contribute to the high $\chi^2$ in our approach. However, it is not clear that an accretion rate enhancement due to radiation drag will have the same effects on the persistent spectrum as the neutron star’s usual movement around the Z-track, since they have very different physical causes. Indeed, in’t Zand et al. (2013) found in their study of a burst from SAX J1808.4–3658 that the persistent spectrum became harder, whereas ordinarily they would expect increased accretion to soften the spectrum.
6. COMPARISON WITH THEORY

W92 performed one-dimensional (1D) simulations of geometrically thin, axisymmetric irradiated accretion disks around a neutron star. Their models include the effects of viscosity and general relativity. W92’s results predict that radiation torque from bursts can enhance the accretion rate by up to two orders of magnitude. If our \( f_a \) is assumed to be entirely an accretion enhancement, then it corresponds identically to their quantity \( \Delta \dot{M}/\dot{M}_\ast \), and is predicted to be inversely correlated with pre-burst accretion rate, accretion disk viscosity parameter \( \beta \), neutron star spin frequency, and neutron star radius. All of W92’s models assume a neutron star of mass \( 1.4 M_\odot \).

Table 1 of W92 lists peak accretion enhancements for the computed models; in Figure 10, we compare the maximum \( f_a \) measured for each burst against \( \gamma \), the pre-burst accretion flux as a fraction of the Eddington flux of the burst source. The Eddington flux for each neutron star is the mean peak flux of every PRE burst observed from that star; see the Appendix for the values and details of their calculation. Following G08, we measure \( \gamma \) by integrating the chosen pre-burst persistent model between 2.5 and 25 keV and dividing the resulting flux by the burst source’s Eddington flux. W92’s Table 1 lists related quantities. W92’s models begin with a non-rotating neutron star with radius 9 km, \( \gamma \) of roughly 0.3, and disk viscosity parameter, \( \beta \), of \( 10^{-4} \). They then allow the spin frequency, accretion rate, \( \beta \), and radius to vary in turn, while holding the other quantities fixed at their original values.

The disk viscosity parameter \( \beta \) (Coroniti 1981) is similar to the Shakura–Sunyaev disk viscosity (Shakura & Sunyaev 1973) but relates the viscosity to the gas pressure rather than the total pressure, which differs in disks which are radiation-pressure dominated. W92 gives accretion rates in dimensionless units: \( \dot{m} = M c^2/L_{\text{Edd}} \), where \( M \) is the mass accretion rate and \( L_{\text{Edd}} \) is the Eddington luminosity, whereas we give accretion rates in terms of the energy release. Since the mass \( M_\ast \) and radius \( R_\ast \) of the neutron stars in W92 are specified, we have

\[
\gamma = \frac{G M_\ast}{c^2 R_\ast} \dot{m}.
\] (4)

Our results in Figure 10 show a decrease in peak \( f_a \) with increasing \( \gamma \), and the slope is consistent with the predictions of W92’s three points representing a non-rotating star with increasing accretion rate, while our peak \( f_a \) values are significantly lower than those predicted for a non-rotating neutron star. If we assume a moderate \( \beta \) and rotation frequency of about 300–600 Hz (e.g., Muno et al. 2001; see also the Appendix),
then not only the observed correlation of peak \( f_a \) with \( \gamma \) but also the normalization appear to be consistent with W92’s predictions (see Figure 10). The models predict that stellar rotation period and disk viscosity parameter \( \beta \) have a large influence on peak \( f_a \) but that neutron star radius apparently has little influence. The upper edge of our measured points appears to be very roughly consistent with \( \gamma f_a \lesssim 1 \), implying that the accretion luminosity cannot greatly exceed \( L_{\text{Edd}} \). This is consistent with the predictions of Burger & Katz (1983) and Miller & Lamb (1996), who find that \( M_{\text{Edd}} \) is a natural cap on the accretion rate.

In Figure 11, we show maximum \( f_a \) against spin rate for all neutron stars in our sample whose spin rate is known. These are listed in the Appendix. W92’s models predict a gradual decrease of maximum \( f_a \) with spin frequency. Our data show maximum \( f_a \) values consistent in magnitude with W92’s models, but it is difficult to discern any trend, because of the large scatter in individual sources (due to the additional dependence on \( \gamma \) and the disk viscosity) and the small range of known neutron star spin frequencies (since these are all accreting neutron stars). We would require PRE bursts from slowly rotating neutron stars to better constrain this relationship. A further difficulty is that W92’s models do not reach the Eddington limit, so we are comparing PRE bursts in observations to non-PRE bursts in models.

As the W92 models are 1D, care must be taken in applying them to accreting neutron star systems in which three-dimensional effects are likely to be important. Further theoretical studies, preferably in three dimensions, would be very valuable.

7. DISCUSSION

We have performed an observational investigation into whether or not the persistent emission contribution varies during PRE bursts. We allowed the pre-burst emission to vary, parameterized by a factor which we denote \( f_a \). We detected a statistically significant increase in \( f_a \) for nearly all the PRE bursts in the catalog, suggesting an enhanced (rather than suppressed) level of persistent emission during a burst. Our new method results in a significant improvement in the reduced \( \chi^2 \) of spectral fits compared to the standard model but not to the level of formal statistical consistency for all the spectra.

Since the persistent emission is known to be an approximate measure of the accretion rate onto the neutron star, we interpret our results to indicate that the accretion rate onto the neutron star generally increases during bursts. Obviously, the persistent spectrum could also change shape in response to a varying accretion rate, and there are suggestions (Homan et al. 2007) that the X-ray luminosity may not be proportional to the mass accretion rate. There are, however, currently no predictions about how the persistent emission spectrum may change in response to rapidly increasing radiation drag, so we make the simplest assumptions that it does not change shape and that \( f_a \propto M \). We have shown that peak \( f_a \) measured during each burst anti-correlates with the pre-burst accretion rate with a slope consistent with that predicted by the theoretical models of Walker (1992), who investigated the effect of radiation drag on the accretion disk. If the effects of neutron star spin are accounted for, the magnitudes of the observed peak \( f_a \) are also consistent with theory. This suggests that our detection of an increased pre-burst persistent emission reflects an enhanced accretion rate due to radiation torques on the accretion disk around the star.

All of W92’s models are sub-Eddington, so some care must be taken in extrapolating their results to PRE bursts. However, W92 points out that the expanding atmosphere in a PRE burst should have very little angular momentum compared with the accretion disk. Radiation coupling between disk and envelope can thereby spin down the disk, increasing the accretion rate. This would also have the effect of spinning up the envelope and boosting its expansion. Such a mechanism may help explain why the atmosphere takes longer to return to the neutron star surface than to reach maximum radius.

It may be argued that a deviation of the burst spectrum from a blackbody could mimic a variable accretion rate by introducing a high-energy excess that our method then attempts to remove. If the deviation is of fixed size, then any spurious \( f_a \) measurement it causes will also anti-correlate with the pre-burst accretion rate \( \gamma \), similar to Figure 10. However, we would then also expect \( f_a \) to be constant with constant burst flux, but we found it to vary greatly during the Eddington-limited phase when the burst flux is approximately constant. We found no anti-correlation between \( f_a \) and blackbody temperature, which would occur if the blackbody component drops out of RXTE’s detection band and leaving only the deviation to be fit out. We also attempted to model a hard tail deviation in the burst spectrum using a power law with fixed index and normalization tied to the burst flux. This did not improve the spectral fits for the entire collection of bursts, and did not cause our detection of \( f_a \) to be suppressed. While in general we do not expect to see discrete spectral features in PRE bursts, in superexpansion bursts they can be visible (in’t Zand & Weinberg 2010). We have found that in these events \( f_a \) consistently drops rather than rises, consistent with zero flux from the source. As suggested by in’t Zand & Weinberg (2010), this may be due to the emission from the burst component dropping out of the band detectable by RXTE together with the persistent emission being obscured by the superexpanding shell, though it is also possible that the vigorously expanding envelope disrupts the accretion disk and thereby temporarily halts accretion. An enhanced \( f_a \) cannot be attributed to the presence of spectral features superimposed on the burst component continuum. While we have attempted to exclude confounding spectral effects intrinsic to the burst component as an explanation for \( f_a \) enhancements, we cannot rule out the possibility of other interpretations.
If our variable persistent fits cause the inferred photospheric radius at touchdown to differ systematically from the standard fits, then this would have implications for determinations of the equation of state of neutron star matter, such as those of Özel et al. (2009), Güver et al. (2010), and Steiner et al. (2010). We investigated this by taking the ratio of the touchdown radii as determined by the variable $f_a$ and standard methods for all the PRE bursts in our sample and obtained a mean value of $0.97 \pm 0.11$. This indicates that the inferred touchdown radius can differ by $\sim 10\%$, and that there is a slight trend toward lower neutron star radii using the variable persistent method. We have found that $f_a$ frequently remains elevated after the end of the Eddington-limited phase; this may have implications for studies that use the cooling tail to constrain the neutron star parameters (e.g., Galloway & Lampe 2012).

7.1. Structure of the Accretion Disk

The details of the transfer of material from the inner edge of the accretion disk to the neutron star surface are still uncertain (e.g., Bildsten 1998). It is not known if it occurs at a close inner boundary layer, or if there is some mechanism that regulates the infall. PRE bursts offer a means of settling this question: to be subject to radiation pressure the expanding photosphere must be optically thick and therefore must obscure our view of everything interior to it. The atmosphere expanding so far that it covers all of the emitting parts of the accretion disk would cause the persistent emission to be reprocessed inside the optically thick atmosphere and effectively become part of the burst emission. Even very modest radius expansion would hide the boundary layer due to this “shrouding,” and cause $f_a$ to decrease, since the boundary layer is thought to be geometrically small and located at a radius $\sim 1.2 R_\ast$ (e.g., Popham & Sunyaev 2001). Thus, our finding of consistently high $f_a$ during a burst argues against the existence of a thin boundary layer that remains near the surface of the star and dominates the persistent emission (see Figure 8), but is consistent with a boundary layer that becomes much wider in response to increased luminosity as suggested by Popham & Sunyaev (2001).

We also note that performing the analysis method of this paper on non-PRE bursts may provide further information about the structure of the accretion disk in these bursts, the atmosphere does not expand and will not obscure any of the accretion disk. A careful comparison of non-PRE bursts against PRE bursts, which progressively obscure parts of the disk, might therefore give insights into structure and properties of the disk. A preliminary investigation of a number of non-PRE bursts using the same analysis method indicates that the $f_a$ values increase during these events as well (see Figure 12), which would be expected if increased $M$ is caused by radiation drag as in W92’s models, but which would not be expected if $f_a$ is tracking spectral changes caused by the emitting photosphere distending. A proper study of non-PRE bursts will be the subject of a subsequent paper.

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\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{Figure12}
\caption{Non-PRE burst from 4U 1636–536 observed on 2005 August 10. The $f_a$ factor is significantly elevated, suggesting that the level of persistent flux rises for non-PRE bursts as well as PRE bursts. The time evolution of $f_a$ is similar to the one shown in Figure 2, indicating that the physical process is similar in both cases.}
\end{figure}

APPENDIX

Table 4 shows the $N_H$ values we adopt for each burst source studied in this work, the reference from which we obtained that value, and the number of PRE bursts recorded by $RXTE$ from that source, including bursts we discarded due to source confusion or unsuitable spectral data (see Section 4.2).

We also give Eddington fluxes, measured using the standard approach, for all sources that have PRE bursts recorded by either $RXTE$ (i.e., in the extended G08 catalog) or the Wide Field Camera on BeppoSAX.\textsuperscript{11} The Eddington fluxes are the means of the peak fluxes for every PRE burst recorded for that source, weighted by the inverse square of the error of the measurement.

If only one PRE burst has been recorded for any source, we simply report the peak flux for that burst and the error on that measurement. For sources with two or more PRE bursts, we calculate a reduced $\chi^2_{\text{meas}}$ assuming that the source has constant Eddington flux. If $\chi^2_{\text{meas}}$ is consistent with a constant flux, we allow the flux to vary up and down such that it now has $\chi^2_{\text{new}} = 1 + \chi^2_{\text{meas}}$; the amount by which we vary it is the error on the original measurement. If $\chi^2_{\text{meas}}$ is not consistent with constant Eddington flux, we artificially scale the errors on the individual measurements until $\chi^2_{\text{meas}} = 1$. Then we allow the flux to vary such that $\chi^2_{\text{new}} = 2$.

The prolific burster 4U 1636–536 has PRE bursts that are known to be bimodal in flux (Ebisuzaki & Nakamura 1988; Galloway et al. 2006). Most of its PRE bursts are thought to take place in a pure helium atmosphere and have peak fluxes around

\textsuperscript{10} See burst.sci.monash.edu/minbar.

\textsuperscript{11} See burst.sci.monash.edu/minbar.
XTE J1759
IGR J17498
IGR J17473
SAX J1747.0
±
SAX J1748.9
4U 1746
EXO 1745
Cyg X
4U 2129+12
0.03 1 (1) 1 40.8
AQL X
1A 1742
GRS 1741.9
4U 1820
±
GX 17+2
1.90 1 (0) 8 41.0 ± 3.8
XTE J1710–429
4U 1705–44
XTE J1710–281
4U 1722–30
4U 1728–34
KS 1731–260
4U 1735–444
GRS 1741.9–2853
1A 1742–294
SLX 1744–300
GX 3+1
SAX J1748.9–2021
EXO 1745–248
4U 1746–37
SAX J1747.0–2853
IGR J17473–2721
IGR J17498–2921
XTE J1759–220
SAX J1750.8–2900
GRS 1747–312
SAX J1808.4–3658
XTE J1810–189
SAX J1810.8–2609
GX 17+2
4U 1820–303
XB 1832–330
HETE J1900.1–2455
AQL X–1
XB 1916–053
4U 2129+12
Cyg X–2
Ser X–1

(68.6 ± 5.5) × 10−9 erg cm−2 s−1. A few bursts have peak fluxes lower by a factor of ≈1.7, and these are believed to take place in a hydrogen-rich atmosphere (G08). We consider both regimes separately. The lower flux bursts include a tentatively identified PRE event recorded by RXTE on 2000 January 22, 04:43:48 UT. We include this burst to calculate the mean Eddington flux for these low-flux events, but exclude it for the rest of the analyses in this paper.

We also list neutron star spin frequencies, where known. These have been calculated either from burst oscillations (BOs; e.g., Watts 2012) or from pulsar timing.
