SUPER-EDDINGTON FLUXES DURING THERMONUCLEAR X-RAY BURSTS

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ABSTRACT

It has been known for nearly three decades that the energy spectra of thermonuclear X-ray bursts are often well fit by Planck functions with temperatures so high that they imply a super-Eddington radiative flux at the emitting surface, even during portions of bursts when there is no evidence of photospheric radius expansion. This apparent inconsistency is usually set aside by assuming that the flux is actually sub-Eddington and that the fitted temperature is so high because the spectrum has been distorted by the energy-dependent opacity of the atmosphere. Here we show that the spectra predicted by currently available conventional atmosphere models appear incompatible with the highest precision measurements of burst spectra made using the Rossi X-ray Timing Explorer, such as during the 4U 1820–30 superburst and a long burst from GX 17+2. In contrast, these measurements are well fit by Bose–Einstein spectra with high temperatures and modest chemical potentials. Such spectra are very similar to Planck spectra. They imply surface radiative fluxes more than a factor of 3 larger than the Eddington flux. We find that segments of many other bursts from many sources are well fit by similar Bose–Einstein spectra, suggesting that the radiative flux at the emitting surface also exceeds the Eddington flux during these segments. We suggest that burst spectra can closely approximate Bose–Einstein spectra and have fluxes that exceed the Eddington flux because they are formed by Comptonization in an extended, low-density radiating gas supported by the outward radiation force and confined by a tangled magnetic field.

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

1. INTRODUCTION

Type I X-ray bursts (hereafter bursts) are produced by thermonuclear burning of matter accumulated in the surface layers of accreting neutron stars (Woosley & Taam 1976; Joss 1977; Lamb & Lamb 1978). These bursts have rise times ranging from a fraction of a second to a few tens of seconds, durations ranging from about tens of seconds to several thousand seconds, recurrence times ~102–105 s, peak luminosities ~1038 erg s−1, and total energy releases ~1039–1042 erg (Strohmayer & Bildsten 2006). The observed X-ray flux typically increases by a factor of ~10–100 during a burst. The properties of the large number of bursts that have been observed using the Rossi X-ray Timing Explorer (RXTE) have recently been summarized by Galloway et al. (2008).

Planck (blackbody) functions are often fit to the energy spectra of bursts (Swank et al. 1977; Hoffman et al. 1977; Galloway et al. 2008). During some, the temperature obtained from such fits drops and the derived emitting area increases. These photospheric radius expansion (PRE) bursts are thought to occur when the radiative flux through the stellar atmosphere exceeds the Eddington critical flux, creating an optically thick wind (see Galloway et al. 2008). The radiative flux is greater than the Eddington flux for any realistic neutron star if the emission has a Planck spectrum with a temperature measured at infinity $kT_{\infty} > 2.0$ keV (see Marshall 1982 and Section 2). Yet fits of Planck functions to burst spectra frequently yield temperatures substantially higher than this expected maximum, even during times when there is no evidence of radius expansion.

Neutron stars are not blackbodies, and conventional model atmosphere calculations show that they generally do not produce Planck spectra (see, e.g., London et al. 1984, 1986; Madej et al. 2004; Majczyna et al. 2005). In conventional atmospheres, energy-dependent absorption and scattering cause the spectrum to peak at an energy higher than the peak of a Planck spectrum with the same effective temperature. This effect led to widespread acceptance of the hypothesis that the effective temperature is substantially smaller than the temperature obtained by fitting a Planck function to the burst spectrum and that the radiative flux is sub-Eddington even when the fitted temperature exceeds 2.0 keV (see, e.g., Ebisuzaki et al. 1984; Galloway et al. 2008, their Section 2.2).

In contrast to conventional neutron star atmospheres, low-density atmospheres extensive enough to fully Comptonize free–free and cyclotron photons will produce Bose–Einstein spectra $dN/dE \propto E^{2}/\exp[(E - \mu)/kT] - 1$ with chemical potentials $\mu$ that satisfy $|\mu| \ll kT$ (see, e.g., Illarionov & Sunyaev 1975). These spectra have almost the same shape and energy flux as a Planck spectrum with the same temperature, because a Planck spectrum is a Bose–Einstein spectrum with $\mu = 0$. An important aspect of Bose–Einstein spectra is that knowledge of the radiation temperature and the chemical potential is sufficient to determine the radiative flux from the emitting surface; knowledge of the distance to the source or its luminosity is unnecessary.

Here we report analyses of RXTE data taken during high-luminosity segments of a superburst from 4U 1820–30 and a long burst from GX 17+2. Such segments provide the best opportunity to test spectral models, because the large number of counts collected allows the spectrum to be measured with exceptionally high precision. We find that the spectra predicted by currently available conventional atmosphere models appear incompatible with the spectra during these segments, whereas Bose–Einstein spectra fit these spectra well. The fits give $|\mu| \lesssim kT$ and values of $kT$ substantially greater than 2.0 keV, implying radiative fluxes at the emitting surface that are more...
than a factor of 3 larger than the Eddington flux. There is no evidence that the emitting surface is expanded at these times. We find that the spectra of other bursts from 4U 1820–30 and GX 17+2 and bursts from many other bursters are well fit by similar Bose–Einstein spectra, suggesting that the radiative flux also exceeds the Eddington flux during these bursts.

2. Maximum Blackbody Temperature

The radiative flux from a neutron star atmosphere confined by gravitation cannot exceed the Eddington flux. As explained in Section 1, the energy fluxes of Bose–Einstein spectra with modest chemical potentials are very similar to the fluxes of Planck spectra with the same temperature, so we can use the Planck form as a proxy. The maximum allowed surface temperature (measured at infinity) for emission with a Planck spectrum from a star with mass $M$ and radius $R$ can be determined by balancing the inward gravitational and outward radiative accelerations at $R$. This maximum temperature is

$$kT_{\infty, \text{max}} = \frac{4.60 \text{ keV}}{(m/m_p)(\sigma_T/\sigma)(M_\odot/M)}^{1/4} \times \left(\frac{GM}{Rc^2}\right)^{1/2} (1 + z)^{-3/4}$$

(see also Lewin et al. 1993, Equation 4.16), where $k$ is the Boltzmann constant, $m$ is the mass per nucleus, $m_p$ is the proton mass, $\sigma_T$ is the Thomson scattering cross section, $\sigma$ is the cross section per nucleus, $M_\odot$ is the solar mass, and $1 + z = (1 - 2GM/Rc^2)^{-1/2}$. Here, $m$ and $\sigma$ are to be evaluated at the photosphere and $z$ is the redshift from the photosphere to infinity. Note that the maximum temperature is independent of the distance to the source and the size of the emitting area and depends only weakly on the mass of the star.

$kT_{\infty, \text{max}}$ is largest for $GM/Rc^2 = 2/7$. This largest value scales as $M^{-1/4}$. Assuming neutron star masses are $\geq 1.2 M_\odot$ (for comparison, the lowest mass determined with high confidence is the 1.25 $M_\odot$ mass of pulsar B in PSR J0737–3039; see Burgay et al. 2003; Kramer & Wex 2009), $kT_{\text{max},\text{H}} = 1.71$ keV for an atmosphere of fully ionized hydrogen ($m = m_p$ and $\sigma = \sigma_T$); $kT_{\text{max},\text{He}} = 2.03$ keV for fully ionized helium ($m = 4m_p$ and $\sigma = 2\sigma_T$). Similar results were obtained by Marshall (1982; see also Hoshi 1981). $T_{\infty, \text{max}}$ depends on the composition of the atmosphere via $m/\sigma \propto A/Z$, where $A$ and $Z$ are the atomic weight and number; hence carbon or oxygen atmospheres have the same $T_{\infty, \text{max}}$ as a helium atmosphere. For the rest of this Letter, we assume $kT_{\infty, \text{max}} = 2.0$ keV.

3. Spectral Analysis and Results

All the data used in our analysis were obtained from the RXTE archive and were analyzed with FTOOLS version 6.8, following the RXTE cook book and using the recently updated RXTE response generator (v11.7) and calibration information. We usually subtracted the average preburst emission during a 16 s interval preceding the burst. We also constructed burst spectra without subtracting any preburst emission, using pcabackest (version 3.8, also recently improved) to estimate the purely instrumental background. In all cases we considered only the energy range 3–27.5 keV (to concentrate on the thermal emission) and used the data from all Proportional Counter Unit layers.

### 3.1. Long Segments from 4U 1820–30 and GX 17+2

A superburst from 4U 1820–30 was observed on 1999 September 9 using RXTE’s Proportional Counter Array (PCA) with 16 s time resolution (Standard2 mode, 129 energy channels). The data were studied by Strohmayer & Brown (2002), who reported best-fit Planck temperatures as high as 2.9 keV for about 800 s, with no evidence of radius expansion during this interval. The PCA spectrum at the burst peak shows an Fe Kα emission line at zero redshift (Strohmayer & Brown 2002), indicating that it is produced outside the neutron star atmosphere.

We analyzed four 64 s segments of data from different parts of this burst. The measured spectra of all of these segments are similar and are well fit by Bose–Einstein spectra, with best-fit temperatures ranging from 2.0 keV to 2.9 keV, but appear inconsistent with the spectra predicted by currently available conventional model atmospheres. Here we describe in detail our analysis of the segment that began at MET = 179460500.0, ~20 minutes after the start of the superburst.

We first tested Bose–Einstein (adjustable $\mu$) and Planck ($\mu = 0$) models for the spectra produced by burst atmospheres by fitting these models to the data. The Bose–Einstein spectrum is not yet in XSPEC and we therefore used our own fitting routines for it. Our routines reproduce the XSPEC results for models that are in the library. We used the XSPEC routine bbody to fit a Planck spectrum to the data. An external emission line was included with both spectral models. Both provide an excellent description of the measured spectrum (see, e.g., Figure 1). The implied radiative flux at the emitting surface during this segment is at least four times greater than the Eddington flux for any realistic neutron star.

We then investigated whether the spectra predicted by conventional model atmospheres with sub-Eddington fluxes are consistent with the spectrum we measured. No analytic descriptions of these model spectra are available, so we used standard methods (see, e.g., Cackett et al. 2009) to construct the PCA photon spectra they predict. We first redshifted the published theoretical spectra by an amount appropriate to the surface gravity of the model, using the APR equation of state (Akmal et al. 1998). We then constructed PCA count spectra using txe2xpec (written by Randall Smith) and fakedet. Finally, we normalized the count spectra to make the total number of counts the same as in the spectrum measured by the PCA.

Too few conventional atmosphere spectra have been published to be able to fit them to the high-precision PCA spectra, so we compared them with the Bose–Einstein spectral shape, which we have shown provides an excellent description of the observed spectrum, adjusting the shape to match the model spectra as closely as possible. No external emission line was included because all these models describe the spectrum produced by the burst atmosphere alone.

The conventional atmosphere models we studied are the $T_{\text{eff}} = 3.0 \times 10^7$ K, $\log g = 14.8$ Hz+He model of Madej et al. (2004) and the $T_{\text{eff}} = 2.0 \times 10^7$ K, $\log g = 14.1, 14.3, 14.5, \text{and} 14.7$ solar composition models of Majczyna et al. (2005). These models span a substantial range of surface effective temperatures $T_{\text{eff}}$, surface gravities $g$, and compositions. These models produce spectra that peak at an energy higher than a Bose–Einstein spectrum with the same effective temperature but all have shapes that deviate systematically, similarly, and strongly ($\chi^2$/dof $\gtrsim 50$; see, e.g., Figure 1) from the Bose–Einstein spectral shape that describes the measured spectra. The deviations of the solar composition models from the observed spectral shape are not caused by the lines in these

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4. [http://heasarc.gsfc.nasa.gov/docs/xte/recipes/cook_book.html](http://heasarc.gsfc.nasa.gov/docs/xte/recipes/cook_book.html)
and have a best-fit temperature $T^\text{best}_\infty$ well above 2.0 keV ($\left(kT^\text{best}_\infty - 2.0\text{ keV}\right)/\left(kT^\text{best}_\infty - kT^\min_\infty\right) > 5$, where $kT^\min_\infty$ is the lower boundary of the 68.3% temperature confidence interval; $kT^\infty$ and $kT^\min_\infty$ are given by Galloway et al.). We found 1834 such segments, from 34 sources, including 4U 1820−30 and GX 17+2; 4U 1728−34 is particularly prolific, with 556 such segments.

We again fitted Bose–Einstein and Planck spectra to the selected data segments. For these segments, we included photoelectric absorption using the XSPEC routine phabs. The results listed in Table 1 are typical of our results for all these segments. The temperatures obtained by fitting Bose–Einstein and Planck spectra to these intervals are consistent with each other and are formally $\sim 10\sigma$ higher than the 2.0 keV upper limit we established in Section 2, implying that the fluxes during all these segments are super-Eddington. These segments were selected as particularly likely to have high temperatures, but they are representative of the general burst population. Kuulkers et al. (2002) suggested that the high fitted temperatures may be artifacts produced by subtracting preburst emission. We therefore constructed spectra without subtracting any preburst emission, but found that the Bose–Einstein model also fits them and gave temperatures at least as high as before.

### 3.3. Summary of Results

We have shown that Bose–Einstein spectral models with high physical temperatures, modest chemical potentials, and substantially super-Eddington fluxes at the emitting surface provide an excellent description of high-precision measurements of the spectrum near the peaks of the 4U 1820−30 superburst and a long burst from GX 17+2. The shapes of the spectra predicted by all the currently available conventional model atmospheres appear incompatible with these measurements. We have also found that the spectra of shorter bursts from these two sources and many bursts from many other bursters are well fit by Bose–Einstein spectra with high temperatures similar to the temperatures of the spectra that fit the 4U 1820−30 superburst and the long GX 17+2 burst, suggesting that the radiative flux also exceeds the Eddington flux during these shorter bursts.

High spectral temperatures appear to be the rule rather than the exception, particularly for PRE bursts. According to the data tables of Galloway et al. (2008), which present fits of Planck spectra, 224 of 235 PRE bursts have at least one 0.25-s segment when $kT_\infty > 2.0$ keV and $\chi^2/\text{dof} < 1$; 488 of the 665 non-PRE bursts also have at least one such segment. If such high spectral temperatures do indicate super-Eddington fluxes, these results show that this phenomenon is widespread.

When the radiative flux falls below the Eddington flux, the burst atmosphere may be supported by gas pressure gradients rather than the radiation force. If so, the atmosphere will become even more dense, and the spectrum is likely to deviate from a Bose–Einstein spectrum. Galloway et al. (2008) have reported that burst spectra are less likely to be described adequately by a Planck spectrum when the flux is much less than the peak flux, results that hint at this effect. It is possible that conventional model atmospheres provide good descriptions of burst spectra when the flux is much less than the Eddington flux.

### 4. DISCUSSION AND CONCLUSIONS

As discussed in Section 2, measurement of a Bose–Einstein spectrum with a temperature greater than $\sim 2$ keV implies that the radiative flux at the emitting surface exceeds the Eddington
flux, independent of unknowns such as the distance to the source, the radiating area on the star, the radius of the star, and its surface redshift. The implied fluxes are accurate because the 2–60 keV bandpass of the PCA captures more than 95% of the flux of a 3.0 keV Bose–Einstein spectrum with $|\mu| \ll kT$. We have found that intervals with temperatures greater than $\sim 2$ keV occur during most bursts, suggesting that the radiative flux exceeds the Eddington flux during most bursts. When combined with the flux profiles seen during PRE bursts from some of these same stars, these results, and the small effective areas inferred during high-temperature intervals, indicate that most of the emission during these intervals comes from only a fraction (in some cases $\sim 20\%$) of the stellar surface.

These high temperatures and fluxes and small emitting areas raise several important questions: How can the flux be super-Eddington without producing a significant wind? What determines the maximum flux from the emitting area, and how big is it? And how do these results fit with evidence that the emitting surface is sometimes far above the stellar surface?

We suggest that the radiative flux can exceed the Eddington flux because the emitting gas is confined by a tangled stellar magnetic field. The sudden nuclear energy release that produces a burst creates a zone of turbulent convection at densities $\rho_t u^2$, where $\rho_t$ is the density in the convection zone and $u_t$ is the turbulent velocity there. The convection will amplify and tangle the star’s weak poloidal magnetic field until the tangled field becomes strong enough to inhibit convection, which occurs when $B_t^2 / 8\pi \approx \rho_t u^2$. The maximum value of $B_t$ is $\approx (8\pi)^{1/2} \rho_t^{1/6} F_i^{1/3}$ and is relatively insensitive to $\rho_t$ and $F_i$. For typical densities in the convection zone and the highest energy fluxes observed from the emitting surface, which are $\sim 10^{36}$ erg cm$^{-2}$ s$^{-1}$, $B_t$ (max) is $\sim$ few $\times 10^{10}$ G, $\sim 10$–100 times stronger than the dipole components inferred from observations and theoretical modeling (see Lamb & Boutloukos 2008).

The tangled field will be strong enough to confine the emitting gas if its tension, $f_{\text{mag}} \approx (1/4\pi) (B_i \cdot \nabla B_i) \approx B_i^2 / 4\pi \ell_B$, exceeds the outward radiation force, $f_{\text{rad}} \approx (F_{\text{rad}}/c)n_e\sigma$. Here, $\ell_B$ is the characteristic scale of the tangled field and $n_e$ is the electron density in the radiative zone. Assuming $\ell_B$ is no larger than the depth $\sim 10^3$ cm of the burning zone, a field $B_t$ (max) can confine the atmosphere in the presence of a radiative flux $\sim 10^{36}$ erg cm$^{-2}$ s$^{-1}$, which is the flux implied by an effective temperature $\sim 3$ keV.

A neutron star atmosphere supported by a super-Eddington radiative flux and confined by magnetic stresses is likely to be more extended and have a lower density than a conventional atmosphere supported by gas pressure and confined by gravity. In a future paper (Lamb et al. 2010, in preparation), we show that such an atmosphere naturally produces a Bose–Einstein photon spectrum with $|\mu| \lesssim kT$. Comptonization by the electrons in the atmosphere drives the photon distribution close to a Bose–Einstein distribution, while weak free–free and cyclotron emission drive the chemical potential to a small value (see, e.g., Illarionov & Sunyaev 1975).

We expect that a region of very hot, confined gas will heat adjacent areas of the stellar surface, which may not be confined by a strong magnetic field. When these adjacent areas become hot enough, they will expand vertically. If the product of the radiative flux from the very hot, confined gas and its emitting area exceeds the Eddington luminosity, adjacent gas will leave the star as a wind, producing a PRE event. Hence the maximum radiative luminosity will be approximately the Eddington luminosity, just as in the conventional picture, even though heat is flowing from below the atmosphere over only a fraction of the stellar surface. The PRE will end when the luminosity of the very hot, confined gas falls below the Eddington luminosity, even if the local flux from this gas exceeds the Eddington flux.

The high temperatures and radiative fluxes and small emitting areas found here, which were first noted nearly three decades ago, have important implications for efforts to determine neutron star masses and radii using bursts. For example, it is often assumed that during high-temperature intervals the entire stellar surface emits exactly the Eddington flux. Our analysis of spectral measurements made using RXTE shows that these assumptions must be reconsidered.

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Table 1

| Model       | $kT$ (keV) | Chemical Potential | $\chi^2$/dof |
|-------------|------------|---------------------|--------------|
| Bose–Einstein | 2.77 ± 0.05 | $-2.5 \leq \mu$ (keV) $\leq -0.5$ | 15.6/26      |
| Planck      | 2.83 ± 0.03 | $\cdots$            | 15.6/27      |
| 4U 1702−429, ObsID = 80033-01-19-04, Starting MET = 33341491.50 |
| Bose–Einstein | 3.07 ± 0.07 | $-2.6 \leq \mu$ (keV) $\leq -0.5$ | 15.4/26      |
| Planck      | 3.04 ± 0.08 | $\cdots$            | 16.6/27      |
| EXO 1745−34, ObsID = 50054-06-11-02, Starting MET = 213117542.50 |
| Bose–Einstein | 2.99 ± 0.06 | $-2.5 \leq \mu$ (keV) $\leq -0.3$ | 21.4/26      |
| Planck      | 3.04 ± 0.05 | $\cdots$            | 22.3/27      |

Notes. All uncertainties are 1σ. The $\mu$ range listed is the 68% confidence interval. The fits are very insensitive to the hydrogen column $N_H$, which we therefore do not list.
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