Biases for neutron-star mass, radius and distance measurements from Eddington-limited X-ray bursts

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ABSTRACT

Eddington-limited X-ray bursts from neutron stars can be used in conjunction with other spectroscopic observations to measure neutron star masses, radii, and distances. In order to quantify some of the uncertainties in the determination of the Eddington limit, we analysed a large sample of photospheric radius-expansion thermonuclear bursts observed with the \textit{Rossi X-ray Timing Explorer}. We identified the instant at which the expanded photosphere “touches down” back onto the surface of the neutron star and compared the corresponding touchdown flux to the peak flux of each burst. We found that for the majority of sources, the ratio of these fluxes is smaller than $\sim 1.6$, which is the maximum value expected from the changing gravitational redshift during the radius expansion episodes (for a $2M_\odot$ neutron star). The only sources for which this ratio is larger than $\sim 1.6$ are high inclination sources that include dippers and Cyg X-2. We discuss two possible geometric interpretations of this effect and show that the inferred masses and radii of neutron stars are not affected by this bias. On the other hand, systematic uncertainties as large as $\sim 50\%$ may be introduced to the distance determination.

Key words: X-rays: bursts — stars: neutron — methods: observational — equation of state

1 INTRODUCTION

Photospheric radius-expansion (PRE) thermonuclear bursts are a key observational tool for studies of low-mass X-ray binaries. These systems consist of a neutron star accreting from a low-mass stellar companion. Thermonuclear (type I) bursts arise when a critical temperature and density is reached in the accumulated fuel layer, and unstable H or He ignition takes place (e.g. Lewin et al. 1993; Strohmayer & Bildsten 2005). The accumulated fuel then burns and is exhausted within 10–100 s. Ongoing accretion leads to subsequent bursts separated by hours to tens of hours (depending upon the accretion rate).

The X-ray flux early in the burst can be sufficient to exceed the local Eddington limit at the surface of the neutron star. In that case, radiation pressure drives an expansion of the photosphere, and excess flux is converted to kinetic and gravitational potential energy. The expansion of the photosphere at approximately constant luminosity produces a characteristic pattern of the X-ray spectral variation in these bursts, giving rise to a peak in the blackbody radius at the same time as a local minimum in the blackbody temperature. Measurement of the X-ray flux during the PRE episode allows determination of the distance to the burst source (e.g. Basinska et al. 1984), as well as the mass and radius of the neutron star (e.g. Damen et al. 1990; Özel 2006). These measurements are hampered by intrinsic variation in the Eddington luminosities between sources and even from burst to burst (e.g. Kuulkers et al. 2003; see also Galloway et al. 2008).

One subtlety that arises for measurements of the Eddington flux $F_{\text{Edd}}$ is the precise instance during the burst at which this value is measured. The observed flux during the PRE episode is expected to vary due to the changing gravitational redshift resulting from the varying height of the photosphere above the neutron star. Ideally, the flux should be measured when the Eddington limit is first reached, just before radius expansion commences, or alternatively when radius expansion ceases and the expanded photosphere “touches down” once again onto the neutron star. The instance when radius expansion commences is typically difficult to identify, since it occurs during the burst rise. Instead, the flux at touchdown, at the end of the PRE episode, has

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long been thought to be the best time to measure the Eddington flux \(\dot{\nu}_\text{Edd}\) (Ozel 2006). Recently, measurements of the X-ray flux at touchdown in radius-expansion bursts from EXO 0748−676 were used (along with other observational constraints) to derive limits on the mass and radius of the neutron star (Ozel 2006). The Eddington flux at touchdown measured from bursts observed by EXOSAT and RXTE, \(2.25 \times 10^{-8}\) erg cm\(^{-2}\) s\(^{-1}\), is significantly lower than the maximum flux reported from the bursts observed by RXTE, of \(5.2 \times 10^{-8}\) erg cm\(^{-2}\) s\(^{-1}\) (Wolff et al. 2005). This discrepancy (also noted by Damen et al. 1990) of more than a factor of 2, is far in excess of that expected from the varying gravitational redshift during radius expansion. If the touchdown flux does indeed correspond to the Eddington limit, it is difficult to understand how the flux earlier in the burst could exceed that value by such a large margin.

Motivated by this result, we undertook a broader study of the relationship between the peak radius-expansion burst flux and the flux at touchdown in different burst sources. In §2 we describe the observations and analysis of the bursts. In §3 we present the results of our study. In section §4 we identify sources with low touchdown fluxes (compared to the peak fluxes), while in §5 we investigate the effect of the maximum radius reached during the expansion. We present the broader conclusions of this study in §6.

2 OBSERVATIONS AND ANALYSIS

We used analyses of thermonuclear bursts observed by the Rossi X-ray Timing Explorer (RXTE) from the catalogue of Galloway et al. (2008). This catalogue contains analyses of all bursts present in public data since shortly after the RXTE launch on 1995 December 30. The primary instrument for burst studies in the Proportional Counter Array (PCA; Jahoda et al. 1996), consisting of five identical, co-aligned proportional counter units (PCUs), sensitive to photons in the energy range 2−60 keV and with a total effective area of \(\approx\) 6500 cm\(^2\).

Data were analysed with LHEASOFT version 5.3 (released 2003 November 17) or later; this release was the first to incorporate a significant reduction of the geometric area of the PCUs for improved consistency with calibration sources (Jahoda et al. 2004). Data with the best spectral and temporal resolution were used to extract time-resolved spectra covering the PCA bandpass every 0.25 s near the peak of each burst, becoming longer in the burst tail to preserve signal-to-noise. Each burst spectrum was fitted using an absorbed blackbody, with a spectrum extrapolated to preserve signal-to-noise. Each burst spectrum was fitted using an absorbed blackbody, with a spectrum extrapolated to preserve signal-to-noise.

To take into account gain variations over the life of the instrument, we generated a separate response matrix for each burst using PCARSP version 10.1. The bolometric flux at each timestep was calculated from the fitted blackbody temperature \(kT_{\text{bb}}\) and radius \(R_{\text{bb}}\). Each burst was inspected visually for evidence of radius expansion, specifically a local maximum in \(R_{\text{bb}}\) near the time the maximum burst flux was reached, synchronous with a minimum in \(kT_{\text{bb}}\). By this criteria, 246 bursts in the catalogue exhibited unambiguous evidence of radius expansion.

We subsequently analysed the bolometric flux evolution of each of these bursts to determine the touchdown flux \(F_t\). Immediately prior to touchdown, the photosphere is expected to be contracting back towards the neutron star, reflected by the decreasing blackbody radius. The long (\(\sim 1\) s) observed timescale of the radius expansion (compared to the \(\sim 1\) ms free-fall timescale) suggests that the atmosphere is still primarily radiation-pressure supported during the contraction phase. Because of this condition, the flux remains equal to the local Eddington limit, and the blackbody temperature must be increasing. Immediately after touchdown, the photospheric radius is roughly constant, but now the burning has more or less ceased and the neutron star gradually cools, giving a decreasing flux and blackbody temperature. We thus identify the time at which the photosphere touches down as the time of a local maximum in the blackbody temperature, following the time of maximum radius.

This definition is illustrated in the two examples of Fig. 1. The time of touchdown can be unambiguously determined from the time-history of \(kT_{\text{bb}}\); in both cases a clear local maximum can be seen (middle panels), following the radius maximum (bottom panels). While not all the cases were as clear-cut as these examples, we nevertheless were able to determine the time of touchdown for each of the radius-expansion bursts in the sample.

3 RESULTS

We measured the flux at touchdown \(F_t\) for each of 246 photospheric radius-expansion bursts in our sample, and calculated its ratio to the peak flux \(f = F_t/F_p\). For 61 bursts (around 1/4 of the sample) the maximum flux was achieved at touchdown, so that \(F_p = F_t = f = 1\). More generally, \(F_t\) was consistent with \(F_p\) to within the 3σ confidence limit (based on the uncertainties of \(F_p\) and \(F_t\)) for 184 of the bursts, or almost 3/4 of our sample (the burst shown in the left panels of Fig. 1 is such an example). In many cases this commensurability of the peak and touchdown fluxes arises from a common behaviour in PRE bursts, where the flux continues to increase following the time the maximum radius is reached (as noted for 4U 1636−536 by Sugimoto et al. 1984). We note that \(f > 1\) for all three radius-expansion bursts from EXO 0748−676, as we expect based on the comparison of the published fluxes by Ozel (2006) and Wolff et al. (2003). Thus, we made a closer examination of what conditions give rise to values of \(f > 1\).

3.1 Sources with low touchdown fluxes

Radius-expansion bursts from eighteen different sources gave rise to values of \(f > 1\). In many cases these values were only a few percent in excess of 1; by comparison, the \(f\)-value for two of the three bursts from EXO 0748−676 were in excess of \(f > 1.9\), and the maximum value over all the bursts was \(f = 6.72\). Bursts with \(f > 1.6\) arose from just seven sources: EXO 0748−676, MXB 1659−28, 4U 1916−053, GRS 1747−312, XTE J1710−281, 4U 1746−37 and Cyg X-2. The remarkable feature of this selection on \(f\) is that six of the
seven sources listed above (excluding Cyg X-2) all exhibit regular X-ray dips (see e.g. Liu et al. 2001) attributable to absorption from structures in the accretion disk, occurring at preferential orbital phases. Since the accretion disk is usually thought to have limited vertical extent, the presence of dips is normally taken as an indication of high system inclination, i.e., \( i \approx 90^\circ \). We thus conclude that systematically large \( f \)-values overwhelmingly (but not exclusively) occur in bursts from systems with high inclination; we discuss the remaining example, Cyg X-2, in §4.

We thus divided the sample between dipping and non-dipping sources, and calculated the combined distribution of \( f \) from each sample (Fig. 2). While there is substantial overlap between the two distributions, the preponderance of bursts with \( f \approx 1 \) for the non-dipping sources makes the two distributions highly discrepant. The K-S test value for the two samples is 0.886, with associated probability \( 2 \times 10^{-21} \); this indicates unambiguously that the two samples arise from different populations. For the dippers, the mean \( f = 2.1 \pm 0.9 \), so that the flux at touchdown was, on average, less than half the maximum flux.

### 3.2 The effect of the maximum radius in dipping sources

While the association of low touchdown fluxes with high system inclination is clear, the underlying cause (as well as the wide range of the \( f \) values for the dipping sources) begs an explanation. The large \( f \)-range was most notable for MXB 1659−298, where the \( f \)-values were between 1.3 and 5.1 for the 12 radius-expansion bursts in the sample. The high end of the distribution in the ratio \( f \) is too large to be explained by the change in the gravitational redshift during the expansion of the photosphere. For example, for a 10 km, \( 2M_\odot \) neutron star, the flux ratio arising from redshift changes can be at most equal to 1.6. Instead, the clear separation between the \( f \)-distributions of the dippers and non-dippers strongly suggests a geometric origin of the \( f \)-ratios.

A geometric interpretation is further supported by the correlation between the ratio \( f \) observed in dippers and the maximum radius attained by the photosphere during the radius expansion episode (Figure 3). In order to calculate the maximum radius, we corrected for the distance to the dipping sources based (in the case of EXO 0748–676, MXB 1659–298, 4U 1916–053 and XTE J1710–281) on the distance derived from the peak flux of the PRE bursts (Galloway et al. 2008). In the case of GRS 1747–312 and
Figure 3. The ratio of peak to touchdown flux $f = F_p/F_t$ as a function of the derived maximum photospheric expansion radius for a sample of bursts observed from 6 dipping sources: EXO 0748−676, MXB 1659−298, 4U 1916−053, XTE J1710−281, GRS 1747−312 and 4U 1746−37. The dashed lines shows the best linear fit excluding the single outlier, an extremely intense burst from GRS 1747−312 which reached an estimated maximum radius of almost 130 km.

4U 1746−37, we used instead the estimated distances to the host globular clusters, Terzan 6 (9.5 kpc) and NGC 6441 (11 kpc), respectively (Kuulkers et al. 2003). We found that, for all but one burst, $f$ is strongly correlated with the maximum radius (Fig. 3). Excluding a single outlier (an unusually intense burst from GRS 1747−312; see also in 't Zand et al. 2003), we find a Spearman’s rank correlation of 0.742, significant at the 4.2σ level.

We suggest that the preferential occurrence of high $f$-ratios in dippers as well as the correlation shown in Figure 3 can be accounted for either by a changing partial obscuration of the neutron star and its expanding photosphere by the disk during the radius expansion or by a varying reflection of the burst emission off the far side of the disk. In the first case, which is illustrated in Figure 4, it is plausible that even during non-dipping intervals, the neutron star in high-inclination systems is subject to a certain degree of obscuration and hence absorption by the disk material. The expanded photosphere present during the radius expansion episode increasingly protrudes above and below (relative to our line of sight) the disk, so that the emitted flux during radius expansion is less subject to absorption by the disk material, and the apparent flux is commensurably larger. When the photosphere touches down onto the neutron star again, the absorption increases once again, giving rise to a significantly lower touchdown flux. This requires a particularly finely-tuned inclination, in which the viewing angle of the observer grazes the accretion disk at its maximum thickness.

In the second interpretation, as the photosphere expands, the far side of the disk intercepts and reflects an increasing fraction of the emitted luminosity. This leads to an artificial increase of the observed flux at the peak of the radius-expansion episode, while the touchdown flux corresponds to the true Eddington limit. Albeit plausible, the large observed $f$-ratios require, in this interpretation, a large amount of reflection off the disk, which can by achieved only in the presence of significant warping.

In either case, the ratio of the peak burst flux to the flux at touchdown is expected to increase with increasing radius of the photosphere, as indicated by the observational correlation shown in Figure 3.

If the origin of the large $f$-ratios is related to interactions of the burst flux with the disk in the high-inclination sources, we might also expect a dependence on the orbital phase. Most of the dippers have only 1–3 radius-expansion bursts each; however, MXB 1659−298 and 4U 1916−053 each have 12. We folded the burst times on the dip/eclipse ephemerides for these two sources (Oosterbroek et al. 2001, and Chou et al. 2001, respectively), and tested for variations in the $f$-ratio as a function of orbital phase. In neither case did we detect significant variation. In MXB 1659−258 the three largest $f$-values were all found in the phase bin 0.8–1.0 (i.e. immediately prior to the eclipse); however, the variation was not significant compared to the scatter on the $f$-values in the other phase bins.

4 DISCUSSION

In this paper, we studied 246 photospheric radius expansion bursts from a large number of accreting neutron stars observed with RXTE to determine the systematic uncertainties that affect the measurement of their masses, radii, and distances using the touchdown (Eddington) fluxes. Comparing the peak fluxes to the touchdown fluxes of the bursts in
our sample, we found that for the majority of the neutron stars, this ratio is \( f \lesssim 1.6 \), which is expected on the grounds of the changing gravitational redshift during the radius expansion episode (Paczynski & Anderson 1986). However, for some neutron stars, this ratio can be as large as \( f \approx 7 \). We found that the only sources for which the ratio of these two fluxes is larger than \( f \gtrsim 1.6 \) are dippers and Cyg X-2.

For the dippers, we attribute the large \( f \)-ratios to geometric effects related to their high inclinations. Determining which of the two candidate mechanisms gives rise to the large ratios may be possible via more detailed X-ray spectroscopic analysis. For example, time-resolved spectral analysis of the radius-expansion bursts from dipping sources may provide evidence of a reflection component from the disk, although the necessity of deconvolving the changing contribution of this component from the underlying burst spectral evolution likely presents a considerable challenge. Such additional analyses are beyond the scope of this paper.

Cyg X-2 is the only source exhibiting bursts with large \( f \)-ratios (\( f > 1.6 \)) that does not also exhibit dips. This source, however, is distinct from the dip sources in several other respects. Cyg X-2 is the prototypical Z-source (Hasinger & van der Klis 1989) and is thought to accrete at a near-Eddington rate, as inferred from observations of its accretion flow in the UV (Vrtilek et al. 1990). This is in sharp contrast to the dippers, all of which accrete at substantially sub-Eddington rates (e.g. Liu et al. 2002). The high accretion rate of this source may influence its behaviour in two different ways.

First, we consider the possibility that the X-ray bursts observed from Cyg X-2 are of a different nature than those of the other bursting sources (see Taam et al. 1996, for models of bursts in near-Eddington sources). Indeed, the bursts in the two high accretion rate sources, Cyg X-2 and GX 17+2, do not show, at first glance, the characteristic patterns of spectral evolution seen in the other bursters, making their classification as type I or type II bursts difficult (Sztajno et al. 1986, Kuulkers et al. 1993). This discrepancy has been attributed, however, to artifacts introduced by the subtraction of the accretion flux, which is comparable to the burst emission in high-luminosity sources.

Second, the large difference in the inferred accretion rates suggests that the accretion disk may be significantly thicker in Cyg X-2 than in the dip sources. As a result, the geometric effect discussed in §3.2 for the dippers may also be responsible for the large \( f \)-ratios found in Cyg X-2, if the latter is observed at a reasonably high inclination.

Modeling the optical lightcurves of the binary constrains the inclination of Cyg X-2 to \( 50° < i < 75° \) (Cowley et al. 1973, Orosz & Kuulkers 1999). Such large values of the inclination are also strongly supported by the secular variations in the X-ray flux of the source (Kuulkers et al. 1993) as well as by the super-orbital periodicities found in its long-term lightcurve (Wijnands et al. 1999). The combination of a relatively high inclination with a geometrically thick disk perhaps makes Cyg X-2 similar to the dippers for the purposes of the observational effect reported here.

The discrepancy between the maximum and touchdown fluxes for the high-inclination systems has implications for the measurement of neutron star masses and radii for bursting neutron stars. For example, the method recently proposed by Özel (2006) relies on the accurate measurement of the Eddington limit at touchdown. Because of this, it is, in principle, affected by systematic effects on the touchdown flux as the one presented here. However, the inferred values of both the mass and the radius of the neutron star depend only on the ratio \( \frac{F_{\text{cool}}}{F_t} \) of the flux during the cooling tail of the burst to that during touchdown. Independent of the particular interpretation of the unusually large \( f \)-ratios observed in dippers, this ratio should remain unchanged because the bias depends on the size of the photosphere and hence affects in the same way both the cooling and the touchdown fluxes. The correlation presented in Figure 3 further supports this conclusion.

In contrast, we note that the distance \( D \) depends upon the ratio of the square root of the cooling flux to the Eddington flux, so that \( D \) is affected by the precise value of the Eddington flux. According to our first geometrical interpretation (where the touchdown flux is lower than the true Eddington flux due to geometric screening) the distance derived from the touchdown flux will be too large by a factor \( f^{1/2} \). For EXO 0748–676, this would indicate that the distance derived by Özel (2004) should be scaled by \( \sqrt{f} \) to yield a revised distance of \( 7.1 \pm 1.2 \) kpc, using the mean ratio \( f = 1.7 \pm 0.4 \) we calculate for this source. On the other hand, in the second geometric interpretation, the touchdown flux represents the true Eddington flux and the distance derived using this value is not affected. Thus, taking into account both possible origins for the discrepancy between the peak and touchdown fluxes, the distance to EXO 0748–676 is in the range 6–10 kpc.

It is also worth considering other possible sources of error on the mass, radius and distance derived via the touchdown flux and burst tail emission. In a previous study which attempted to determine the gravitational redshift from the variation of the burst flux during photospheric radius-expansion episodes, Damen et al. (1990) concluded that systematic effects arising from variations in the (i) persistent emission, (ii) the shape of the burst spectrum, and (iii) photospheric composition could not be neglected. The geometric effect described here illustrates that these three additional factors will only influence the derived mass and radius if they alter the ratio of the cooling flux to the Eddington flux, and the distance if they alter the ratio of the square root of the cooling flux to the Eddington flux.

A possible change in the persistent emission during the burst may indeed affect either the touchdown flux or the cooling flux. Given that this effect will be most significant for sources with high persistent luminosities such as Cyg X-2 (as also shown by Damen et al. 1990), using low persistent luminosity sources to determine the neutron star mass and radius minimizes this uncertainty.

As for the second effect, assuming the observed spectra are consistent with a blackbody (which is usually the case) the spectral shape will affect the derived fluxes only if the spectrum deviates significantly from a blackbody outside the instrumental bandpass. In the case of bursts observed with RXTE, the contribution of flux from above and below the bandpass is at most 10%, which likely represents a conservative limit on the degree of this effect.

Finally, theoretical burst models as well as observations of 4U 1636-536 suggest that variations in composition may occur in the beginning of the burst, prior to the peak. In the touchdown and cooling phases, such variations are not
expected. Moreover, the color correction factors during this cooling stage, which enter the calculation of neutron star mass and radius, depend very weakly on metallicity (Özel 2006), thus limiting any additional bias.

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