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 ten seconds to several thousand seconds, recurrence times $\sim 10^3$–10^6 s, peak luminosities $\sim 10^{38}$ erg s^{-1}, and total energy releases $\sim 10^{39}$–10^{42} erg (Strohmayer & Bildsten 2006). The observed X-ray flux typically increases by a factor of $\sim$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 μ 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-temperature 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

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

(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, σ_T is the Thomson scattering cross section, σ is the cross section per nucleus, $M_\odot$ is the solar mass, and $1+z = (1 - 2GM/Rc^2)^{-1/2}$. Here, m and σ 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.

$kT_{\infty,\max}$ is largest for $GM/Rc^2 = 2/7$. This largest value scales as $M^{-1/4}$. Assuming neutron star masses are $\geqslant 1.2\,M_\odot$ (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), $kT_{\max,\mathrm{H}} = 1.71$ keV for an atmosphere of fully ionized hydrogen ($m = m_p$ and $\sigma = \sigma_T$); $kT_{\max,\mathrm{He}} = 2.03$ keV for fully ionized helium ($m = 4m_p$ and $\sigma = 2\sigma_T$). Similar results were obtained by Marshall (1982; see also Hoshi 1981). $T_{\infty,\max}$ 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 $T_{\infty,\max}$ as a helium atmosphere. For the rest of this Letter, we assume $kT_{\infty,\max} = 2.0$ 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[4] 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 μ) 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 txt2xspec (written by Randall Smith) and fakeit. 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 $T_{\mathrm{eff}} = 3.0 \times 10^7$ K, $\log g = 14.8$ H+He model of Madej et al. (2004) and the $T_{\mathrm{eff}} = 2.0 \times 10^7$ K, $\log g = 14.1, 14.3, 14.5$, and 14.7 solar composition models of Majczyna et al. (2005). These models span a substantial range of surface effective temperatures T_{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 ($\chi^2/\mathrm{dof} \gtrsim 50$; 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
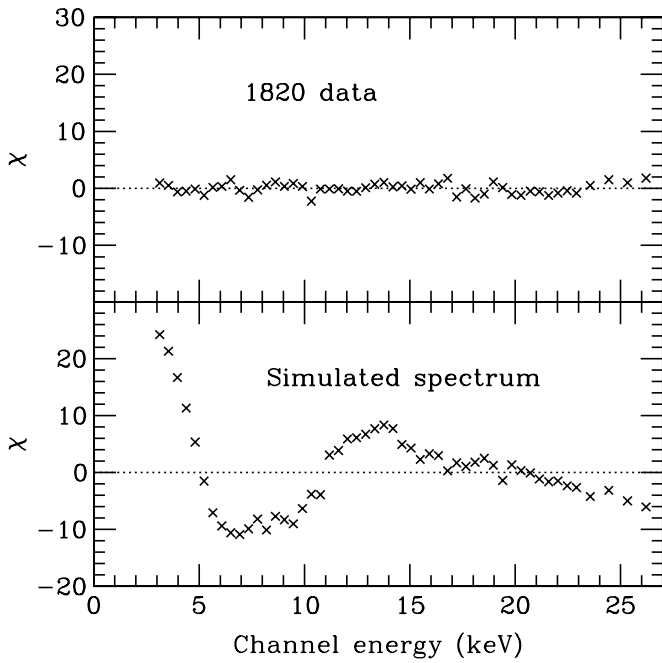

Figure 1. Residuals from fits of a Bose–Einstein spectrum to a spectrum of the 4U 1820−30 system measured by *RXTE* during a superburst (top panel) and to the spectrum predicted by the conventional H+He atmosphere model of Madej et al. (2004; bottom panel). The fitting procedure is described in the text. In the top panel, χ is the observed counts minus the Bose–Einstein plus emission line counts, divided by the square root of the observed counts; the best-fit temperature is 2.881 keV (1σ range: 2.878 keV to 2.889 keV); the best-fit chemical potential is −0.48 keV (1σ range: −0.53 keV to −0.40 keV); and $\chi^2/\text{dof} = 43.8/44$. Setting $\mu = 0$ (the Planck value) gives a slightly inferior fit ($\chi^2/\text{dof} = 53.5/45$). In the bottom panel, χ is the simulated counts minus the Bose–Einstein counts, divided by the square root of the simulated counts. Comparison of the simulated spectrum with the best-fitting Bose–Einstein spectral shape gives $\chi^2/\text{dof} = 2918/48$. Results like these indicate that the emitted spectrum is close to a Bose–Einstein spectrum, the effective temperature is ≈3.0 keV, and the radiative flux at the emitting surface exceeds the Eddington flux.

spectra: the energy response of the PCA is much broader than these lines and the fit is not improved significantly by excising them.

A long (∼500 s) burst from GX 17+2 was observed on 1999 October 6 using the PCA. Kuulkers et al. (2002) have reported that during a ∼100 s interval the spectrum of this burst is well fit by Planck spectra with $kT \geqslant 2.5$ keV and that there is no evidence of radius expansion during this interval. We have analyzed a 64 s segment of PCA data starting 10 s after the beginning of this burst and confirm that Planck and Bose–Einstein spectra fit these data well, whereas the available conventional atmosphere spectra are again incompatible with the measured shape of the spectrum ($\chi^2/\text{dof} = 1768/48$ for the conventional H+He model atmosphere of Madej et al. 2004).

3.2. Shorter Data Segments

In addition to analyzing four data segments from the 4U 1820−30 superburst and a segment from the long GX 17+2 burst, we also analyzed shorter segments of PCA data on many other, shorter bursts, to determine whether their spectra are also well fit by Bose–Einstein spectral models. These data were taken using the Event mode, which provides 64 energy channels.

Using tables of the results obtained by Galloway et al. (2008), kindly provided by Duncan Galloway, we selected segments that are well fit by a Planck spectrum ($\chi^2/\text{dof} < 1.0$)

and have a best-fit temperature T_∞^{best} well above 2.0 keV (($kT_\infty^{\text{best}} - 2.0$ keV)/($kT_\infty^{\text{best}} - kT_\infty^{\text{min}}$) > 5, where kT_∞^{min} is the lower boundary of the 68.3% temperature confidence interval; kT_∞^{best} and kT_∞^{min} 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 photo-electric 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 $>10\,\sigma$ 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 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 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 that the Eddington flux.

4. DISCUSSION AND CONCLUSIONS

As discussed in Section 2, measurement of a Bose–Einstein spectrum with a temperature greater than ∼2 keV implies that the radiative flux at the emitting surface exceeds the Eddington

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Table 1
Best-fitting Parameters for 0.25-s Segments of Burst Data

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Model	kT (keV)	Chemical Potential	χ^2/dof
Aql X-1, ObsID = 60054-02-03-03, Starting MET = 237409883.25			
Bose–Einstein	2.77 ± 0.05	$-2.5 \leqslant \mu(\text{keV}) \leqslant -0.5$	15.6/26
Planck	2.83 ± 0.03	$\cdots$	15.6/27
4U 1702−429, ObsID = 80033-01-19-04, Starting MET = 333414491.50			
Bose–Einstein	3.07 ± 0.07	$-2.6 \leqslant \mu(\text{keV}) \leqslant -0.5$	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	$-2.5 \leqslant \mu(\text{keV}) \leqslant -0.3$	21.4/26
Planck	3.04 ± 0.05	$\cdots$	22.3/27

Notes. All uncertainties are 1σ. The μ range listed is the 68% confidence interval. The fits are very insensitive to the hydrogen column N_{H}, which we therefore do not list.

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 ~ 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 $\sim 10^5$–10^7 g cm^{-3} (see, e.g., Fushiki & Lamb 1987). The convective energy flux is $F_t = \rho_t u_t^3$, where ρ_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 B_t becomes strong enough to inhibit convection, which occurs when $B_t^2/8\pi \approx \rho_t u_t^2$. The maximum value of B_t is $\approx (8\pi)^{1/2} \rho_t^{1/6} F_t^{1/3}$ and is relatively insensitive to ρ_t and F_t. For typical densities in the convection zone and the highest energy fluxes observed from the emitting surface, which are $\sim 10^{26}$ erg cm^{-2} s^{-1}, B_t(max) is $\sim$ few $\times$ 10^{10} G, ~ 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, $f_{\mathrm{mag}} \approx (1/4\pi)(B_t \cdot \nabla B_t) \approx B_t^2/4\pi \ell_B$, exceeds the outward radiation force, $f_{\mathrm{rad}} \approx (F_{\mathrm{rad}}/c) n_e \sigma$. Here, ℓ_B is the characteristic scale of the tangled field and n_e is the electron density in the radiative zone. Assuming ℓ_B is no larger than the depth $\sim 10^3$ cm of the burning zone, a field $\sim B_t$(max) can confine the atmosphere in the presence of a radiative flux $\approx 10^{26}$ erg cm^{-2} s^{-1}, which is the flux implied by an effective temperature ≈ 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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