The impact of neutron star spin on X-ray spectra

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ABSTRACT

We investigate whether the intrinsic spin of neutron stars leaves an observable imprint on the spectral properties of X-ray binaries. To evaluate this we consider a sample of nine NSs for which the spins have been measured that are not accreting pulsars (for which the accretion geometry will be different). For each source, we perform spectroscopy on a majority of RXTE hard state observations. Our sample of sources and observations spans the range of the Eddington ratios $L_X/L_{Edd} \sim 0.005 – 0.100$.

We find a clear trend between key Comptonization properties and the NS spin for a given accretion rate. Specifically, at a given $L/L_{Edd}$, for more rapidly rotating NSs we find lower seed photon temperatures and a general increase in Comptonization strength, as parametrised by the Comptonization $y$ parameter and amplification factor $A$. This is in good agreement with the theoretical scenario whereby less energy is liberated in a boundary layer for more rapidly spinning NSs, resulting in a lower seed photon luminosity and, consequently, less Compton cooling in the corona. This effect in extremis results in the hard states of the most rapidly spinning sources encroaching upon the regime of Comptonization properties occupied by BHs.

Key words: circumstellar matter – infrared: stars.
sation leading to increased Comptonization losses for hot

electrons, as proposed by Shakura & Sunyaev (1988) and

Sunyaev & Titarchuk (1989).

The main result of Paper I is a dichotomy observed in

the Comptonisation strength between hard state spectra

of NS and BH XBs. Comptonisation in NSs is suppressed by

additional seed photons that are produced in the vicinity

of the NS surface, on the surface itself or in a boundary

layer between the surface and geometrically thin accretion

disc. Theoretically such a boundary layer forms to facilitate

the change in angular momentum between the innermost

portions of the disc and the surface (Shakura & Sunyaev

1988, giving rise to blackbody-like emission, which has been

observed using Fourier-resolved spectroscopy of soft state

spectra (Gilfanov et al. 2003; Revnivtsev & Gilfanov 2006).

It is not clear whether the classical boundary layer exists
during the hard state (see Done et al. 2007; Gilfanov 2009) for

review) when the innermost portion of the accretion disc is

thought to be truncated at many gravitational radii, how-

ever, there must still be some mechanism to bridge the dif-

culty in linear velocities between the accreting material and

the neutron star surface. When the disc extends to the sur-

face of the NS, at moderate accretion rates ($L/L_{\text{Edd}} \sim 0.1$),

the scale height of the boundary layer is expected to be

$\sim 1 - 2$ km, whereas at high $L/L_{\text{Edd}}$ the scale height

expands such that the NS is enveloped by accreting material

(see Popham & Sunyaev 2001, fig. 1). However, in this work

we consider only sources in the hard spectral state which

roughly correspond to luminosities of $L/L_{\text{Edd}} \lesssim 0.1$.

In the Newtonian approximation the boundary layer

contributes approximately 50\% of the total source emission

(Shakura & Sunyaev 1988). However, Sibatgullin & Sunyaev

(1998) & Sibatgullin & Sunyaev (2000) showed that by consid-

ering realistic space time metrics the energy released by the

boundary layer for a non-rotating NS is of order 70\% of the

total emission, and that this fraction decreases with increasing

frequency of prograde rotation. In Paper I we estimated the

emission from the vicinity of the NS as a fraction of the total

emission to be in the range $\approx \frac{2}{3} - \frac{1}{2}$.

There are few concrete connections between spin fre-

quencies and other observable quantities. Possible connec-
tions between the NS spin and the frequencies of the

so-called kHz Quasi-periodic oscillations (QPOs) remain

the most studied and debated proposition. kHz QPOs

(van der Klis et al. 1996) are high frequency QPOs that are

occasionally detected in pairs that vary in a correlated

way (Barret et al. 2003) by tens to hundreds of Hz (see

van der Klis 2006, for review of X-ray variability). Early

studies noted that the measured difference in frequencies

of the two kHz QPO was compatible with either the NS spin

frequency or its half, depending on the source (van der Klis

2001; Psaltis 2001). This scenario is attractive in the con-
text of beat frequency models, where the lower frequency

QPO arises from the beat between the upper kHz QPO and

spin frequency (Miller et al. 1998; Lamb & Miller 2001).

However, other authors have argued that QPOs are actu-

ally a manifestation of the effects of strong gravity (e.g.,

Stella & Vietri 1999; Abramowicz et al. 2003; Zhang 2004;

Stuchlík et al. 2008). Wang et al. (2014) plot 12 sources

with measured kHz QPO pairs against spin, and conclude

there is a ‘clustering with a high scatter’ around $\Delta \nu_{\text{kH}} \approx

0.5\nu_{\text{spin}}$ and $\Delta \nu_{\text{kH}} \approx \nu_{\text{spin}}$, but it is not clear whether there

is a relationship. It was also found that the kHz-QPO fre-

quency correlates with the X-ray flux and spectral shape as

characterised by the position on the colour-colour diagram

(Méndez et al. 1998; Barret 2003).

Muno et al. (2001) were the first to suggest different

patterns of behaviour between ‘slow’ ($\approx 300$ Hz) and ‘fast’

($\approx 600$ Hz) sources, noting that burst oscillations were al-

most always found during bursts exhibiting PRE for fast

sources, whereas slower sources showed oscillations in all

types of burst. In subsequent studies the picture proved to

be more complicated; bursts with and without PRE are

found from both slow and fast samples, but predominantly

bursts containing oscillations are PRE bursts in the most

rapidly rotating systems, and non-PRE bursts for other

sources (Muno et al. 2004; Galloway et al. 2008). In addi-
tion to this, Galloway et al. (2008) found that burst du-
rations are consistently short for slow sources, while the

bursts for faster sources tend to have longer durations.

Piro & Bildsten (2007) suggest that predominantly shorter

bursts from more slowly rotating NSs could be a result of

the greater velocity differential between the NS surface and

the infalling material leading to greater mixing between the

ashes of burned material and that which is freshly accre-

ted, exhausting H and leading to faster, H-rich bursts. On the

other hand, slow rotators could be accreting from compan-

ions that happen to be degenerate, which is why the burning

material is lacking in H, and if confirmed would indicate a

different evolutionary path for differently spinning sources

(Galloway et al. 2008).

In this paper we set out to identify possible links be-

tween the persistent hard state spectra of NS XBs and their

spin. In doing so we build upon the work of Paper I, first

expanding our sample of NSs of known spin and the num-

ber of spectra for each source, and then by comparing their

behaviour as a function of accretion rate. It may be worth

noting that the effects we report here are unrelated to the

GR effect of the NS spin similar to the effect of the BH spin

on X-ray spectral formation in the vicinity of Kerr black

hole. Rather, these effects are a result of the dependence of

the energy released in the boundary layer on the velocity
difference between the accreting material and the NS surface.

Although accurate quantitative prediction of these effects

requires knowledge of the precise metrics of the space-time

in the vicinity of the neutron star (Sibatgullin & Sunyaev

1998), they can be understood in terms of Newtonian me-

chanics through the well known formula

$$L_{\text{bl}} = \frac{1}{2} \dot{M} (\alpha v_K - v_{\text{NS}})^2 \quad (1)$$

where $\alpha v_K$ is velocity of the infalling material expressed

in terms of the Keplerian velocity $v_K$ near the NS surface,

the factor $\alpha$ ($\leq 1$) accounts for the possibility that in the

hard state the accreting material can arrive at the stellar surface

with sub-Keplerian velocity, and $v_{\text{NS}}$ is linear velocity of

the NS surface (Shakura & Sunyaev 1988; Kluzniak 1983).

2 SAMPLE SELECTION

To add additional sources to our sample we choose to con-

sider only those for which the NS spin frequency is well
The impact of neutron star spin on X-ray spectra

3 DATA REDUCTION AND ANALYSIS

We extract PCA and HEXTE spectra of each source as detailed in Paper I, taking care to remove any contamination by X-ray bursts. For complete consistency, we consider PCA data from PCU2 from each source and HEXTE data from cluster B only. We fit the spectra with an absorbed Comptonisation model with an additional Gaussian component to model the fluorescent Fe emission. In the spectral fitting package Xspec, this model takes the form of \(\text{const} \times \text{phabs} \times \text{compps} \times \text{gauss} \), within which COMPPS models the Comptonised emission and its reflection by material in the accretion disc. As this work concerns the nature of NSs exclusively, we adjust the model from the approach in Paper I such as to have a blackbody-shaped seed photon spectrum, which is the same as the Xspec model BHODYRAD.

We model emission from the Galactic ridge (GR) as an additional set of fixed components comprising a \(\Gamma = 2\) power-law and zero-width Gaussian that peaks at an energy of 6.6 keV (Revnivtsev 2003), the flux of which we calculate using the relation of Revnivtsev et al. (2001). As noted in Paper I, the close proximity of 4U 1728~−33 to the Galactic centre means that there should be a substantial contribution of GR emission to these spectra. In this work we consider an additional two datasets from earlier in the RXTE mission, when the source was less luminous. On attempting to fit these spectra we noticed clear residual excesses in the spectral model at energies consistent with the line from GR emission, and unusual residuals at lower energies. This is clearly indicative that we have over-compensated for the GR emission in this source. To obtain our best estimate of the strength of GR in this instance, we perform a joint fit using all the spectra of 4U 1728~−33, with the GR flux as the only tied parameter and with the GR spectral shape fixed. We recover a value of \(3.2 \times 10^{-11}\) erg cm\(^{-2}\) s\(^{-1}\), just over half of our original estimate of \(6.15 \times 10^{-11}\) erg cm\(^{-2}\) s\(^{-1}\), which we use in all subsequent analysis. In figure 1 we show an

### Table 1. Source Properties.

| Source      | \(N_H \) \(10^{22}\) cm\(^{-2}\) | Spin Hz | \(F_{\text{peak}} \) erg s\(^{-1}\) cm\(^{-2}\) |
|-------------|---------------------------------|---------|-----------------|
| 4U 1608-52  | 1.81                            | 620     | 132             |
| GS 1826-238 | 0.171                           | 611     | 33              |
| SAX J1750.8-2900 | 4.3*                  | 601     | 49.2            |
| 4U 1636-536 | 0.27                            | 581     | 64              |
| Aql X-1    | 0.28                            | 550     | 89              |
| KS 1731-260| 0.31                            | 524     | 43              |
| 4U 0614+09 | 0.448                           | 415     | 200             |
| 4U 1728-33 | 1.24                            | 363     | 84              |
| 4U 1702-429| 1.12                            | 329     | 76              |
| 4U 1705-44 | 0.67                            | 298**   | 39.3            |

Determined. This limits our considerations to only those sources for which oscillations have been observed during thermonuclear bursts (see Galloway et al. 2008), which we further refine by excluding millisecond pulsars, as these will almost certainly obey a different accretion geometry from non-pulsing XBs (see Patruno & Watts 2012, for review). We note that burst oscillations have only been detected once in the case of GS 1826-238 (Thompson et al. 2005), despite many bursts having been observed over the course of the RXTE lifetime. We discuss this source in more detail in 1. The sample was further reduced by observational constraints, such as sources that were too faint (such as MXB 1659~−298) or are not observed in a hard state. At this stage we were left with 8 sources out of 10 LMXBs with coherent pulsations detected during the X-ray bursts but not in their persistent emission (Watts 2012), and Aql X-1 (which once displayed coherent oscillations in its persistent emission over a period of \(\approx 100\) s, Zhang et al. 1998). We include 4U 1705~−44 from Paper I for completeness, despite no burst oscillations having been detected from this source, with a view to excluding it for analysis from which we seek to make firm conclusions about spin. We list our final sample, with their pertinent properties in table 1. We reduce all hard state datasets, which we define as those data possessing a mean hardness ratio \(\geq 2\) using the intensities measured in the 7.50~−18.50 keV and 4.0~−6.0 keV bands. We present the final list of observations in tables 2 & 3.
example best-fit of our model to a spectrum from 4U 1608-52. To explore the parameter space we make use of Bayesian X-ray Analysis software (BXA, Buchner et al. 2014) that connects nested sampling algorithm MultiNest (Feroz et al. 2009) to Xspec. We bin samples from the posterior distribution produced by BXA for a given spectrum to produce 1D and 2D confidence regions in a given parameter space. We measure the 3–200 keV flux for every point in each posterior chain, and calculate the Compton amplification factor $A$ as a ratio of the total luminosity $L_{\text{Tot}} = 4\pi f_{\text{f}_{\text{3–200}}}$ $D^2$ to the seed photon luminosity $L_{BB} = 4\pi R_{BB}^2 \sigma T_{BB}^4$, where $R_{BB} = N(D/10\text{ kpc})^2$. Both $L_{\text{Tot}}$ and $L_{BB}$ are proportional to the distance squared, $A$ is actually a distance independent quantity.

Finally, to calculate the luminosity as a fraction of Eddington luminosity we take the ratio of the measured 3–200 keV flux to the peak flux of type-I X-ray bursts (table 1) that exhibit PRE, when a source is presumed to be emitting at the Eddington luminosity $L_{\text{Edd}}$. This ratio, which we henceforth refer to as $L/L_{\text{Edd}}$, can be considered an excellent proxy for the accretion rate of the source and is a particularly convenient tool for discussing the luminosity of Galactic sources because it negates the need to involve source distances, which are often subject to various uncertainties. We note that for GS 1826–238 PRE bursts were not detected during the RXTE era, however, the type-I X-ray bursts from this source had a remarkably consistent profile with an average peak flux $3.3 \times 10^{-8}$ erg s$^{-1}$ cm$^{-2}$ (Galloway et al. 2004). A recent investigation by Chenevez et al. (2016) using NuSTAR data found evidence for PRE in one burst, with peak bolometric flux of $40 \pm 3 \times 10^{-9}$ erg s$^{-1}$ cm$^{-2}$, however, in the interests in consistency across the source sample we will use the RXTE-era value in our calculation of $L/L_{\text{Edd}}$.

### Table 2. RXTE Observations

| Source       | Proposal ID | Observation Suffix |
|--------------|-------------|-------------------|
| 4U 0614+09   | 50031       |                   |
| 4U 1608-52   | 10094       |                   |
| 4U 1636-536  | 90409       |                   |
| 4U 1702-429  | 40025       |                   |
| 4U 1705-44   | 20073       |                   |

The line-of-sight absorption column to SAX J1750.8-2900 is not well-known. The HEAsoft $N_H$ tool, which uses the 21 cm survey of Kalberla et al. (2003), displays a wide

### 3.1 SAX J1750.8-2900

The line-of-sight absorption column to SAX J1750.8-2900 is
ing the literature, we find that Allen et al. (2015) discussed the analysis of several RXTE Observations. Data (Natalucci et al. 1999) and for between the fits. Their procedure obtained $N = 0$,

$\Delta \chi^2 = 1$.

The impact of neutron star spin on X-ray spectra

| Source       | Proposal ID | Observation Suffix |
|--------------|-------------|--------------------|
| 4U 1728-33   | 10073       | -01-10-00          |
|              | 40027       | -01-06-00          |
|              | 91023       | -01-06-00          |
|              | 92023       | -03-17-10          |
| Aql X-1      | 20092       | -01-01-02          |
|              | 40033       | -01-01-02          |
|              | 40048       | -01-01-02          |
|              | 40049       | -01-01-02          |
|              | 40432       | -01-01-02          |
|              | 50049       | -01-01-02          |
|              | 70426       | -01-01-02          |
|              | 90017       | -01-01-02          |
|              | 91028       | -01-01-02          |
| KS 1731-260  | 40025       | -02-03-02          |
|              | 50031       | -02-03-02          |
|              | 80048       | -01-01-01          |
|              | 80049       | -01-01-01          |
|              | 80105       | -11-01-00          |
|              | 90043       | -01-01-00          |
|              | 91017       | -01-01-01          |
|              | 92031       | -01-01-01          |
|              | 92703       | -01-01-01          |
| SAX J1750.8-2900 | 93432   | -01-05-02          |
| GS 1826-238  | 30060       | -03-03-00          |
|              | 50035       | -01-01-00          |
|              | 70025       | -01-01-00          |
|              | 70044       | -01-01-00          |
|              | 80048       | -01-01-00          |
|              | 80049       | -01-01-00          |
|              | 80105       | -11-01-00          |
|              | 90043       | -01-01-00          |
|              | 91017       | -01-01-01          |
|              | 92031       | -01-01-01          |
|              | 92703       | -01-01-01          |

Table 3. RXTE Observations

The range of values from $0.5 - 1.6 \times 10^{22}$ cm$^{-2}$ and presents an average weighted value of $0.927 \times 10^{22}$ cm$^{-2}$. Consulting the literature, we find that Allen et al. (2013) discussed the value of $N_H$ in some detail, and performed an analysis of several Swift spectra with the value of $N_H$ tied between the fits. Their procedure obtained $N_H = 4.3 \times 10^{22}$ cm$^{-2}$, which is consistent with the model-dependent extremes of $2.5 - 6.0 \times 10^{22}$ cm$^{-2}$ found using BeppoSAX data (Natalucci et al. 1999) and $4.0 - 5.9 \times 10^{22}$ cm$^{-2}$ using XMM data (Lowell et al. 2012). In our analysis we therefore adopt $N_H = 4.3 \times 10^{22}$ cm$^{-2}$.

All hard state observations of this source were made during 2008. We have concerns about HEXTE data obtained during this epoch. We analysed two observations of the Crab nebula (93802-02-15-00, 93802-02-16-00) taken in the same week as one of the SAX J1750.8-2900 datasets. Fitting with the standard absorbed ($N_H = 0.38 \times 10^{22}$ cm$^{-2}$) power law model gave a best fit $\chi^2_\nu = 100/82 \sim 1.23$ and $112/82 \sim 1.37$ whereas in earlier epochs $\chi^2_\nu$ is typically $< 0.9$. Inspection of the fit residuals in this case shows that the HEXTE data form a slope in the fit residuals, with the model in excess of the data at low energy ($\approx 20 - 40$ keV) and a deficient at higher energies ($\approx 50 - 65$ keV). We choose not to utilise the HEXTE data during this epoch. To compensate for the lack of high energy coverage we include PCA data in the range 20.0 - 45.0 keV. Two potential problems with this approach are that the PCA is less well calibrated at energies $> 20$ keV, and that we might not be able to constrain the electron temperature if it is particularly high [i.e. if $kT_e > 50$ keV, as in the case of 4U 1608-52]. In terms of calibration, we note the work of Garcia et al. (2014), who computed an epoch-dependent ‘correction curve’ for PCA spectra based on accumulated Crab observations. For data such as these SAX J1750.8-2900 observations, from later PCA epochs, the calibration is accurate to within 1% up to $\approx 31$ keV (compared to 3% - 4% in earlier epochs) and can underestimate the flux by 2% - 4% from 34 - 45 keV. The spectra of SAX J1750.8-2900 typically have $20 - 150$ net counts per channel at en-
ergies > 35 keV, therefore calibration inaccuracies should have a negligible effect on our analysis.

4 RESULTS

In figure 2 we present key spectral properties as a function of $L/L_{Edd}$, with sources denoted by different colours. Each datum represents the mean posterior estimate of a single spectrum and the associated standard deviation. To aid our investigation into the effects of NS spin, we divide the sample into two broad spin frequency groups divided about the mean value of our sample, $\approx 500$ Hz, and in figure 2 denote members of each group with circles and triangles respectively. We note that if the peak bolometric flux measured during a type-1 X-ray burst showing signs of PRE from GS 1826-238 is accurate (Chenevez et al. 2016), the true $L/L_{Edd}$ for this source will be at $\approx 82\%$ of the values shown, and emphasise that this change would not be significant enough change to alter our conclusions.

There are clear trends with $L/L_{Edd}$ in all four main parameters characterising the Comptonized spectra. Formally, the correlations are extremely significant. For example, for the Comptonization parameter, the Spearman rank test indicates a compatibility with the null hypothesis $p_a < 2.2 \times 10^{-16}$ and a correlation of 0.85 between $y$ and $L/L_{Edd}$. It is also clear that there is significant overlap for each parameter for sources with different spins. This is further illustrated by the posterior distributions for groups of low- and high-spin sources, figures 3 which discussed in detail below. However, figure 2 suggests differences in behaviour correlated with spin do exist at a given accretion rate. Specifically, the low frequency sources all occupy a higher $kT_{BB}$ at a given $L/L_{Edd}$ compared to sources that contain more rapidly rotating NSs. Likewise, the more slowly rotating NSs appear to have lower $y$ and $A$.

To test these possible trends connected to source spin we compute for each source the luminosity resolved mean values of spectral parameters and quantiles of their distributions. Each element of the posterior chains for every spectrum was allocated a bin based on $L/L_{Edd}$, and then used to compute quantiles for each source if it has a significant presence (equivalent to one entire posterior) in a given flux bin. In figure 4 we plot these quantiles (25%, 50% and 75%) as a boxplot with each box representing one source for each flux bin, with the spin of each source indicated by the strength of shading.

Figure 3 shows that the distributions of $kT_{BB}$ occupy higher values for the three most slowly rotating NSs in all flux bins. Moreover, these same sources have consistently lower $y$-parameter across the full $L/L_{Edd}$ range, while more rapid rotators have increasingly large values with increasing accretion rate. The picture in terms of $A$ is less clear cut, with some sources occupying a wider range of values. However, for a majority of flux bins a slow spinning source will have lower $A$ and $y$ than a more rapidly spinning source.

In figure 4 we present the one dimensional posterior distributions of $kT_{BB}$, $y$ and $A$ for low and high-spin sources in three broad $L/L_{Edd}$ bins. For $y$ and $A$ these distributions are compared with the corresponding distributions for black holes from Paper I. These distributions complement figures 2 and 3 in illustrating the dichotomy between low and high spin sources and their trends with the Eddington ratio. These will be further discussed in section 5.

We ask what is the probability that $kT_{BB}$ will correctly rank the sources by spin when temperature is drawn from a uniform distribution for fixed $L/L_{Edd}$? Considering all 10 sources, we can broadly consider to fall into three groups within which the sources overlap. This makes groups of two groups of three sources, and one group of four sources. What is the probability that that $kT_{BB}$ can rank the spectra into such groups by chance? Assuming $L/L_{Edd}$ is fixed, we generate 10 random values of $kT_{BB}$ from a uniform distribution over the observed range of $kT_{BB}$ at that point ($\approx 0.6 - 0.85$ keV), and repeat for a large number of iterations. We then ask how many times are the first three numbers lower than the next 4 numbers, and at the same time those numbers are lower than the final 3 numbers? This analysis suggests a uniform distribution would produce this ranking result by chance with the probability of $\approx 2.4 \times 10^{-4}$.

As mentioned in section 2, in the case of GS 1826–238 burst oscillations have only been reported once by Thompson et al. (2003) who analysed three RXTE observations that had been simultaneously observed with Chandra in their search. Their detection is unconfirmed in many other bursts from this source observed by RXTE. In particular, Watts (2012) suggested that the authors underestimated the number of search trials in arriving at their significance estimate. Given these considerations we assume that the burst frequency is unknown, so as to test the impact on our results of withdrawing GS 1826-238 from the sample (just as we excluded many other NS LMXBs with unknown or unconfirmed spikes). Withdrawing this source does not affect our conclusion that the Comptonizing properties are a function of both the accretion rate and spin.

5 DISCUSSION AND CONCLUSIONS

We have performed a systematic study of a sample of NS LMXB hard state spectra to investigate possible trends between the spectral properties and the NS rotation frequency. To this end, we modelled the hard state spectra as Comptonization of blackbody seed photons on thermal electrons, and explored the available parameter space for this model using nested sampling. We note that our approach does not account for the effects of inclination (as the emission will be locally anisotropic), second-order reflection effects in both the disc and boundary layer caused by the photons from each other, or relativistic effects from the vicinity of the NS (see discussion in Lapidus & Sunyaev 1985).

Overall, spectral properties depend strongly on the Eddington luminosity ratio, with different sources and and different observation of the same source following same dependence, albeit with large scatter. In addition, at the given
Eddington luminosity ratio (i.e. same mass accretion rate), there is a difference in spectral properties between different sources correlated with the NS rotation frequency. These differences are most apparent in terms of the seed photon temperature $kT_{BB}$ and in the behaviour of the Compton $y$-parameter and Compton amplification factor $A$. Specifically, we find that at a given accretion rate the seed photon temperature is lower and Compton $y$-parameter and $A$ are higher for more rapidly rotating NSs (figure 3). We do not find such a clear correlation with the NS spin in the case of the electron temperature $kT_e$.

For the standard Shakura-Sunyaev accretion disc around a slowly rotating NS, more than a half of the energy possessed by infalling material is released on the stellar surface \cite{SS1973} in a narrow boundary or spreading layer \cite{ShakuraSunyaev1973, SibgatullinSunyaev2000}. In this layer, the material decelerates between the Keplerian velocity of the disc and the rotational velocity of the NS surface. Analysis of Fourier-frequency-resolved spectra of multiple sources by Gilfanov et al. \cite{Gilfanov2003} and Revnivtsev & Gilfanov \cite{RevniGilfanov2006} suggests that in the soft spectral state, the boundary layer has an approximately blackbody spectrum of common characteristic temperature $\approx 2.4$ keV. While no such spectral component has been identified in the NS hard state spectra, some fraction of the energy of the accreting matter is still expected to be released on the surface of the neutron star, in some form of boundary layer, but its emission is presumably intercepted by the Comptonizing material along the line-of-sight. Paper I showed that Comptonisation is generally weaker (smaller $A$ & $y$) in NS systems than for their BH cousins.

\textbf{Figure 2.} Variation of key spectral properties with $L/L_{Edd}$.\hspace{1em}
Figure 3. Comptonization model parameters binned by $L/L_{\text{Edd}}$, with grey vertical lines indicating the bin boundaries. Each box represents the weighted 25% – 75% interquartile range and each vertical line the 0.05 – 0.95% bounds for the distribution of that parameter across all posterior chain elements that fall in a given $L/L_{\text{Edd}}$ bin for each source, with the line inside the box indicating the position of the median value. Boxes are offset in $x$ for clarity.
The impact of neutron star spin on X-ray spectra

Figure 4. Flux-resolved posterior distributions of Compton y-parameter (left), Amplification factor A (center), and $kT_{BB}$ (right) contrasting rapidly spinning NSs (> 500 Hz, turquoise) and more slowly rotating NSs (< 500 Hz, pink) with the equivalent distributions for BHs from Paper 1 (grey, left and centre only). Rows correspond to $L/L_{Edd} = 0.015−0.03, 0.03−0.05$ and $0.05−0.10$ (top-bottom). BH distribution of y shifted by +0.05 (see text).

and this can be understood in terms of additional seed photons emitted by the neutron star instigating greater energy losses of hot electrons and reducing the Comptonizing strength of the corona. In Paper I we estimated that about $\sim 1/3−1/2$ of the accretion energy must be released on the surface of the neutron star in order to explain the difference in the parameters of the Comptonized spectra in BH and NS systems.

$\frac{c}{\sim 2.5 \text{ keV}}$ for the distant observer, including colour correction, see Gilfanov & Sunyaev (2014) for details.
picture of the Eddington flux-limited levitating spreading layer supported by the radiation pressure, proposed earlier by Inogamov & Sunyaev (1999). In their model, the spectral shape of the boundary layer emission is determined only by the neutron star compactness (see Suleimanov & Pontaner 2004, for detailed calculation) and its luminosity is regulated by the surface area of the spreading layer. In the present work we find that in the hard spectral state on the contrary, the seed photon temperature is significantly smaller that the local Eddington value and varies with X-ray luminosity of the source, i.e. with the mass accretion rate. This points at the difference in the structure and dynamics of the boundary layer in the soft and hard spectral states.

The greater the differential between the linear velocity of the accreting material and that of the NS surface, the more energy is liberated at the boundary layer. In the Newtonian approximation the luminosity of the boundary layer \( \mathcal{L}_{\text{bd}} \) is given by equation [1] which can be expressed in terms of the respective rotation frequencies \( f_K \) and \( f_{\text{NS}} \),

\[
\mathcal{L}_{\text{bd}} = 2\pi^2 M R^2 (\alpha f_K - f_{\text{NS}})^2.
\]

One can see from these equations that the luminosity of seed photon produced by the NS surface anti-correlates with the NS spin. For higher spin sources supply of the seed photons will be reduced resulting in stronger Comptonization, in particular in large Compton amplification factor \( A \) and Comptonization parameter \( y \), in the same way as the dichotomy between BH and NS sources had been explained in Paper I.

Furthermore, assuming the emission from the boundary layer is well-approximated by a blackbody spectrum, then \( \mathcal{L}_{\text{bb}} \propto T^4 \). This means that if all other factors (especially the emitting surface area) are similar across the population of NSs, the temperature of the seed photons \( kT_{\text{bb}} \propto (\alpha f_K - f_{\text{NS}})^2 \). The maximal Keplerian frequency in the accretion disc is of the order \( f_K \sim 1.6 - 1.8 \) kHz (Sibgatullin & Sunyaev 2000), while NS spins vary in the \( f_{\text{NS}} \sim 0.3 - 0.6 \) kHz range. At \( L_X / L_{\text{Edd}} \sim 0.05 \), the seed photon temperature varies from \( kT_{\text{BB}} \sim 0.8 - 1.0 \) keV, i.e. by a factor of about \( 1.2 - 1.3 \), between low- and high-spin sources (Fig. 4). In order to explain such a difference between \( f_{\text{NS}} \sim 0.3 \) kHz and \( f_{\text{NS}} \sim 0.6 \) kHz sources, \( \alpha \sim 0.7 \) is required, which is broadly consistent with the conclusions of Paper I that the accreting material reaches the surface of the neutron star still possessing about \( 1/3 - 1/2 \) of its initial energy.

5.1 Can fast spinning neutron stars mimic black holes?

From equation 2 at sufficiently high NS spin frequencies the luminosity of the boundary layer can become small. Theoretically, this can make accreting neutron stars similar to black holes from the point of view of the energy balance in the Comptonization region. Indeed, such a behaviour is evident in Figure 3 where the high-spin sources at high Eddington ratios progressively overlap with the region of Comptonization parameters, identified with black holes in Paper I. This dilutes the boundary between black holes and neutron stars. From Figure 2 one can see that three sources expand into \( y \gtrsim 1.0 \) regions at higher \( L_X / L_{\text{Edd}} \). The behaviour is strongest at the highest Eddington ratios (but still compatible with the source being in the hard spectral state). All these sources have high spin (> 500 Hz), and their behaviour markedly contrasts with that of the slower sources at similar \( L_X / L_{\text{Edd}} \), such as 4U 1728 – 34, the Comptonizing strength of which remains low. For GS 1826 – 238, which has one of the highest spins and mass accretion rates in our sample, the Comptonization parameter can reach values \( y \sim 1.25 \), which is inside the region occupied by BH LMXBs. However, such high values of \( y \) are achieved only at high Eddington ratios, \( L_X / L_{\text{Edd}} \sim 0.1 \), at which neutron stars are characterised by extremely low electron temperature, \( kT_e \sim 10 - 20 \) keV (Figure 4), well below values typical for black holes (Fig. 5 in Paper I). This behaviour in \( kT_e - y \) distinguishes NSs from black holes and is illustrated in figure 5. A detailed comparison of high spin neutron stars with black holes will be a subject of a separate study. As a final point, we mention that withdrawing GS 1826 – 238 from the sample (see discussion in §4) does not negate the encroachment of the more luminous and high-spin sources onto the territory of Comptonization strength occupied by BHs (Fig. 3), but makes it less extreme. This is illustrated in figure 6 where the GS 1826 – 238 points are shown in grey.

2 We note that in the strictest sense these \( y \) should not be compared directly; the different seed photon model used in the current work means that we are in effect comparing two different models, however, experimentation by fitting the spectra in this work with both models shows that \( y \) is fairly resilient between both approaches, and on average \( y \) from using the blackbody seed photon spectrum is \( \approx 0.05 \) higher than that recovered from fitting using a multicolour disc blackbody seed spectrum.
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