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Hard state neutron star and black hole X-ray binaries in the radio:X-ray luminosity plane

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ABSTRACT

Motivated by the large body of literature around the phenomenological properties of accreting black hole (BH) and neutron star (NS) X-ray binaries in the radio:X-ray luminosity plane, we carry out a comparative regression analysis on 36 BHs and 41 NSs in hard X-ray states, with data over 7 dex in X-ray luminosity for both. The BHs follow a radio to X-ray (logarithmic) luminosity relation with slope $\beta = 0.59 \pm 0.02$, consistent with the NSs' slope ($\beta = 0.44_{-0.04}^{+0.05}$) within 2.5σ . The best-fitting intercept for the BHs significantly exceeds that for the NSs, cementing BHs as more radio loud, by a factor ~ 22 . This discrepancy cannot be fully accounted for by the mass or bolometric correction gap, or by the NS boundary layer contribution to the X-rays, and is likely to reflect physical differences in the accretion flow efficiency, or the jet powering mechanism. Once importance sampling is implemented to account for the different luminosity distributions, the slopes of the non-pulsating and pulsating NS subsamples are formally inconsistent ($>3\sigma$), unless the transitional millisecond pulsars (whose incoherent radio emission mechanism is not firmly established) are excluded from the analysis. We confirm the lack of a robust partitioning of the BH data set into separate luminosity tracks.

Key words: methods: statistical – X-rays: binaries – stars: neutron – stars: black holes.

1 INTRODUCTION

In spite of recent major advancements in our phenomenological understanding of X-ray binary (XRB) outflows, and their connection with the accretion flow behaviour, the launching mechanism of relativistic jets is still a matter of debate (see e.g. Fender 2016 for a recent review). While XRBs jets are typically studied in the radio band, where their synchrotron emission dominates over any other mechanism, they are likely launched and accelerated within a few 100s of gravitational radii of the compact object (Gandhi et al. 2017), where the X-ray emission originates. Coordinated radio and X-ray luminosity studies of outbursting XRBs tend to be biased towards the black hole (BH) population. This is likely due to the combination of two main factors. First, the somewhat slower state transition time-scales of BH XRBs make it easier to schedule coordinated space and ground observations. Secondly, and arguably more important, BH XRBs have long been known to be radio brighter than neutron stars (NSs). Seminal work by Fender & Kuulkers (2001) showed that transient BH XRBs are more radio loud (in terms of their radio to X-ray luminosity ratio, where both luminosities were measured at peak) than transient NSs. At around the same time, Fender & Hendry (2000) noted that the mean radio luminosity of

persistent NS Z sources and BHs was broadly consistent with each other, with the persistent Atolls and the transient X-ray pulsars (again at peak) being fainter by a factor of ≈ 5 –10 (the reader is referred to Muñoz-Darias et al. 2014 for recent, detailed reviews on NS X-ray states and nomenclature, and to Belloni & Motta 2016 for the BHs).

These early studies were concerned with mean and/or peak radio luminosities. Significant advancement came with the onset of multiwavelength outburst monitoring campaigns (joint with major correlator/receiver upgrades for the Very Large Array and Australia Telescope Compact Array), where a growing number of systems, albeit primarily BHs, have been monitored aggressively in the radio and X-ray band, often over multiple outbursts, and down to very low Eddington ratios. Thanks to these efforts, a coherent phenomenological picture that links distinct X-ray spectral states to different radio properties has emerged for the BHs (Fender 2006; Fender, Homan & Belloni 2009). Broadly speaking, the hard state is associated with (flat/inverted spectrum) radio emission arising from a partially self-absorbed synchrotron emitting outflow. Compact, hard state radio sources have indeed been resolved into mas-scale collimated jets in two (bright) BHs (GRS1915+205 and Cyg X-1; Dhawan, Mirabel & Rodríguez 2000; Stirling et al. 2001), and possibly a NS (Cir X-1; Miller-Jones et al. 2012). As a system enters into outburst, and its X-ray luminosity starts to increase, so does the radio luminosity of the compact jet. Based on data compiled by Hannikainen et al.

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(1998) and Corbel et al. (2000), Corbel et al. (2003) first reported on a tight, non-linear correlation between the radio and X-ray luminosity of the BH XRB GX339–4 over about 8 yr covering three major outbursts: $L_X \propto L_r^{0.7}$, over about three orders of magnitude in L_X . Shortly thereafter, based on quasi-simultaneous radio and X-ray observations of nine more systems, Gallo, Fender & Pooley (2003) argued for a universal radio:X-ray luminosity correlation in the hard state of BH XRBs.

On the NS front, Migliari & Fender (2006) conducted the first systematic investigation, including data from Z sources, accreting millisecond X-ray pulsars (AMXPs), and Atoll systems, both in hard and soft states. For the two (Atoll) systems with hard state data (namely, Aql X-1 and 4U 1728–34) they found $L_X \propto L_r^{1.4 \pm 0.2}$, yielding a significantly steeper correlation than found for the BHs, albeit over a significantly narrower dynamic range. Secondly, they confirmed that, whether in absolute or Eddington-scaled units, the ‘the NSs remain stubbornly less radio loud than the BHs for a given X-ray luminosity’, by a factor ~ 30 .

For the reasons discussed above, NS XRB studies have been hampered by the lack of radio detections at X-ray luminosities below $\lesssim 10^{36}$ erg s $^{-1}$. With the exception of the so-called transitional millisecond pulsars (tMSPs; Archibald et al. 2009; Papitto et al. 2013), for which a similar correlation to hard state BHs has been claimed over more than three orders of magnitude in L_X (Deller et al. 2015; see however, Bogdanov et al. 2018), the limited L_X dynamic range makes it challenging to reliably assess the presence of a luminosity correlation for hard state NSs. In an effort to extend previous investigations to lower luminosities/accretion rates, Tetarenko et al. (2016) and Tudor et al. (2017) assembled coordinated radio:X-ray observations of a handful additional hard state systems (including new data for the globular cluster Atoll EXO 1745-248, three AMXPs, and the non-pulsating system Cen X-4, both in quiescence as well as in outburst, plus a re-analysis of 4U 1728–34 and Aql X-1 data). Their results point towards a complex pattern of behaviour, with different systems exhibiting different degrees of disc–jet coupling.

In this letter, we present the largest yet collection of quasi-simultaneous radio:X-ray observations of hard state BH and NS XRBs. A broader study will be presented in a companion work (Van den Eijnden et al. in preparation, including thermal and very high state BHs, Z sources, soft-state Atolls, and slowly pulsating NSs). We start by collating data points from Gallo et al. (2014), for BHs, and Migliari & Fender (2006) plus Migliari, Miller-Jones & Russell (2011), for the NSs. Additional data points come from further literature searches and/or new data collected by our group. For the NSs, we select data for hard state Atolls and AMXPs, including the three known tMSPs. In the case of reported radio fluxes with no accompanying, dedicated X-ray coverage, X-ray fluxes around the time of the radio observation(s) are obtained from the 1 daveraged all-sky monitors on board the *Ross X-ray Timing Explorer (RXTE)* or *The Monitor of All-sky X-ray Image (MAXI)*. X-ray and radio fluxes are converted to unabsorbed 1–10 keV X-ray luminosities and 5 GHz luminosities, respectively. A flat radio spectrum is assumed for the purpose of converting radio flux densities to 5 GHz radio luminosity. Overall, our sample is composed of 36 BH and 41 NS systems fainter than $L_X \lesssim 10^{38}$ erg s $^{-1}$; data points, along with a list of adopted distances and references, can be downloaded from <https://jakobvdeijnden.wordpress.com/radioxray/>.

2 REGRESSION ANALYSIS

We start by assessing whether the distribution of ℓ_X for the NSs (109 data points) is consistent with being drawn from that of the

Table 1. The dependence of radio luminosity upon X-ray luminosity is parametrized as $(\ell_r - 28.57) = \alpha + \beta(\ell_X - 36.30)$, where ℓ denotes logarithmic values in CGS units. The best-fitting intercept (α), slope (β), and intrinsic scatter (σ_0) are defined as the median of the posterior distribution. Errors are quoted at the 1σ c.l.; for β , 3σ errors are also given in brackets.

Sample	α	β	σ_0
BH	$+1.18^{+0.03}_{-0.03}$	$0.59^{+0.02}_{-0.02}$ ($+0.07$ -0.06)	$0.46^{+0.02}_{-0.02}$
NS	$-0.17^{+0.05}_{-0.05}$	$0.44^{+0.05}_{-0.04}$ ($+0.15$ -0.13)	$0.43^{+0.05}_{-0.04}$
NS-tMSP	$-0.18^{+0.05}_{-0.05}$	$0.49^{+0.06}_{-0.05}$ ($+0.22$ -0.15)	$0.41^{+0.05}_{-0.04}$
Atoll	$-0.25^{+0.06}_{-0.06}$	$0.71^{+0.11}_{-0.09}$ ($+0.36$ -0.24)	$0.30^{+0.05}_{-0.04}$
AMXP	$-0.28^{+0.14}_{-0.15}$	$0.27^{+0.09}_{-0.10}$ ($+0.29$ -0.33)	$0.59^{+0.12}_{-0.09}$
AMXP-tMSP	$-0.33^{+0.14}_{-0.16}$	$0.19^{+0.13}_{-0.14}$ ($+0.45$ -0.50)	$0.56^{+0.14}_{-0.10}$
w1 Atoll	$-0.23^{+0.09}_{-0.11}$	$1.16^{+0.28}_{-0.24}$ ($+0.91$ -0.59)	$0.29^{+0.12}_{-0.10}$
w2 Atoll	$-0.18^{+0.07}_{-0.08}$	$1.39^{+0.35}_{-0.30}$ ($+1.36$ -1.02)	$0.21^{+0.11}_{-0.09}$

BHs (306 data points, inclusive of three X-ray upper limits), where ℓ denotes logarithmic luminosities in units of erg s $^{-1}$. A two-sample Kolmogorov–Smirnov (KS) test probability $p = 0.04$ implies that the two distributions are marginally consistent. For each sample, we parametrize the dependence of radio upon X-ray luminosity as $(\ell_r - 28.57) = \alpha + \beta(\ell_X - 36.30)$, with intrinsic random scatter included in the fitting. Centring is based on the median luminosities for the combined sample. We run the Bayesian modelling routine described by Kelly (2007) and implemented in IDL as LINMIX_ERR.PRO, which enables us to include censored data in the analysis. In line with previous work (Gallo, Miller & Fender 2012; Gallo et al. 2014), we assume 0.15 dex uncertainties in both ℓ_X and ℓ_r , with Gaussian likelihood functions on ℓ_r and ℓ_X , and uniform probability below upper limits. For the purpose of estimating the most likely values of the correlation intercept (α), slope (β), and intrinsic scatter (σ_0), we calculate the median of 10000 draws from the posterior distributions; 1σ confidence errors are calculated as the 16–84th percentiles of the posterior distributions (Table 1). Fig. 1 illustrates the results from the BH versus NS regression analysis: the BH data points follow a relation with slope $\beta = 0.59 \pm 0.02$, intercept $\alpha = +1.18 \pm 0.03$, and large intrinsic scatter, $\sigma_0 = 0.46 \pm 0.02$. For the NSs, $\beta = 0.44^{+0.05}_{-0.04}$, $\alpha = -0.17 \pm 0.05$, and $\sigma_0 = 0.43^{+0.05}_{-0.04}$. Whereas the two correlation slopes are consistent with each other within 2.5 σ , the best-fitting BH intercept exceeds that for the NS by 1.35 dex, confirming the BHs as substantially more radio loud, by a factor ~ 22 .

A separate question we wish to address is whether there is any statistically significant difference among different classes of NSs. We start by comparing the sub-sample of X-ray pulsating systems (i.e. the AMXPs, including the three tMSPs, for a total of 38 data points) to the (non-pulsating) Atolls (71 data points). Taken at face value, AMXPs are best described by a shallow relation, with slope $\beta = 0.27^{+0.09}_{-0.10}$, whereas $\beta = 0.71^{+0.11}_{-0.09}$ for the Atolls (solid purple and dashed cyan lines, respectively, in Fig. 2). Although the slopes are consistent within 3 σ (see Table 1), this comparison is intrinsically flawed. A two-sample KS test rules out with high confidence that the two ℓ_X distributions are consistent with each other. To control for this, we conduct a weighted comparison by drawing random sub-samples from the Atoll population, weighted to match the AMXP probability density distributions (PDFs) as weighting functions (Fig. 3), including and excluding the tMSPs. The AMXP-weighted Atoll sub-sample (denoted as w1-Atolls in Table 1) yields $\beta = 1.16^{+0.28}_{-0.24}$ (dash-dotted green line in Fig. 2), which is formally

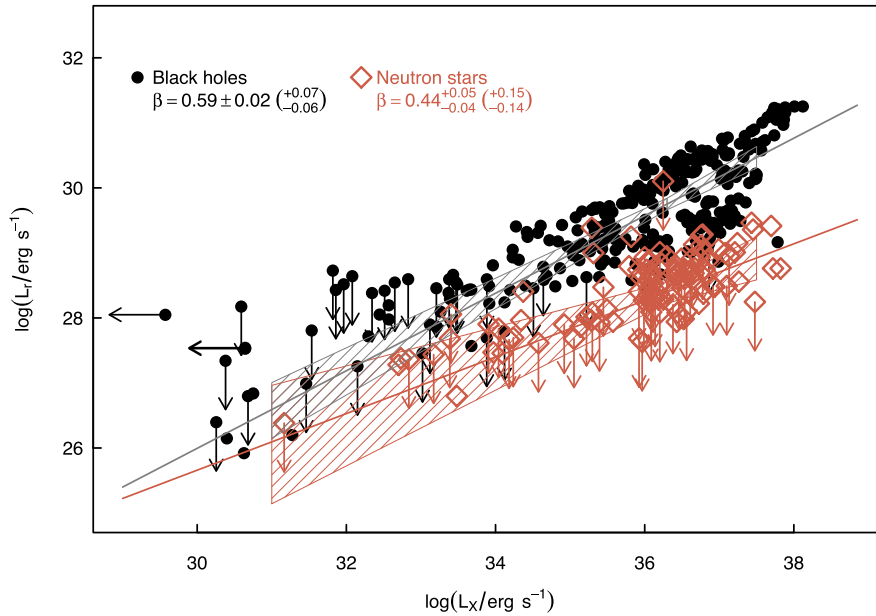


Figure 1. Radio (5 GHz) versus X-ray (1–10 keV) luminosity for a sample of 36 BHs (dark grey circles) and 41 NSs (orange diamonds) in hard states. Solid lines represent the median of the slope (β) posterior distribution, with 3σ errors enclosed by the shaded areas. Quoted errors on β are at the 1 (3) σ confidence level.

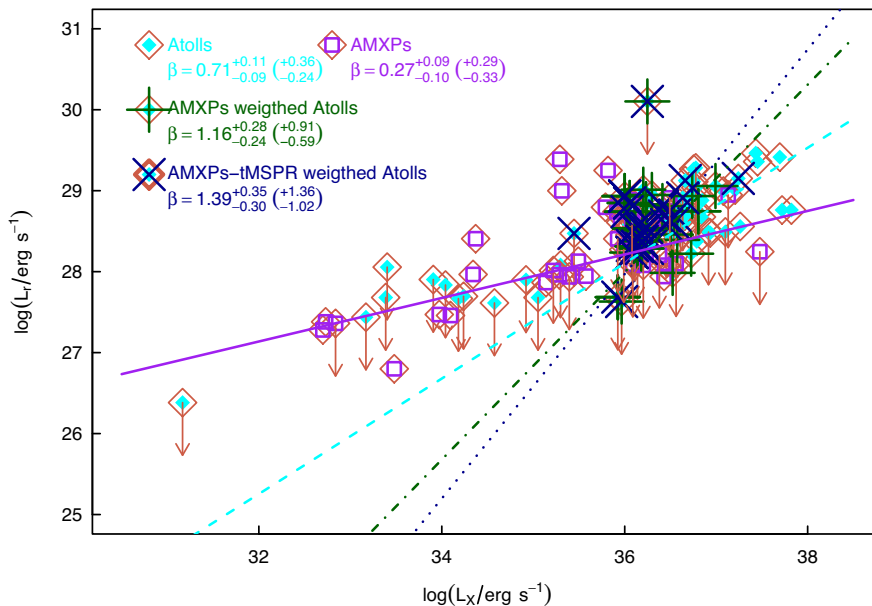


Figure 2. L_X distribution-weighted NS regression analysis, with weighting functions defined in Fig. 3. Quoted errors on β are at the 1 (3) σ confidence level.

inconsistent ($>3\sigma$) with the AMXP’s slope (the significantly steeper slope of the AMXP-weighted Atolls with respect to the full Atoll sample can be understood noting that the majority of the data points at $\ell_X \gtrsim 36$ are excluded by the importance sampling). The same exercise is carried out excluding the three tMSPs (five data points) from the AMXPs population. Controlling for the different ℓ_X distribution as above (i.e. using PDF 2 in Fig. 3 as a weighing function), we find that the (AMXP-tMSP)-weighted Atoll distribution (w2 Atolls in Table 1) is best described by $\beta = 1.39^{+0.35}_{-0.30}$ (dotted blue line in Fig. 2), which is consistent with the (AMXP-tMSP)’s slope ($0.19^{+0.13}_{-0.14}$) within 2.5σ .

This begs the question whether the NS versus BH comparison, too, is affected by the inclusion of the tMSPs. A two-sample KS test shows that, after the exclusion of tMSPs from the NS sample, the NS and BH ℓ_X distributions are still consistent with each other ($p = 0.05$), so no importance weighting is required. Re-fitting (NS-tMSP) sample yields a best-fitting slope $\beta = 0.49^{+0.06}_{-0.05}$, which is still consistent with the BHs’ within 2σ .

Last, we apply the same formalism described in Gallo et al. (2012, 2014) to assess whether the BH sample is best described by a single versus two or more clusters of data points (this approach is intrinsically limited to radio and X-ray detections only). After normalizing the axes to standardized coordinates and rotating them

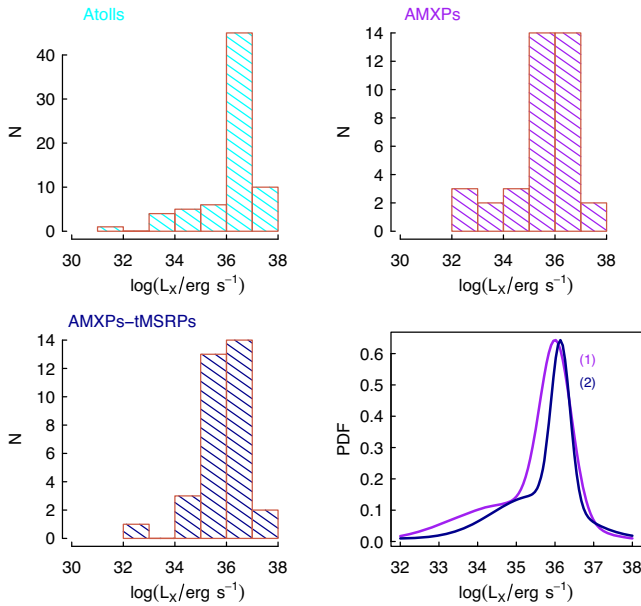


Figure 3. X-ray luminosity distributions for the different NS sub-populations: Atolls, AMXPs, and tMSRs. The comparative regression analysis is carried out through importance sampling, i.e. using the AMXP (1) and AMXP-tMSP (2) PDF as weighing functions.

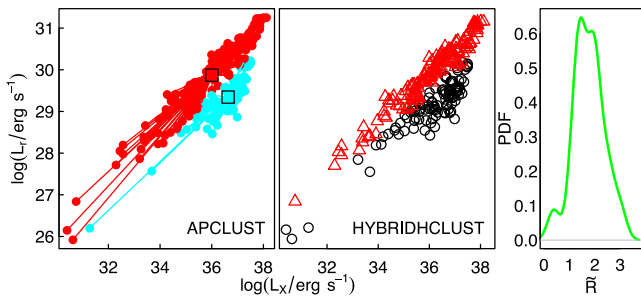


Figure 4. HYBRIDHCLUST/APCLUST Clustering analysis on the BH data points (detections only): both (left) and (centre) return a two cluster partitioning, albeit with slightly different membership. Right: PDF of the median radio loudness for individual systems, calculated above $\ell_X = 36.2$.

to unit variance, we run the clustering algorithms ‘affinity propagation’ (APCLUST; Frey & Dueck 2007), and HYBRIDHCLUST (Chipman & Tibshirani 2006). At face value, both prefer a two-cluster description of the data (left-hand and middle panel in Fig. 4). Interestingly, both algorithms identify nearly *parallel tracks*, rather than a main track across the entire ℓ_X dynamic range, plus a steeper track at $\ell_X \gtrsim 35$ (see e.g. Coriat et al. 2011). The actual cluster membership, however, is not robust. Additionally, after scrambling the data points with a Gaussian distribution of width $\sigma \approx 0.15$, different cluster centres and group memberships are identified. The lack of a reliable partitioning is confirmed by the fact that the median radio loudness (here defined as $\ell_r - \ell_X$) for individual systems (calculated above $\ell_X = 36.3$, i.e. in the range where two diverging tracks are often claimed), while consistent with a multimodal distribution (Fig. 4, right-hand panel), does not reflect any of the above clustering analysis results. To summarize, our analysis confirms the lack of a robust partitioning in the BH sample, defined as the ability to reliably and independently define two distinct tracks (this does not, however, constitute proof that the BH data are best described

by a single distribution). Owing to this uncertainty, no multitrack regression analysis is warranted for the BH sample.

3 DISCUSSION

As discussed by Tudor et al. (2017), individual NS systems exhibit a broad and complex range of behaviour in the radio:X-ray luminosity plane, including anticorrelations (albeit over a limited dynamic range). Additionally, the nature of the incoherent radio emission from tMSRs, i.e. the only NSs with radio detections below $\ell_X \lesssim 35$, is still a matter of debate (Bogdanov et al. 2018). Our result that the Atoll and AMXP populations are described by formally consistent scaling relations only if the tMSRs are excluded from the weighted regression analysis goes to show how these kinds of investigations hinge on properly accounting for the different luminosity distributions, and further stresses the importance of unravelling the tMSP radio emission mechanism during the X-ray pulsating mode.

Regarding the BH sample, we confirm the conclusions by Gallo et al. (2014) that no *robust* partitioning into two or more clusters (or tracks) can be identified. Several authors have investigated the possible origin of the so-called radio-quiet BH track (Soleri & Fender 2011; Dincer et al. 2014; Meyer-Hofmeister & Meyer 2014; Drappeau et al. 2015; Espinasse & Fender 2018). While it is entirely possible that the large scatter about the correlation, particularly above $10^{35} \text{ erg s}^{-1}$, can indeed arise from an enhanced disc contribution to the X-ray signal, or somewhat steeper radio spectral indices, the formal divide between the so-called standard and radio quiet track is rather blurred, with our latest clustering analysis indicating two nearly parallel tracks. Additionally, in spite of numerous claims to the contrary, the scatter about the NS relation is as large as that of the BHs.

This study confirms the enhanced radio loudness of the BH population across a broad dynamic range in X-ray luminosity. The factor of $\gtrsim 5$ difference in the accretor mass cannot possibly entirely account for the discrepancy: (naively) correcting for the mass term using the Fundamental Plane of Black Hole Activity relation¹ yields a difference of 0.81 dex in the best-fitting intercept, implying that the BHs remain more radio loud, by a factor ~ 6.5 , after accounting for the mass term. The gap could be further reduced if the total (as opposed to 1–10 keV) accretion luminosity were considered: such bolometric correction can be as high as 5–8 for the BHs (Zdziarski et al. 2004), versus a factor 2–3 for the NSs (Galloway et al. 2008). Adding this to the mass term correction would reduce the radio loudness difference to a factor of 3. Finally, contribution to the quoted 1–10 keV luminosities from the NS boundary layer up to between 30 and 50 per cent of the total X-ray luminosity (Burke, Gilfanov & Sunyaev 2017) could further reduce the BH-to-NS radio loudness ratio to a minimum of 2.5 (notice that this is obtained by conservatively adopting the largest possible ‘colour’ corrections in all of the above cases). This can be equally interpreted as the NSs being significantly brighter in X-rays than the BHs at a given radio luminosity. Advection of energy across the BH event horizon (Narayan & Yi 1995) is unlikely to be responsible for this difference, as one would expect the BHs to become progressively X-ray dimmer with respect to the NSs towards lower X-ray luminosities, which, in turn, would yield inconsistent (at the

¹Where we adopt the best-fitting parameters of Merloni, Heinz & di Matteo (2003) and use compact object masses from Casares, Jonker & Israelian (2017), when available, or $2 M_\odot$ versus $10 M_\odot$ for the NSs and BHs, respectively, otherwise.

$>3\sigma$ level) slopes. Whereas increasing evidence has solidified the discrepancy in radio loudness between BH and NS XRBs, its origin remains unclear. Spin-powering of BH jets remains an appealing explanation, albeit several studies on the matter have failed to reach a compelling conclusion (Fender, Gallo & Russell 2010; Narayan & McClintock 2012; Russell, Gallo & Fender 2013; Steiner, McClintock & Narayan 2013). Additionally, it has to be noted that the radio luminosity (in and of itself a poor indicator of total jet power) of NSs in soft X-ray states can approach that of the BHs. This will be further investigated in a companion paper (Van den Eijnden et al. in preparation).

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