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# Jets in neutron star X-ray binaries: a comparison with black holes

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## ABSTRACT

We present a comprehensive study of the relation between radio and X-ray emission in neutron star (NS) X-ray binaries, use this to infer the general properties of the disc–jet coupling in such systems and compare the results quantitatively with those already established for black hole (BH) systems. There are clear qualitative similarities between the two classes of object: hard states below about 1 per cent of the Eddington luminosity produce steady jets, while transient jets are associated with outbursting and variable sources at the highest luminosities. However, there are important quantitative differences: the NSs are less radio loud for a given X-ray luminosity (regardless of mass corrections) and they do not appear to show the strong suppression of radio emission in steady soft states that we observe in BH systems. Furthermore, in the hard states, the correlation between radio and X-ray luminosities of the NS systems is steeper than the relation observed in BHs by about a factor of 2. This result strongly suggests that the X-ray emission in the BH systems is radiatively inefficient, with an approximate relation of the form $L_X \propto \dot{m}^2$, consistent with both advection-dominated models and the jet-dominated scenario. In contrast, the jet power in both classes of object scales linearly with accretion rate. This constitutes some of the first observational evidence for the radiatively inefficient scaling of X-ray luminosity with accretion rate in accreting BH systems. Moreover, based on simultaneous radio/X-ray observations of Z-type NSs (the brightest of our Galaxy, always near or at the Eddington accretion rate), we draw a model that can describe the disc–jet coupling in such sources, finding a possible association between a particular X-ray state transition [horizontal branch to normal branch] and the emission of transient jets.

**Key words:** binaries: close – binaries: general – ISM: jets and outflows – radio continuum: stars.



## 1 INTRODUCTION

Multiwavelength studies of X-ray binaries (XRBs), especially in the past decade, have shown that a significant fraction of the dissipated accretion power may be released in form of radiatively inefficient collimated outflows, or jets. In general, relativistic jets are very common features associated with accretion onto relativistic compact objects on all mass scales, from neutron stars (NSs) and stellar-mass black holes (BHs) in XRB systems to supermassive BHs in active galactic nuclei (AGN), and are thought to be at the origin of gamma-ray bursts (GRBs), the most powerful transient phenomena in the Universe. The advantage of studying relativistic jets in XRBs is mainly due to the fact that the accretion process varies on much faster (humanly accessible) time-scales than in AGN, allowing us to observe and follow significant evolution of the systems and to investigate the link between the jet production and the different accretion regimes. At present, most of our knowledge about jets in XRBs has come from studies of BH candidates. This is mainly due to the fact that, in general (exceptions are the so-called Z-type NSs), BH XRBs are more radio loud than NSs, hence easier to detect.

### 1.1 Black hole X-ray binaries

A non-linear correlation has been found, linking the radio to the X-ray luminosities in BH XRB systems over more than 3 orders of magnitude in X-rays, when the BHs are in the hard state. This relation takes the form $L_R \propto L_X^b$, where $L_R$ and $L_X$ are the radio and X-ray luminosities, and $b \sim 0.7$ (Corbel et al. 2003; Gallo, Fender & Pooley 2003). In the hard state (i.e. below a few per cent the Eddington luminosity), the radio emission is observed to be optically thick, with a flat or slightly inverted spectrum, and although a jet has been spatially resolved only in two sources so far (Cyg X-1, Stirling et al. 2001; GRS 1915+105, Dhawan, Mirabel & Rodríguez 2000),

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indirect evidence indicates that this is the signature of a continuously replenished steady jet, the so-called 'compact jet' (see Fender 2005 for a review).

In BH XRBs (but maybe also in AGN, see Maccarone, Gallo & Fender 2003), there is evidence for a quenching of radio emission when the source is steadily in the soft state, probably due to a physical suppression of the jet (Fender et al. 1999; Gallo et al. 2003). The rapid X-ray transition from hard to soft states [i.e. the very high state (VHS) or steep power-law state] is associated with radio flares that show optically thin spectra. These radio flares are the signatures of powerful ejection events, spatially resolved as large-scale (from tens to thousands of milliarcsec) extended jets (e.g. Mirabel & Rodriguez 1994; Hjellming & Rupen 1995; Fender et al. 1999; Corbel et al. 2001; Gallo et al. 2004). A unified semi-quantitative model for the disc–jet coupling in BH XRBs, covering both steady and transient jets, has been presented by Fender, Belloni & Gallo (2004a).

Extending the correlation found for BH XRBs in the hard state also to supermassive BHs and with the addition of the mass parameter, there is evidence for a 'fundamental plane of BH activity' in which a single three-dimensional power-law function can fit all the BH data (XRBs and AGN) for a given X-ray luminosity, radio luminosity and mass of the compact object. This plane takes the approximate form $L_{\rm R} \propto L_{\rm X}^{0.6} M^{0.8}$, where $M$ is the mass of the compact object (Merloni, Heinz & Di Matteo 2003; Falcke, Körding & Markoff 2004). The existence of this relation connecting BH XRBs and AGN points towards the same physical processes as drivers of the disc–jet coupling, regardless of the mass of the BH involved. The radio:X-ray luminosity power-law correlation previously found by studying only BH XRBs has, within uncertainties, the same slope found in the correlation of the 'fundamental plane' with BH XRBs and AGN. Clearly, the study of XRBs can be fundamental for our understanding of the physical properties of discs and jets in compact objects in general, including supermassive BHs in the centres of distant galaxies.

### 1.2 Neutron star X-ray binaries

Low-magnetic-field NS XRBs have been classified, based on their X-ray spectral and timing properties, into two main distinct classes whose names derive from the shape they trace in the X-ray colour–colour diagram (CD): Z-type and atoll-type NSs (see Hasinger & van der Klis 1989). The 'broad' definition of atoll sources as having the apparent characteristics of low-magnetic-field NSs accreting at relatively low rates (compared to the Z sources) rather oversimplifies the more complex classifications of, for example, 'burster', 'dipper', etc., but is appropriate for the discussion in this paper. Fig. 1 summarizes the simplified classifications adopted in this paper (see van der Klis 2005 for a more detailed classification).

The Galactic Z-type NS XRBs represent a class of six low-mass XRBs (possibly seven if we include Cir X-1, which may be considered as a 'peculiar' Z source; Shirey, Bradt & Levine 1999) accreting near or at the Eddington rate and are the most luminous NS XRBs in our Galaxy. The name of this class of sources derives from the typical 'Z' track traced by their CD (Fig. 1). The three branches that form the Z-shaped CD are called the horizontal branch (HB), normal branch (NB) and flaring branch (FB), top-left to bottom-right, and define three distinct spectral states of the systems. Z sources are rapidly variable in X-rays and can trace the whole CD, transiting in the different states, in hours to days. This variability is thought to be physically related to changes in the mass accretion rate, which should increase along the Z track from the HB to FB (Hasinger &

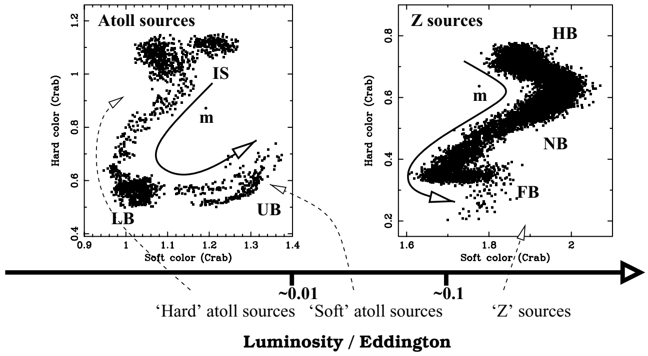


**Figure 1.** A summary of the simplified description of the relation of accretion/luminosity to patterns of X-ray behaviour, for low-magnetic-field NSs, as adopted in this paper. For both types of sources the expected direction of increasing mass accretion rate, $\dot{m}$, is indicated. For the atoll sources, the acronyms are: IS = island state; LB = lower banana; UB = upper banana. For the Z sources, the acronyms are: HB = horizontal branch; NB = normal branch; FB = flaring branch. CDs are from Jonker et al. (2000) and van Straaten et al. (2003).

van der Klis 1989). In the radio band, we also observe large and rapid variability, optically thick and optically thin emission. All the Z-type NS sources have been detected in radio. Looking in detail at the radio behaviour of Z sources as a function of X-rays, Penninx et al. (1988) first found in GX 17+2 a qualitative relation between disc and jet properties: the radio emission varies as a function of the position in the X-ray CD, decreasing with increasing (inferred) mass accretion rate from the HB (strongest radio emission) to the FB (weakest radio emission). A behaviour consistent with GX 17+2 has been found also in Cyg X-2 (Hjellming et al. 1990a) and Sco X-1 (Hjellming et al. 1990b). An exception is GX 5-1, which showed a low and steady radio flux when the source was in the HB, then increasing when in the NB (Tan et al. 1992). Extended radio jets have been spatially resolved for two Z sources: Sco X-1 (Fomalont, Geldzahler & Bradshaw 2001a) and Cir X-1 (Fender et al. 1998). In these two sources, there is also evidence for an association between radio flares and powerful (ultrarelativistic) ejections from the system (Fomalont, Geldzahler & Bradshaw 2001b; Fender et al. 2004b).

Atoll-type NS XRBs share many X-ray spectral and timing properties with BH XRBs and show two distinct (hard and soft) X-ray states, defined by the position in the CD, that can be directly compared to the hard and soft state of BH XRBs: the hardest X-ray state is called 'island' and the softest 'banana' (Fig. 1). Although atolls represent the largest class of known XRBs, only a few are detected in the radio band because of their lower radio luminosity (~30 times less 'radio loud' than BH and Z-type NS XRBs: Fender & Kuulkers 2001; Migliari et al. 2003; Muno et al. 2005; this paper). To date, five atoll sources have been detected in the radio band during simultaneous radio/X-ray observations: 4U 1728−34, 4U 1820−30, Ser X-1, Aql X-1 and MXB 1730−335 (Migliari et al. 2003, 2004; Rupen, Mioduszewski & Dhawan 2004; Rutledge et al. 1998; Moore et al. 2000, respectively). In particular, 4U 1728−34, which is to date the only atoll source detected in radio when steady in its hard state, shows a positive correlation between radio and X-ray fluxes, similar to what is observed in black hole candidates (BHCs) (Migliari et al. 2003). Homan et al. (2004) have also investigated the 'peculiar' atoll source GX 13+1, which is persistently at a very high X-ray luminosity of a few tens of per cent Eddington, showing that its radio behaviour is much more similar to Z sources.

Two accreting millisecond (ms) X-ray pulsars, SAX J1808.4−3658 (e.g. Gaensler, Stappers & Getts 1999) and IGR J00291+5934 (Pooley 2004), have shown transient radio emission related to X-ray outbursts. These flares may be signatures of transient relativistic outflows from the system as observed in BH XRBs and Z sources. In the context of the general picture of low-magnetic-field NSs, we assume (initially at least) that these systems behave like atoll sources, although Chakrabarty (2005) has suggested they may have systematically higher magnetic fields.

None of the high-magnetic-field X-ray pulsars has ever been convincingly detected as a synchrotron radio source (e.g. Fender & Hendry 2000 and references therein). This has been explained by the fact that the surface high magnetic field, which probably disrupts the inner regions of the accretion disc around the NS (e.g. White, Nagase & Parmar 1995; Bildsten et al. 1997) or that may strongly interact with the jet magnetic fields coupled with the inner regions of the disc (Migliari, Fender & van der Klis 2005), results in suppressed jet formation (Fender & Hendry 2000).

## 2 THE SAMPLE

In Table 1, we list the names, X-ray states, fluxes and estimated distances of all the NS XRBs in our sample.

**Table 1.** Name of the source of our sample, X-ray state (LB = lower banana; IS = island; MB = middle banana; H-OUTB = hard outburst; S-OUTB = soft outburst; ASM/PCA mean = the mean over more than one X-ray state), X-ray flux in the range 2–10 keV, radio flux density at 8.5 GHz, distance to the source in kpc and references.

| Source | X-ray state | $F_{2–10}$ ($\times 10^{-9}$ erg cm$^{-2}$ s$^{-1}$) | $F_{8.5}$ (mJy) | $D$ (kpc) | Ref. |
|---|---|---|---|---|---|
| | | Atoll-type NSs | | | |
| 4U 1728−34 | LB | $1.03 \pm 0.05$ | $0.5 \pm 0.08$ | 4.6 | M03, G03 |
| | IS | $2.25 \pm 0.15$ | $0.6 \pm 0.2$ | | |
| | LB | $1.54 \pm 0.10$ | $0.33 \pm 0.15$ | | |
| | IS | $1.81 \pm 0.11$ | $0.62 \pm 0.1$ | | |
| | IS | $2.42 \pm 0.16$ | $0.11 \pm 0.02$ | | |
| | IS | $0.60 \pm 0.07$ | $0.09 \pm 0.02$ | | |
| | IS | $0.61 \pm 0.06$ | $0.11 \pm 0.02$ | | |
| | IS | $0.62 \pm 0.06$ | $0.15 \pm 0.02$ | | |
| | IS | $0.69 \pm 0.12$ | $0.16 \pm 0.02$ | | |
| | IS | $0.70 \pm 0.05$ | $0.09 \pm 0.02$ | | |
| 4U 1820−30 | MB | 8.7 | $0.10 \pm 0.02$ | 7.6 | M04, H00 |
| Ser X-1 | MB | 4.4 | $0.08 \pm 0.02$ | 12.7 | M04, JN04 |
| Aql X-1 | H-OUTB | 0.79 | $0.210 \pm 0.050$ | 5.2 | RMD04, JN04 |
| | H-OUTB | 1.00 | $0.214 \pm 0.035$ | | |
| 4U 1608−52 | IS? | 0.93 | <0.19 | 3.3 | MF05, JN04 |
| 4U 0614−09 | IS | 0.78 | <0.09 | <3 | MF05, B92 |
| MXB 1730−335 | S-OUTB | 2.92 | $0.370 \pm 0.030$ | 8.8 | R98, M00, K03 |
| | S-OUTB | 3.06 | $0.290 \pm 0.030$ | | |
| | S-OUTB | 5.34 | $0.330 \pm 0.050$ | | |
| | | Low-magnetic-field accreting ms X-ray pulsar | | | |
| SAX J1808.4−3658 | S-OUTB | 0.14 | $0.8 \pm 0.18$ | 2.5 | GSG99, Z01, R02, R05 |
| | S-OUTB | 1.82 | $0.44 \pm 0.06$ | 2.5 | |
| | S-OUTB | 0.56 | $0.44 \pm 0.07$ | 2.5 | |
| IGR J00291+5934 | S-OUTB | 0.62 | $1.5 \pm 0.3$ | <3? | G05, P04 |
| | | Z-type NSs | | | |
| Sco X-1 | ASM mean | 253.80 | $10 \pm 3$ | 2.8 | FH00, P89, C76, BFG97 |
| GX 17+2 | ASM mean | 12.90 | $1.0 \pm 0.3$ | 14 | FH00, P89, P88, JN04 |
| GX 349+2 | ASM mean | 14.39 | $0.6 \pm 0.3$ | 5 | FH00, CP91, CS97 |
| Cyg X-2 | ASM mean | 10.75 | $0.6 \pm 0.2$ | 13.3 | FH00, P89, H90, CCH79, JN04 |
| GX 5-1 | ASM mean | 20.36 | $1.3 \pm 0.3$ | 9.2 | FH00, P89 |
| GX 340+0 | ASM mean | 8.54 | $0.6 \pm 0.3$ | 11 | FH00, P93 |
| GX 13+1 | PCA mean | 18 | $1.8 \pm 0.3$ | 7 | FH00, H04, JN04 |
| | | High-magnetic-field accreting X-ray pulsars | | | |
| X Per | ? | 0.46 | < 0.08 | 1 | MF05, D01 |
| 4U 2206+54 | ? | 0.26 | < 0.039 | 3 | B05, NR01 |

References: M03 = Migliari et al. (2003); G03 = Galloway et al. (2003); M04 = Migliari et al. (2004); H00 = Heasley et al. (2000); JN04 = Jonker & Nelemans (2004); RMD04 = Rupen et al. (2004); MF05 = Migliari et al. (2005); B92 = Brandt et al. (1992); R98 = Rutledge et al. (1998); M00 = Moore et al. (2000); K03 = Kuulkers et al. (2003) and references therein; GSG99 = Gaensler et al. (1999); Z01 = in't Zand et al. (2001); R02 = Rupen et al. (2002); R05 = Rupen et al. (2005); G05 = Galloway et al. (2005); P04 = Pooley (2004); FH00 = Fender & Hendry (2000); P89 = Penninx 1989; C76 = Crampton et al. (1976); BFG97 = Bradshaw, Fomalont & Geldzahler (1997); P88 = Penninx et al. (1988); CP91 = Cooke & Ponman (1991); CS97 = Christian & Swank (1997); H90 = Hjellming et al. 1990a; CCH79 = Cowley, Crampton & Hutchings (1979); P93 = Penninx et al. (1993); H04 = Homan et al. (2004); D01 = Delgado-Martí et al. (2001); B05 = Blay et al. (2005); NR01 = Negueruela & Reig (2001).

### 2.1 New radio observations of NS XRBs

The atoll-type NS XRB 4U 1608−52 (located at a distance of ∼3.3 kpc; Jonker & Nelemans 2004) was observed in 2004, on March 31 and April 03 for a total of ∼12 h with the Australian Telescope Compact Array (ATCA) at 8.5 GHz. During the observation, ATCA was in configuration 1.5A. We have analysed the data with the package MIRIAD (Sault, Teuben & Wright 1995), using PKS 1934−638 as the flux calibrator and 1646−50 as the phase calibrator. At the best (X-ray) coordinates (RA $16^{h}12^{m}43\overset{s}{.}0$, Dec. $-52°25'23''$), we did not detect the radio counterpart with a $3\sigma$ radio flux density upper limit of $F < 0.19$ mJy. The source was in a quiescent (hard) X-ray state with a mean (2-day average) count rate of $3.21 \pm 0.15$ in the All-Sky Monitor (ASM; 2–10 keV) on board the *Rossi X-ray Timing Explorer* (*RXTE*). The X-ray flux reported in Table 1 has been estimated converting the ASM count rates to Crab based on Levine et al. (1996: 1 Crab = 75 count $s^{-1}$) and then to 2–10 keV flux.

The atoll-type NS XRB 4U 0614−09 (which is at a distance of less than 3 kpc; Brandt et al. 1992) was observed on 2001 April 24 for 12 h with the Westerbork Synthesis Radio Telescope (WSRT) at 5 GHz. We have analysed the data with the package MIRIAD, using 3C286 as the flux calibrator. At the best (optical) coordinates (RA $06^{h}17^{m}07\overset{s}{.}3$, Dec. $+09°08'13''$), we did not detect the radio counterpart with a $3\sigma$ radio flux density upper limit of $F < 0.09$ mJy. The source was in a quiescent (hard) X-ray state with a one-day averaged *RXTE*/ASM count rate of $2.71 \pm 0.81$ count $s^{-1}$.

The XRB pulsar X Per (the nearest known, at a distance of only $0.7 \pm 0.3$ kpc) was observed on 2004 November 25 for 12 h with the WSRT at 1.4 GHz. We have analysed the data with the package MIRIAD, using 3C286 as the flux calibrator. At the best (optical) coordinates (RA $03^{h}55^{m}23\overset{s}{.}08$, Dec. $+31°02'45\overset{''}{.}0$), we did not detect the radio counterpart with a $3\sigma$ radio flux density upper limit of $F < 0.08$ mJy. The simultaneous 1-day averaged *RXTE*/ASM count rate was $1.61 \pm 0.34$ count $s^{-1}$.

No radio counterparts of the X-ray sources 4U 1608−52, 4U 0614−09 and X Per have ever been detected and these are the most stringent upper limits to date.

### 2.2 Other atoll-type NS XRBs

#### *2.2.1 4U 1728−34*

Based on two distinct epochs of observations, we found correlations between radio flux density and both X-ray flux and X-ray timing features (Migliari et al. 2003). One data point (that with the highest X-ray flux) lay well off the correlation, possibly indicating 'quenching' of the jet as observed in BHs (but see discussion in Migliari et al. 2003). 4U 1728−34 has been detected in the radio band, both when the source was steadily in its hard state (island) and when it was repeatedly transiting between the island state and a softer state (lower banana). The strongest and most variable radio emission seems to be related to the X-ray state transitions. These radio detections also allowed us to quantify the difference in radio power between BH and NS XRBs when steadily in their hard state: NSs are a factor of ∼30 less 'radio loud' than BHs (at a soft X-ray luminosity of $\sim 10^{36}$ erg $s^{-1}$). Setting the upper limit on the brightness temperature of the radio emitting region to $10^{12}$ K (above which, for steady states, inverse Compton losses will rapidly cool the plasma), we can estimate a lower limit on the size $R$ of the emitting region of $R > 1.4 \times 10^{11}$ cm, likely to be larger than the binary stars separation [typical low-luminosity ($10^{36}$–$10^{37}$ erg $s^{-1}$), low-mass XRBs have star separations smaller than $\sim 3 \times 10^{11}$ cm; White et al. 1995] and thus unbound to the system. The dual-band radio spectra of these observations are consistent with a steady jet emission as observed in BH XRBs in the hard state (even if errors on the detections cannot definitely rule out an optically thin spectrum). In Table 1, we show X-ray and radio fluxes reported in Migliari et al. (2003) and the mean of the estimated distances in Galloway et al. (2003).

#### *2.2.2 4U 1820−30 and Ser X-1*

We detected the radio counterparts of 4U 1820−30 and Ser X-1 when the sources were steadily in their soft X-ray state (lower banana; Migliari et al. 2004). From the measured radio flux densities, we estimate the size of the radio emitting regions to be $R > 7 \times 10^{10}$ cm for 4U 1820−30, larger than the star binary system separation ($\sim 1.3 \times 10^{10}$ cm; e.g. Arons & King 1993), and $R > 10^{11}$ cm for Ser X-1, also likely to be larger than the binary stars separation (White et al. 1995). In Table 1, we show the X-ray and radio fluxes reported in Migliari et al. (2004) and the estimated distances from Jonker & Nelemans (2004).

#### *2.2.3 Aql X-1*

Rupen et al. (2004) reported a radio transient emissions in Aql X-1 associated with an X-ray, optical and infrared (IR) outburst of the source. Note that, during the X-ray outburst, the source never entered the soft state (see also Reig, van Straaten & van der Klis 2004). Hereafter, we will refer to such an outburst as a 'hard' X-ray outburst, while we will call 'soft' outbursts, X-ray outbursts during which the source enters the soft state. On 2004 May 26, two quasi-simultaneous observations at 8.5 and 5 GHz gave a spectral index $\alpha = +0.4 \pm 0.8$ (where $S_\nu \propto \nu^\alpha$ and $S_\nu$ is the radio flux density at a frequency $\nu$), which seems to suggest optically thick emission typical of BH XRBs in their hard state, although uncertainties on the estimated flux densities cannot rule out the possibility of an optically thin emission (usually with $\alpha \sim -0.6$). In Table 1, we report the mean of the estimated distances in Jonker & Nelemans (2004), the flux densities of the radio detections reported in Rupen et al. (2004) and the X-ray flux calculated from simultaneous *RXTE*/ASM (2–10 keV) daily averaged observations.

#### *2.2.4 MXB 1730−335 (the Rapid Burster)*

Rutledge et al. (1998) and Moore et al. (2000) reported simultaneous observations with *RXTE*/ASM and the Very Large Array (VLA) at 5 and 8.5 GHz that revealed a transient radio emission correlated with the X-ray flux, during a (soft) X-ray outburst. The dual-frequency radio observations indicate a flat or slightly inverted spectral index. In Table 1, we show the X-ray and radio fluxes reported in Rutledge et al. (1998) and the distance in Kuulkers et al. (2003) and references therein.

### 2.3 Low-magnetic-field accreting ms X-ray pulsars

#### *2.3.1 SAX J1808.4−3658*

Gaensler et al. (1999) reported a radio detection of SAX J1808.4−3658 during the (soft) X-ray outburst in 1998. The size of the radio emission region can be constrained to be $R > 3.6 \times 10^{10}$ cm, larger than the binary star separation (Chakrabarty &

Morgan 1998). In Table 1, we show radio flux densities reported in Gaensler et al. (1999) and the estimated distance from in't Zand et al. (2001). Rupen et al. (2002); Rupen, Mioduszewski & Dhawan (2005) reported radio detections at 8.5 GHz during the X-ray outbursts on 2002 October 16 and 2005 June 16, both at the same flux level (∼0.44 mJy). We estimated the 2–10 keV X-ray fluxes of the observations in 1998 and 2002 analysing the X-ray energy spectrum of the *RXTE*/Proportional Counter Array (PCA) observations coordinated to the radio detection (see also Gilfanov et al. 1998 and Gierlinski, Done & Barret 2002). The 2–10 keV luminosity of the observation on 2005 June 16 was estimated using the ASM count rate of 1.9 ± 0.4. We fitted the PCA energy spectra in the range 3–20 keV with a Gaussian emission line at ∼6.4–6.6 keV, a blackbody with temperatures of $kT \sim 0.6$–0.7 keV and a power law with a photon index of ∼1.9 (the equivalent hydrogen column density was fixed to $N_{\mathrm{H}} = 4 \times 10^{21}$ cm$^{-2}$).

#### 2.3.2 *IGR J00291+5934*

The newly discovered accreting ms X-ray pulsar IGR J00291+5934 (Eckert et al. 2004; Markwardt, Swank & Strohmayer 2004) has been detected in radio at 15 GHz at the peak of the (soft) X-ray outburst (Pooley 2004). In Table 1, we show the X-ray flux reported in Markwardt et al. (2004), radio flux densities in Pooley (2004) and the estimated distances in Galloway et al. (2005). The radio flux density at 15 GHz has been converted to 8.5 GHz assuming an optically thin emission with $\alpha = -0.6$.

### 2.4 Other high-magnetic-field NS XRBs

#### 2.4.1 *4U 2206+54*

Blay et al. (2005) reported results from *INTEGRAL* and VLA observations of the XRB 4U 2206+54. High-energy spectral analysis reveals the presence of an absorption line at 32 keV, which indicates the presence of a cyclotron scattering feature, thus identifying the XRB as a high-magnetic-field (∼3.6 × 10$^{12}$ G) NS (see also Masetti et al. 2004). VLA observations at 8.5 GHZ did not detect the radio counterpart with a 3$\sigma$ upper limit of 0.039 mJy. In Table 1, we report the distance from Negueruela & Reig (2001), the radio flux density in Blay et al. (2005) and the 2–10 keV X-ray flux from the *RXTE*/ASM simultaneous daily averaged count rate.

### 2.5 Z-type NS XRBs

For all the Z sources (Sco X-1, GX 17+2, GX 349+2, Cyg X-2, GX 5-1, GX 340+0) and for GX 13+1, we have calculated the mean X-ray flux based on the ASM count rate since the beginning of the *RXTE* mission until 2004 December 14. The mean radio flux is from Fender & Hendry (2000). Note that, even though the classification of GX 13+1 as either an atoll- or Z-type NS is controversial (e.g. Schnerr et al. 2003), we decided to list it among Z sources because, as far as radio power is concerned, this source seems to be part of this group (see Homan et al. 2004).

### 2.6 Transient BH XRBs

In our sample, we consider the jet ejection events associated with X-ray outbursts of eight transient BH XRBs [GRS 1915+105 (flare), GRO J1655−40, XTE J1859+226, XTE J1550−564, GX 339-4, V4641 Sgr, Cyg X-1 and XTE J1748−228] from Fender et al. (2004a and references therein). We used the values for distance and radio and X-ray luminosities listed in Table 1 in Fender et al. (2004a); the radio flux densities at 5 GHz has been converted to flux densities at 8.5 GHz, assuming a radio spectral index $\alpha = -0.6$, and the fraction of X-ray Eddington luminosity at the peak of the outburst in the VHS has been converted to 2–10 keV luminosity, assuming that the latter is 80 per cent of the bolometric flux (see Section 2.8).

### 2.7 Persistent BH XRBs

For clarity, we plot in Fig. 2 only GX 339-4 as a sample of BH XRBs in the hard state (for a complete sample of BH XRBs see Gallo et al. 2003). We used fluxes from Corbel et al. (2003); the 2–10 keV X-ray fluxes have been extrapolated from the 3–9 keV ones they reported, assuming a spectral index of 1.7. We calculated the luminosities assuming the (minimum) distance of 7 kpc, inferred by Zdziarski et al. (2004).

### 2.8 Conversion from 2–10 keV luminosities to Eddington units

In order to extrapolate the bolometric flux of the XRBs and then to convert their X-ray luminosities in Eddington units, we have divided the XRBs into five main groups: BHs in the hard state, BHs during X-ray outbursts, atoll sources in the hard state, atoll sources in the soft state and Z sources. We assumed that each group has the same fraction of bolometric luminosity in the 2–10 keV band. For each group, we used the best-fitting model parameters for the PCA–High Energy X-ray Timing Experiment (HEXTE) energy spectra to create a simulated spectrum with XSPEC. For the NSs, we used PCA and HEXTE response matrices and ancillary files to calculate the flux in the range 3–200 keV and a *Chandra* High Energy Transmission Grating Spectrometer (HETGS; Medium Energy Grating, MEG) response matrix and ancillary file to extend the range below 3 keV, down to 0.5 keV, which is especially important for soft X-ray states. The 0.5–200 keV has been taken as a good approximation of the bolometric flux of the sources. For the BHs in the hard state, we used as bolometric fluxes the 3–200 keV fluxes of GX 339-4 in Nowak, Wilms & Dove (2003). For the BHs during outbursts, we used the bolometric fluxes calculated in Fender et al. (2004a). The conversion to Eddington units is given dividing the bolometric luminosity by $1.3 \times 10^{38} \times (M/\mathrm{M}_{\odot})$ erg s$^{-1}$, where $M = 1.4\,\mathrm{M}_{\odot}$ for all the NSs, while for the BHs we used the masses listed in table 1 of Fender et al. (2004a). The bolometric flux will be $F_{2-10} = F_{\mathrm{bol}} \times \xi$, where we used $\xi = 0.2$ for BHs in the hard state, $\xi = 0.8$ for BHs during X-ray outbursts, $\xi = 0.4$ for atoll sources in the hard state, $\xi = 0.7$ for atoll sources in the soft state and $\xi = 0.8$ for Z sources: the actual $L_{2-10\,\mathrm{keV}}/L_{\mathrm{bol}}$ ratio of the single observations are always within 10 per cent of these $\xi$ values.

## 3 RESULTS

### 3.1 X-ray/radio luminosities in NS XRBs

In Fig. 2, we show the radio/X-ray luminosity plane with all the NS XRBs in our sample. Four groups of sources are plotted: Z-sources, atoll sources in the hard state, atoll sources steadily in the soft state and sources in soft outbursts (i.e. the Rapid Burster and the two accreting ms X-ray pulsars). There is an overall positive ranking correlation between radio and X-ray luminosities, at a significance level of >99 per cent. The fit with a power law to the Z- and atoll-type NS XRBs (excluding the ms X-ray pulsars) gives a slope of $\Gamma = 0.66 \pm 0.07$ (where $L_{\mathrm{R}} \propto L_{\mathrm{X}}^{\Gamma}$).

Z sources (triangles) lie towards the top-right part of the plot, with X-ray and radio luminosities higher than atolls. We have plotted the



 

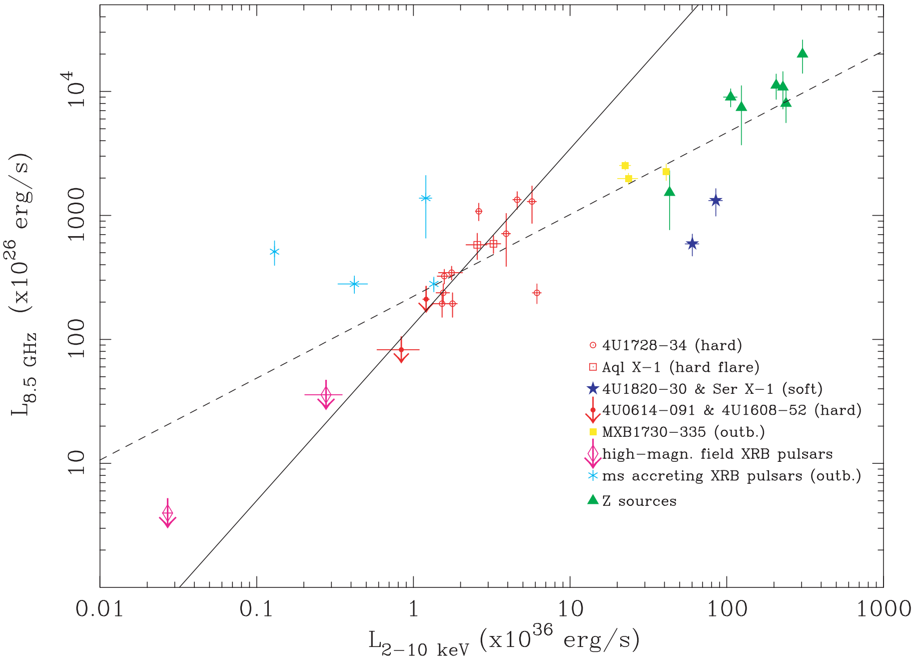


**Figure 2.** Radio (8.5 GHz) luminosity as a function of X-ray (2–10 keV) luminosity of NS XRBs: atoll sources in the hard state (4U 1728−34, open circles; Aql X-1, open squares; 4U 1608−52 and 4U 0614−09, filled circles with radio upper limits), atoll sources steadily in soft state (4U 1820−30 and Ser X-1, filled stars), an 'atoll' source in an X-ray outburst (MXB 1730−335, filled squares), accreting ms X-ray pulsars in X-ray outbursts (SAX J1808.4−3658 and IGR J00291+5934, asterisks; IGR J00291+5934 is the one with the highest radio luminosity), the high-magnetic-field XRBs (open diamonds with radio upper limits) and Z sources (filled triangles). The solid line is the fit to the NSs in hard state, i.e. 4U 1728−34 and Aql X-1, with a slope of $\Gamma \sim 1.4$, and the dashed line is the fit to all the atolls and Z sources (excluding only the ms accreting XRBs and the radio upper limits) with a slope of $\Gamma \sim 0.7$ (see Section 3.1).

mean of the radio and X-ray luminosities: their radio luminosities are the superposition of optically thick emission and optically thin flaring activity, while the X-ray luminosities are the average of the luminosities in their three possible X-ray states (see a more detailed discussion in Section 4.5). There is only marginal evidence for a positive ranking correlation between radio and X-ray luminosities in the Z sources as a separate group (∼96 per cent significance level; power-law fit index $\Gamma = 1.08 \pm 0.22$).

Atoll sources in the hard X-ray state (4U 1728−34, open circles; Aql X-1, open stars) show a positive correlation between radio and X-ray luminosities over 1 order of magnitude in X-rays (with the exception of the point with the highest X-ray luminosity: see discussion in Migliari et al. 2003): a rank-correlation test gives a significance of >99 per cent. In order to compare the luminosity correlations in NSs with those in BHs (see also Section 3.2), we fitted the correlation with a power-law model: 4U 1728−34 gives $\Gamma = 1.40 \pm 0.25$ and, considering also Aql X-1, we obtain $\Gamma = 1.38 \pm 0.23$. We should stress once more that the NS observations span a range of only about 1 order of magnitude in X-ray luminosity, to be compared with the 3 orders of magnitude of the BH XRBs (see Fig. 3). However, we can place constraints on the slope of the power law over a larger range of luminosities. If we consider also the radio upper limits of 4U 0614+09 at low X-ray luminosities, fitting them as detections, we obtain a lower limit on the slope of the power law of $\Gamma > 1.60 \pm 0.27$, clearly indicating that the radio/X-ray luminosity correlation in NSs is steeper than that in BHs. This has important consequences for our understanding of the relation of $L_X$ and $L_R$ to the accretion rate $\dot{m}$ as shall be discussed later. [Note that the overall flatter slope of the radio/X-ray luminosity correlation considering the whole sample of NSs ($\Gamma \sim 0.6$–0.7, see above) is dominated by the slopes within the transients and between the hard-state sources and the transients.]

Atoll sources steadily in the soft state (filled stars) have been detected in radio. This is contrary to what is found in BHs, where there is a quenching of radio emission in the soft state (see Fig. 4). This finding indicates that NSs may not suppress completely the (compact?) jet in the soft state. In fact, considering the ensemble of NS data points, there is no strong evidence *at all* for suppressed radio emission in steady soft states.

The Rapid Burster (filled squares) shows radio flaring emission associated with X-ray outbursts. It has X-ray luminosities consistent with atoll sources in the soft state. There is a significant (99 per cent) positive ranking correlation between radio and X-ray luminosities in atoll sources plus the Rapid Burster, suggesting that it lies on a sort of natural extension of atolls in the hard state (as in persistent and transient BHs; see Fender et al. 2004a).

The radio peak of IGR J00291+5934 is consistent with the Rapid Burster radio peak and with the highest radio emission from 4U 1728−34 (maybe also in a radio flaring emission state; see Migliari et al. 2003). SAX J1808.4−3658 has been detected in radio a few days after the peak of the outburst in 1998, when the X-ray and radio emissions had already faded (but see Gaensler et al. 1999) and during the outbursts in 2002 and 2005 (Rupen et al. 2002, 2005). The radio luminosities seem to be consistent with those of Aql X-1, lower than those of IGR J00291+5934. Additional discussion of the radio emission from the ms X-ray pulsars is presented in Migliari et al. (2005), in which it is suggested that they *may* be slightly less radio loud than other atoll sources as a result of a generally higher surface magnetic field (Chakrabarty 2005).

The high-magnetic-field NSs (X Per and 4U 2206+54) have not been detected in the radio band. The radio upper limits are still consistent with the radio/X-ray luminosity expected extrapolating the correlation for atoll sources to lower X-ray luminosities. This in fact means that we cannot confidently state that the high-magnetic-field

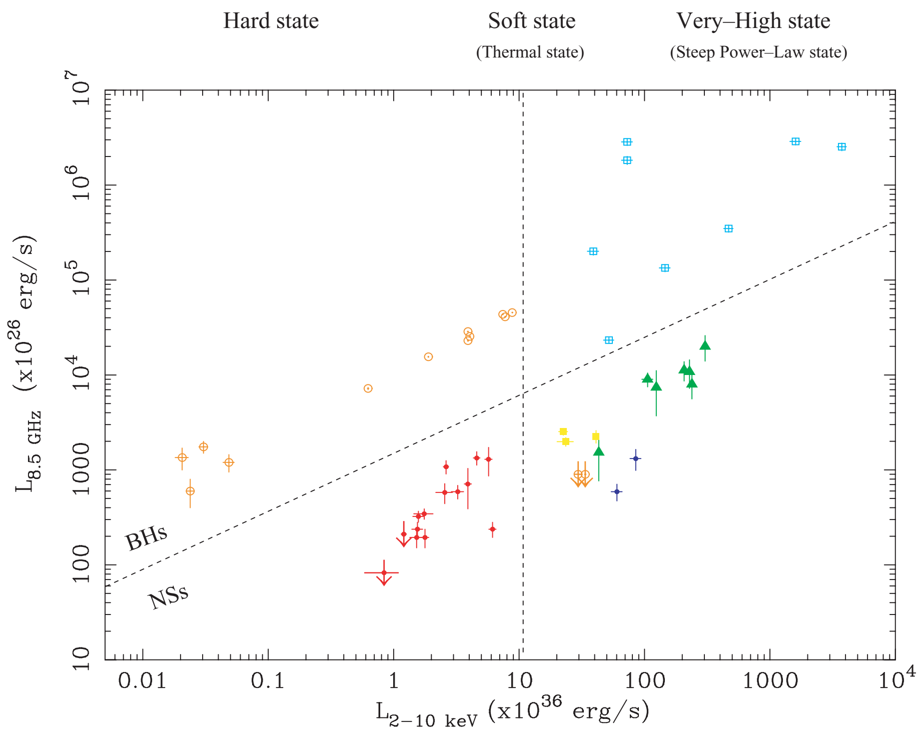


**Figure 3.** Radio (8.5 GHz) luminosity as a function of X-ray (2–10 keV) luminosity for NS and BH XRBs: GX 339-4 in the hard state (open circles), transient BHs (open squares), atoll sources steady in a hard or soft state (filled circles), MXB 1730−335 during a soft outburst (filled squares) and Z sources (filled triangles).

NSs are significantly fainter in the radio band than 'normal' atoll sources, when at relatively low ($<10^{-2}$ Eddington) luminosities.

### 3.2 Neutron stars versus black holes

Is the 'fundamental plane of BH activity' also a fundamental plane for NSs? Put in another way, is the X-ray:radio coupling in accreting BHs related exclusively to the properties of the accretion flow, or also to some property unique to BHs? Clearly, we may attempt to address this question by comparing the X-ray:radio coupling in NS XRBs with that of BHs in XRBs and AGN.

Observationally, there are clear qualitative similarities in the disc–jet coupling between NSs and BHs (see Figs 3 and 4):

(i) below a certain X-ray luminosity, in hard X-ray states (i.e. $L_X < 0.1 \times L_{Edd}$), both classes of objects seem to make steady, self-absorbed jets (caveat very poor measurements of radio spectra in the case of NSs) that show correlations between $L_X$ and $L_R$; and

(ii) at higher X-ray luminosities, close to the Eddington limit, bright, optically thin, transient events occur (specifically associated with rapid state changes).

These similarities indicate that the coupling between the jet and the innermost regions of the accretion disc does not depend (at least entirely) on the nature of the compact object, but is related to the fundamental processes of accretion in strong gravity.

However, there are quantitative differences in the disc–jet coupling also:

(i) the NSs in the hard state appear to show a steeper dependence of $L_R$ on $L_X$, also with a lower normalization in $L_R$; and

(ii) the NSs do not appear to show anywhere near as much suppression of radio emission in steady soft states as the BHs.

We performed a Kolmogorov–Smirnov test on the ratios between $L_X$ and $L_R$ in the two XRB systems, to check if the BHs and NSs X-ray/radio luminosities are drawn from the same distribution. The null hypothesis that the data sets are drawn from the same distribution is $\sim 10^{-3}$ for the observations in the hard state only (i.e. GX 339-4 versus 4U 1728−34 and Aql X-1) and $\sim 10^{-5}$ using the whole sample. This indicates clearly a different dependence of $L_R$ over $L_X$ in the two systems.

In fact, whether in absolute units, Eddington-scaled units, or applying the mass-correction appropriate for the 'fundamental plane of black hole activity' ($L_R \propto M^{0.8}$; Merloni et al. 2004), the NSs remain stubbornly less radio loud than the BHs for a given X-ray luminosity. However, bolometric corrections are only poorly estimated at lower luminosities and could conceivably bring the data sets significantly closer together if severely underestimated for the BH sample.

## 4 DISCUSSION

In the following, we will briefly discuss some possible implications deriving from the comparison between disc–jet coupling in BHs and NS systems.

### 4.1 Jet velocity and power

Observations of the ultrarelativistic radio jets in the NS XRB Cir X-1 (i.e. with a bulk Lorentz factor $>15$; Fender et al. 2004b) have already shown that the (often accepted) 'escape velocity' paradigm, which states that the velocity of the jets should be about the escape velocity of the compact object involved, is not valid in the relativistic regime. Their observations also indicate that properties unique to

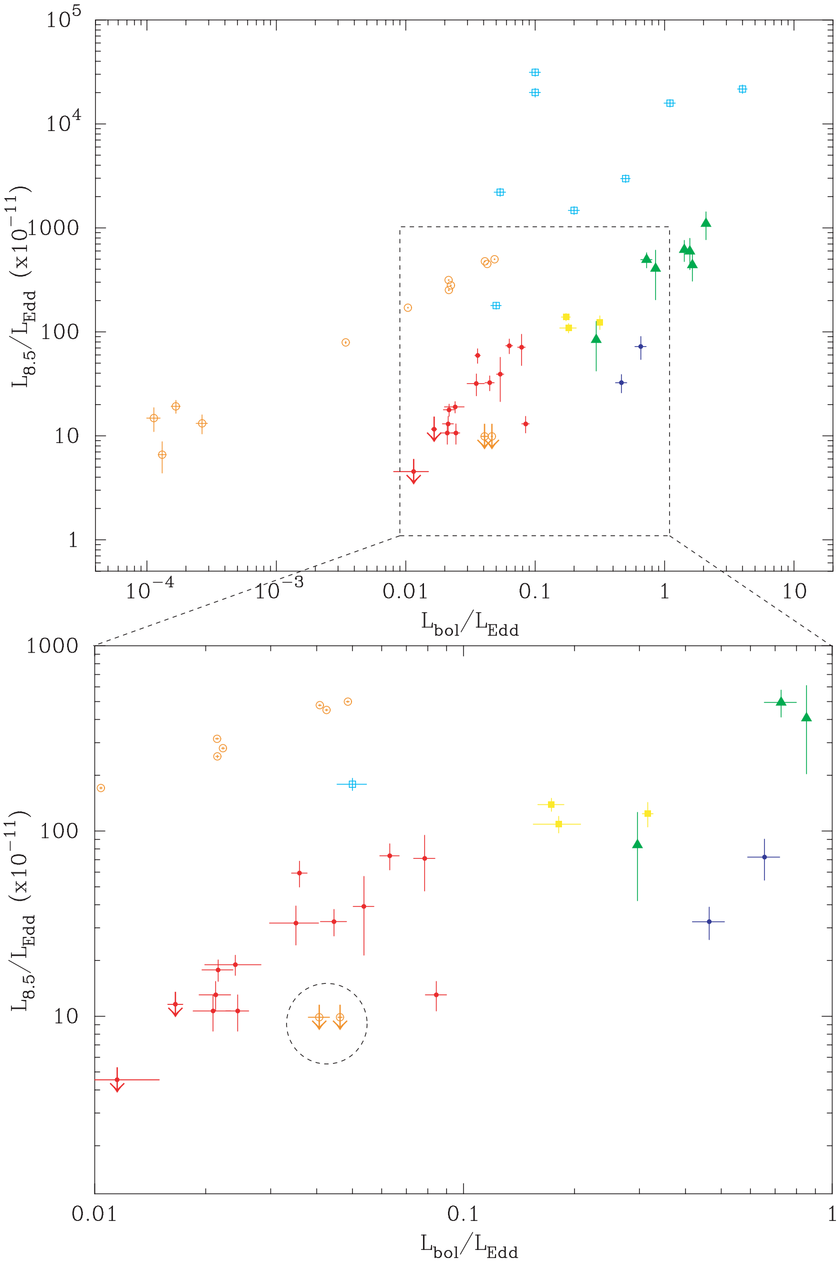


**Figure 4.** Upper panel: the same as Fig. 2, but in Eddington units (see Section 2.1). Lower panel: zoom in the $L_{Edd}$ range 0.01–1 showing that in this range there is a radio quenching in BHs (dashed circle), while in NSs the suppression of the jet is not observed (at least as extreme as in BHs).

BHs are *not necessary* for the production of relativistic jets. However, proper characteristics of the compact object seem to play, at least partially, a role in the jet production.

Regarding radio and jet power, it is important to know at what $L_X$ to compare the NS and BH samples. We would argue (see below) that the least radiatively inefficient point, while still in the hard state and therefore producing a steady jet in both samples, should be selected. This point naturally corresponds to the brightest hard state in BHs and 'atoll-hard' state in NSs. Comparison of the fits to the NS and BH samples indicates that, at $L_X \sim 0.02$, the ratio of radio luminosities is ~30. As noted in Migliari et al. (2004), assuming a scaling $L_R \propto L_J^{1.4}$ this indicates that NS jets are about one order of magnitude less powerful than BH jets at this X-ray luminosity. As we shall see below, the diverging $L_R : L_X$ correlations do *not* require that this ratio change as a function of accretion rate.

### 4.2 Event horizons and radiatively inefficient flows

The different correlations between $L_X$ and $L_R$ in the BH and NS samples (to recall, $b_{BH} \sim 0.7$, $b_{NS} \gtrsim 1.4$, where $L_{radio} \propto L_X^b$) are telling us something quite fundamental about the accretion processes in these two types of object. In the following, we shall take $b_{NS} = 1.4$. Assuming, as before, that $L_R \propto L_J^{1.4}$, we get

BH $\quad L_J \propto L_X^{0.5}$,

NS $\quad L_J \propto L_X$,

where the quadratic relation for the BHs was already presented in Fender, Gallo & Jonker (2003). The linear relation between jet and X-ray powers in the NS sample implies that NS systems will never reach a jet-dominated state (unless sources like 4U 1728−34 are already in jet-dominated states, but this seems unlikely).

The different relations may seem to imply, at face value, that the coupling between accretion rate and jet power may be different in these two sets of sources. If we assume that the relation between $L_X$ and $\dot{m}$ is the same for both BH and NS, this is clearly true. However, we believe it is far more likely that it is the coupling between $L_X$ and $\dot{m}$ that is different in the two samples, as we shall outline below.

Assuming that the relation between $L_J$, not $L_X$, and the accretion rate $\dot{m}$ is the same for both classes of object, we can draw some simple yet important conclusions. Assuming that accretion in NS sources is essentially radiatively efficient (in the presence of a solid surface, the only way to avoid this criterion is if a large fraction of the accreting *mass* were ejected before it had radiated or impacted on the NS surface), then for NS we get simple linear relations:

NS $\;L_J \propto L_X \propto \dot{m}$,

and, since $\dot{m} \propto L_X + L_J$ and we estimate $L_X > L_J$, then in Eddington units

NS $\;L_X \sim \dot{m}$.

Keeping the same coupling between accretion rate and jet power for BHs, we arrive at

BH $\;L_J \propto L_X^{0.5} \propto \dot{m}$.

This is exactly the prescription presented in Fender et al. (2003) for jet-dominated states in XRB systems. Therefore, one clear explanation for the observed differences between the $L_R : L_X$ correlations in the two samples is that the NS are in an ‘X-ray dominated’ state and the BH are ‘jet dominated’. The different coupling between $L_X$ and $\dot{m}$ ensures that the samples remain fixed in these states as the accretion rate decreases. In Fig. 5, we plot the situation as we now envisage it. Note that we have adopted jet power normalizations of $A_{\mathrm{steady,BHC}} = 0.1$, $A_{\mathrm{steady,NS}} = 0.01$ (where $L_J = A \times L_R^{1/1.4}$; Fender et al. 2003; Fender, Maccarone & van Kesteren 2005). The value of $A_{\mathrm{steady,BHC}} = 0.1$ corresponds to equipartition between jet and X-ray powers at around the hard $\rightarrow$ soft transition luminosity of $L_{X,\mathrm{trans}} \sim 0.02$. This is a larger normalization than the conservative lower limit presented in Fender et al. (2003), but we consider it to be more likely given the lack of apparent accretion efficiency transitions *within* the hard state (see discussions in e.g. Malzac, Merloni & Fabian 2004; Maccarone 2005) and recent, higher, estimates of the steady jet power (e.g. Gallo et al. 2005). In this framework, the difference in quiescent luminosities of BH and NS XRBs (e.g. Garcia et al. 2001) are simply explained by the jet removing most of the liberated gravitational potential energy in the quiescent BH, but not in the NS, conclusions identical to those drawn in Fender et al. (2003). Accretion rates $10^{-6} \lesssim \dot{m} \lesssim 10^{-4}$ (Eddington units) for both classes of object in quiescence can produce the observed discrepancy in $L_X$ (Fig. 5).

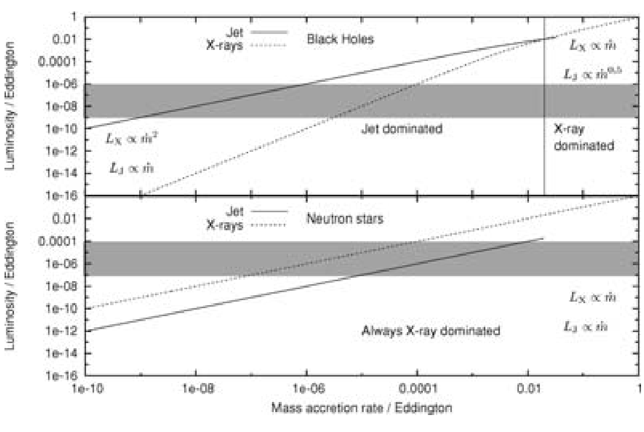


**Figure 5.** Computed variation of jet and X-ray power as a function of mass accretion rate (all in Eddington units) for BHs (upper panel) and NSs (lower panel). This is a reworking of the model presented in Fender et al. (2003), based upon the new observational evidence presented in this paper and elsewhere. We now presume that in all hard X-ray state BHs are jet-dominated, whereas NS systems never enter the jet-dominated regime. The grey bars indicate the observed ‘quiescent’ X-ray luminosities of most X-ray transients.

However, the result that for the BH $L_X \propto \dot{m}^2$ is generically indicative of *radiatively inefficient* accretion in the BH systems. We define radiatively inefficient to mean that the majority of the liberated gravitational potential is carried in the flow and not radiated locally; in this sense, the jet-dominated configuration outlined above corresponds to radiatively inefficient accretion, because most of the liberated accretion power is in the form of the internal and bulk kinetic energy of the ejected matter. There is of course another appealing possibility, namely that we are witnessing the observational effect of advection-dominated accretion flows (ADAFs; e.g. Ichimaru 1977; Narayan & Yi 1994; 1995), in which case the discrepancy between $L_X$ and $\dot{m}$ corresponds to the majority of the liberated gravitational potential energy being advected across the BH event horizon.

Clearly, despite their similarities in being radiatively inefficient accretion configurations, the jet-dominated scenario and the ADAF model are very different. Estimates of the jet power normalization (see above) indicate that, in our opinion, ADAF-like solutions in which most of the available gravitational potential crosses the event horizon are not *required* by the observations. However, uncertainties in the estimates of the jet power normalization, the true accretion rate, etc., mean that it may still be an important, even dominant, channel. Models of radiatively inefficient accretion flows in which powerful outflows are driven (e.g. Blandford & Begelman 1999) may be the most appropriate. It is worth noting that relation $L_J \propto \dot{m}$ is similar or identical to several previous models of jet powering (e.g. Falcke & Biermann 1996; Meier 2001).

### 4.3 The role of the magnetic field

It is a generally accepted idea that very high magnetic fields at the surface of the NSs inhibit the production of *steady* jets (while a large amount of energy can be extracted from magnetic fields to power extremely energetic transient jets as, for example, in the case of the magnetar SGR 1806−20; Gaensler et al. 2005; Cameron et al. 2005). However, besides theoretical arguments, actual observational proofs are missing. The upper limits on previous observations (e.g. Fender & Hendry 2000 and references therein), although significantly lower than radio detections of BH XRBs, are not at all stringent if compared with other NS sources detected in radio and are actually higher than the radio detection levels of atoll sources at the same accretion rate (as traced by the X-ray luminosity). Chakrabarty (2005) suggested that accreting ms X-ray pulsars have a slightly higher magnetic field than other atoll sources. This would suggest that we should see a decreasing radio luminosity (for a given mass accretion rate) from atoll sources to accreting ms X-ray pulsars to high-magnetic-field X-ray pulsars. Note that all the radio detections of the accreting ms X-ray pulsars have been made during the outburst and no information is available of their steady compact jet, whose radio power should be anyway lower than the transient jet detections (see also discussion about ms X-ray pulsars in Migliari et al. 2005). Although high-magnetic-field NS XRBs have not yet been detected in the radio band, their upper limits (the lowest upper limits to date are shown in Fig. 2), are still consistent with the extrapolation at low X-ray luminosities of the radio/X-ray luminosity correlation of the low-magnetic-field NS XRBs. Upcoming radio observations of high-magnetic-field and accreting ms X-ray pulsars will give us the opportunity to test these ideas and quantify the role of the magnetic field in the jets production.

### 4.4 X-ray timing features and radio jet power

There is a correlation between the radio luminosity and the characteristic frequencies of the low-frequency timing components in the X-ray power spectra in NS and BH XRBs (Migliari et al. 2005): the timing features are direct tracers of the radio jet power. The fitting power laws of the correlations between radio luminosity and the characteristic frequencies of the $L_{\rm h}$ Lorentzian component of the power spectrum in NSs and the $L_\ell$ Lorentzian component in the BH GX 339-4 are: $L_{\rm R} \propto \nu_{\rm h}^{1.30\pm0.10}$ and $L_{\rm R} \propto \nu_\ell^{1.37\pm0.02}$.

Timing features are related to accretion disc properties, and in particular kHz quasi-periodic oscillation (QPO) frequencies are generally interpreted as being related to the motion of matter in the accretion disc at a preferential radius, very close to the compact object (see van der Klis 2005 for a review). In XRBs, all the variability components in the power spectra follow a universal scheme, when plotted against the upper-kHz QPO (e.g. Psaltis, Belloni & van der Klis 1999; Belloni, Psaltis & van der Klis 2002; van Straaten et al. 2002; van Straaten, van der Klis & Méndez 2003; Altamirano et al. 2005; Linares et al. 2005), therefore $\dot{m}$ may be in principle inferred also by low-frequency timing features. In particular, a tight correlation exists between the characteristic frequency of the upper-kHz QPO $\nu_{\rm u}$ and $\nu_{\rm h}$ in atoll sources: the best-fitting power law is $\nu_{\rm h} \propto \nu_{\rm u}^{2.43\pm0.03}$ (van Straaten, van der Klis & Wijnands 2005). In jet models, the total power of a steady compact jet is related to the radio power as $L_{\rm R} \propto L_{\rm J}^{1.4}$ (Blandford & Konigl 1979; Falcke & Biermann 1996; Markoff, Falcke & Fender 2001). A linear relation between $L_{\rm J}$ and the mass accretion rate $\dot{m}$ is suggested by the comparative quantitative study of the radio/X-ray luminosity correlations between NS and BH XRBs in the hard X-ray state (see above). If this scaling is correct, $\nu_{\rm h}$ in NSs and $\nu_\ell$ in BHs scale about linearly with $\dot{m}$. Using the $\nu_{\rm h} \propto \nu_{\rm u}^{2.43\pm0.03}$ empirical correlation and $L_{\rm R} \propto \nu_{\rm h}^{1.30\pm0.10}$ found in atoll NSs, we obtain a relation that links about quadratically the upper kHz QPO frequency (possible indicator of the inner disc radius) and the mass accretion rate: $\dot{m} \propto \nu_{\rm u}^{2.16\pm0.20}$.

Furthermore, these relations can be important for a direct comparison to AGN. In particular, the relation between the radio luminosity and the 'break' frequency (Migliari et al. 2005), a timing feature observed also in AGN (e.g. McHardy et al. 2005), opens the possibility of the existence of a 'new fundamental plane' for BHs. Taking into account the mass scaling, we can directly compare stellar-mass and supermassive BHs in a three-dimensional space where the variables are the mass of the BH, the radio luminosity and the frequency of the break component (which is independent from the distance to the source). The existence of another 'fundamental plane' would further support the idea of a unified description of the coupling between disc and jet in BHs of all masses and possibly including also NSs.

### 4.5 Z sources: the NS equivalents of GRS 1915+105

Studying the disc–jet connections in BH XRBs during X-ray outburst events (throughout transitions between X-ray states), Fender et al. (2004a) developed a sketch-model that shows how the accretion disc properties (as traced in X-rays) are connected to the jet

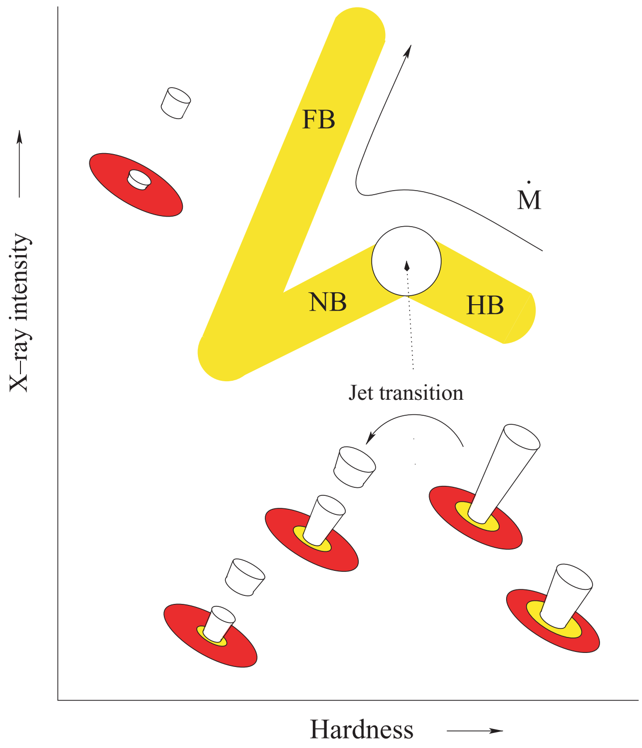


**Figure 6.** Sketch of the disc–jet coupling in Z-type sources, which we believe to be the NS equivalents of the BH GRS 1915+105, constantly accreting at approximately Eddington rates and producing powerful jets associated with rapid state transitions. See Section 4.5 for a discussion.

production (traced with radio). In their picture, sources like GRS 1915+105 are persistently at the 'edge' between the X-ray state in which the source produces a core compact jet (hard state) and the state (VHS or steep power-law state in the nomenclature introduced by McClintock & Remillard 2005) in which the compact jet is disrupted and a radio optically thin flare (associated to a fast ejection of matter) is observed. The semicontinuous crossing of the 'line' between the hard and soft states could explain the sequence of rapid radio flares observed in this source (Fender & Belloni 2004; Fender et al. 2005). Z-type NS XRBs, strongly variable in X-rays, show rapid variability also in the radio band where we observe, besides the approximately steady optically thick emission, frequent optically thin flares (see Fig. 6). These optically thin radio flares are possible signatures of fast ejected plasmons, already observed as extended lobes in Sco X-1 (Fomalont et al. 2001a,b) and Cir X-1 (Fender et al. 1999). Z sources, which are always near or at the Eddington accretion rate, seem to be, like e.g. GRS 1915+105, semicontinuously at the edge between the state in which a powerful core compact jet still exists and the launch of optically thin plasmons that follow the disruption of this compact jet. We might say that Z sources are the NSs 'counterpart' of transient BHs at very high accretion rates.

#### 4.5.1 *A disc–jet coupling for Z-type neutron stars*

In four Z-type NSs (Sco X-1, GX 17+2, Cyg X-2 and GX 5+1), an association between the position on the CD and the radio flux have been reported, the radio flux decreasing from HB to NB to FB (Penninx et al. 1988; Hjellming et al. 1990a,b; with the exception of GX 5+1 for which the radio flux is higher in the NB than in the HB; Tan et al. 1992). Z sources show a variable radio activity, where rapid and powerful flares are often observed besides a more steady radio emission. Sco X-1, in particular, is the only Z source among the four for which the extended radio jets have been spatially resolved moving away form the radio core. Sco X-1 was observed for 56 h on 1999 June 11–13 (MJD 513 40–513 42.5) simultaneously in radio with the Very Long Baseline Interferometer (VLBI) and in X-rays with *RXTE*. The results are reported in Fomalont et al. (2001b; radio analysis) and Bradshaw, Geldzahler & Fomalont (2003; X-ray analysis). These are the most complete observations of a Z source we have to date in order to study the disc–jet coupling. The radio activity of Sco X-1, i.e. the flux and spectral evolution of each of the spatially resolved radio components (core, north-west lobe and south-east lobe), can be monitored in relation to the changes of the X-rays properties (e.g. position on the CD). In the following, we will concentrate on these observations, in particular using figs 3 and 4 in Fomalont et al. (2001b) and table 1 and fig. 1 in Bradshaw et al. (2003), and will attempt to draw a phenomenological disc–jet coupling model accounting for these and the other observations of the Z sources (see Fig. 6).

We follow in detail the evolution of two radio components of Sco X-1, the core and the north-west (NW) extended jet, from MJD 513 40 to MJD 513 42.5 (figs 3c, d and 4a, b in Fomalont et al. 2001b). From table 1 and fig. 1 of Bradshaw et al. (2003), we know that Sco X-1 is mainly in the HB on MJD 513 40, in the NB on MJD 513 41 and in the FB on MJD 513 42.

(i) On MJD 513 40 (HB), the radio flux of the core rises. The radio spectrum is optically thick, indicating that the radio emission likely comes from a compact jet. Contemporaneously, the NW extended jet is fading, meaning that it is still decoupled from the activity of the core jet.

(ii) On MJD 513 40 (NB), the core shows optically thin radio emission, suggesting a renewed transient ejection activity (not yet spatially resolved). Note that Fomalont et al. (2001a) already noted that flares in the core are followed by flares in the NW lobe indicating (unseen) relativistic ejections from the core. Put in another way, what we see in the core is likely the superposition of the optically thick compact jet and of the optically thin emission from discrete plasmon ejections. Making a parallel with the behaviour of BHs where transient jets are associated with X-ray state changes (e.g. Mirabel et al. 1998; Gallo et al. 2003; see Fender et al. 2004a), we can associate the HB-to-NB state change with the ejection of transient jets [in BHs the transient jets are associated with the VHS (or steep power-law state); Fender et al. 2004a]. Around MJD 513 41.5, the flux in the core decreases while the source is in the FB, to increase again in correspondence with the FB-to-NB transition. We do not have dual-frequency monitoring during this period, so we cannot know the nature of the radio spectrum of the flare, although, given the optically thin decay of the flare observable on MJD 513 42, a transient jet activity associated with the FB-to-NB state change as well is a plausible scenario.

(iii) On MJD 513 42 (FB), we observe a decay in the core radio flux with an optically thin radio spectrum. In general, during the FB, the source has been observed to have the lowest radio flux, therefore suggesting a suppression of the (compact) jet and of the transient plasmons ejection activity (the faint optically thin emission we observe is possibly the 'relict' of a transient jet previously ejected).

In Fig. 6, we show the schematic of the disc–jet coupling in Z sources. The typical hardness intensity diagram (HID) of a Z source is sketched as a 'snake' track. The mass accretion rate $\dot{m}$ is thought to increase along the track from HB to FB. Starting from HB, as $\dot{m}$ increases so does the compact jet power. Crossing the HB-to-NB state transition point (circle on the HID track), a transient jet is launched. Meanwhile, the compact jet power decreases. When the source is in the FB, the jet activity is quenched, possibly due to a very high mass accretion rate. The cycle HB–NB–FB–NB–HB lasts no more than a few days. Therefore, Z sources, like GRS 1915+105, are continuously crossing the 'jet transition' point, showing a frequent transient jet activity.

All the other coordinated X-ray/radio observations of Z sources (Penninx et al. 1988; Hjellming et al. 1990a,b; Tan et al. 1992) are consistent with this model. Note that Tan et al. (1992) reported that the radio flux in GX 5+1 is weaker in the HB than in the NB (contrary to the more simple qualitative association between an X-ray state and a radio flux: the radio flux decreasing from the HB to the NB to the FB). Looking at their fig. 1, we can see that, during the observations on 1989 September 1, the source was in a 'very hard' state, i.e. at the bottom right of the HID track in our Fig. 6 (with the lowest $\dot{m}$), where the compact jet was possibly still not very powerful. On 1989 September 4, they observed a powerful radio flare when the source was in the NB where, indeed, we expect (optically thin) flaring activity.

## 5 CONCLUSIONS

Comparing the connections between X-ray and radio properties in NS and BH systems, we have found many similarities and differences, which can be read in terms of physical ingredients for the production of jets.

(i) Below a certain X-ray luminosity, in hard state (i.e. $L_X \leqslant 0.02 L_{Edd}$), both classes of objects seem to make steady, self-absorbed jets; while at higher X-ray luminosities, close to the Eddington limit, bright, optically thin, transient events occur (specifically associated with rapid state changes).

(ii) In the hard X-ray states, correlations between radio and X-ray emission have been found in both BHs and NSs. This indicates that the link between the power of the jet and the innermost regions of the accretion disc does not depend (at least entirely) on the nature of the compact object, but it is related to the fundamental processes of accretion in strong gravity and can be inferred as the mass accretion rate.

(iii) NS XRBs are definitely less 'radio loud' than BH XRBs. At a given X-ray luminosity and at a given fraction of Eddington luminosity, the BHs produce more powerful jets than NSs. The difference in radio power is $\gtrsim$30, which can be reduced to $\gtrsim$7 if we consider possible mass corrections as derived from the fundamental plane of the BHs or to a factor of $\gtrsim$5 if we consider the mass correction coming from the conversion of the 2–10 keV luminosities in Eddington units.

(iv) In contrast to BHs, atoll-type NSs have been detected in radio when steadily in soft X-ray states, suggesting that quenching of jet formation in disc-dominated states may not be so extreme, or that NSs have another channel for producing radio emission.

(v) The slope of the power-law correlation in the hard state of BHs is ~0.7, while for NSs it is steeper (possibly $\gtrsim$1.4)

(vi) A power-law slope greater than 1.4 in NSs implies that NSs never enter a jet-dominated state.

(vii) Both the jet-dominated and ADAF frameworks can naturally explain the difference in the slope of the radio/X-ray luminosity correlations between NSs and BHs, if the total jet power is about linearly proportional to the disc mass accretion rate: $L_J \propto \dot{m}$. In particular, both frameworks derive the same relations between the

X-ray luminosity and the mass accretion rate: $L_X \propto \dot{m}$ for NSs and $L_X \propto \dot{m}^2$ for BHs. This is strong independent evidence that the X-rays in hard state BHs originate in a radiatively inefficient flow, independent of whether the 'missing' energy escapes to infinity in an outflow or crosses a BH event horizon.

(viii) There are correlations between radio luminosity and the characteristic frequency of X-ray timing components in NSs and in BHs: timing features are direct tracers of the radio jet power. Assuming a linear relation between the total jet power and the mass accretion rate, a relation between the characteristic frequency of the upper kHz QPO and the mass accretion rate can be inferred: $\dot{m} \propto \nu_u^{\sim 2}$.

(ix) The role in the production of jets of the magnetic field at the surface of the NS is not clear yet, although it is believed that, the higher the magnetic field, the lower should be the jet power: further radio observations of X-ray pulsars and ms accreting X-ray pulsars are needed to give observational constraints and quantify its role.

(x) Z-type NSs, which are always near or at the Eddington accretion rate, seem to be like GRS 1915+105 semicontinuously at the edge between the state in which a powerful core compact jet still exists and the launch of optically thin plasmons. Following, in particular, detailed simultaneous radio/X-rays observations of Sco X-1, we draw a model that can describe the disc–jet coupling in Z sources, finding a possible association between the HB-to-NB state change and the emission of transient jets.

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