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 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 systems. There are clear qualitative similarities between the two classes of object: hard states below about 1% 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 neutron stars 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 which we observe in black hole systems. Furthermore, in the hard states the correlation between radio and X-ray luminosities of the neutron star systems is steeper than the relation observed in black holes by about a factor of two. This result strongly suggests that the X-ray emission in the black hole systems is radiatively inefficient, with an approximate relation of the form $L_X \propto \dot{m}^2$, consistent with both advection-dominated models and jet-dominated scenario. On the contrary 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 black hole systems. Moreover, based on simultaneous radio/X-ray observations of Z-type neutron stars (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 brach-to-normal branch) and the emission of transient jets.

Key words: binaries: close – stars: binaries – 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 to 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 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) timescales 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 black hole 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 three orders of magnitude in X-rays, when the BHs are in 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 percent 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), 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. very-high (VHS) or steep power-law state] is associated with radio flares which 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 & Rodríguez 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 (2004).

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 3D 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 \( L_R \propto L_X^{0.6} M^{0.8} \) 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 in which a single 3D power-law function can fit all the BH data (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 black holes 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, in 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 neutron stars accreting at relatively low rates (compared to the Z sources) rather oversimplifies the more complex classifications of e.g. ’burster’, ’dipper’, etc., but is appropriate for the discussion in this paper. Fig. 1 summarises 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 which form the Z-shaped CD are called Horizontal (HB), Normal (NB) and Flaring (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, transitioning 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 HB to NB (Hasinger & 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 HB (strongest radio emission) to 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 et al. 2001a) and Cir X-1 (Fender et al. 1998). In this two sources there is also evidence for an association between radio flares and powerful (ultra-relativistic) ejections from the system (Fomalont et al. 2001b; Fender et al. 2004).

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 X-ray binaries, 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; Munro 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 et al. 2004; Rutledge et al. 1998; Moore et al. 2000). 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 observed in BHs (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 per cent Eddington, showing that its radio behaviour is much more similar to Z sources.

Two accreting ms X-ray pulsars, SAX J1808.4-3658 (e.g. Gaensler, Stappers & Gotts 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 X sources. In the context of the general picture of low magnetic field neutron stars, 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 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 which 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.

#### 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) has been observed in 2004, on March 31 and April 03 for a total of ~12 hr 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 flux calibrator and 1646-50 as phase calibrator. At the best (X-ray) coordinates, RA 16h12m43.0 Dec -52°25’23” , we did not detect the radio counterpart with a 3σ radio flux density upper limit of $F < 0.19$ mJy. The source was in a quiescent (hard) X-ray state with a mean (two-day average) count rate of 3.21 ± 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 have been estimated converting the ASM count rates to Crab based on Levine et al. (1996: 1 Crab=75 c/s) 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) has been observed on 2001 April 24 for 12 hr with the Westerbork Synthesis Radio Telescope (WSRT) at 5 GHz. We have analysed the data with the package MIRIAD, using 3C286 as flux calibrator. At the best (optical) coordinates, RA 06h17m07.3 Dec +09h08 13, we did not detect the radio counterpart with a 3σ 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 ± 0.81 c/s.

The XRB pulsar X Per (the nearest known, at a distance of only 0.7 ± 0.3 kpc) has been observed on 2004 November 25 for 12 hr with the Westerbork Synthesis Radio Telescope (WSRT) at 1.4 GHz. We have analysed the data with the package MIRIAD, using 3C286 as flux calibrator. At the best (optical) coordinates, RA 03h55m23.0 Dec +31°02’45”.0, we did not detect the radio counterpart with a 3σ radio flux density upper limit of $F < 0.08$ mJy. The simultaneous one-day averaged RXTE/ASM count rate was 1.61 ± 0.34 c/s.

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

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 black holes (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 ~10$^{37}$ 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 $R > 1.4 \times 10^{13}$ cm, likely to be larger than the binary stars separation (typical low-luminosity (10$^{36} - 10^{37}$ erg/s) low-mass XRBs have stars separations smaller than ~3 × 10$^{13}$ 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).

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 (~1.3 × 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).

Aql X-1: Rupen et al. (2004) reported a radio transient emissions in Aql X-1 associated with an X-ray, optical and 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 GHz and 5 GHz, give 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 $\alpha \sim -0.6$).
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; references

| Source       | X-ray state | F$_{2-10}$ ($\times 10^{-6}$ erg cm$^{-2}$ s$^{-1}$) | F$_{8.5}$ (mJy) | D (kpc) | Ref.       |
|--------------|-------------|-----------------------------------------------|----------------|--------|------------|
| 4U 1728-34   | LB          | 1.03 ± 0.05                                   | 0.5 ± 0.08     | 4.6    | M03,G03    |
| IS           | 2.25 ± 0.15 | 0.6 ± 0.2                                     |                |        |            |
| LB           | 1.54 ± 0.10 | 0.33 ± 0.15                                   |                |        |            |
| IS           | 1.81 ± 0.11 | 0.62 ± 0.1                                    |                |        |            |
| IS           | 2.42 ± 0.16 | 0.11 ± 0.02                                   |                |        |            |
| IS           | 0.60 ± 0.07 | 0.09 ± 0.02                                   |                |        |            |
| IS           | 0.61 ± 0.06 | 0.11 ± 0.02                                   |                |        |            |
| IS           | 0.62 ± 0.06 | 0.15 ± 0.02                                   |                |        |            |
| IS           | 0.69 ± 0.12 | 0.16 ± 0.02                                   |                |        |            |
| IS           | 0.70 ± 0.05 | 0.09 ± 0.02                                   |                |        |            |
| 4U 1820-30   | MB          | 8.7                                           | 0.10 ± 0.02    | 7.6    | M04,H00    |
| Ser X-1      | MB          | 4.4                                           | 0.08 ± 0.02    | 12.7   | M04,JN04   |
| Adl X-1      | H-OUTB      | 0.79                                          | 0.210 ± 0.050  | 5.2    | RMD04,JN04 |
| H-OUTB       | 1.00        | 0.214 ± 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 ± 0.030  | 8.8    | R98,M00,K03|
| S-OUTB       | 3.06        | 0.290 ± 0.030                                 |                |        |            |
| S-OUTB       | 5.34        | 0.330 ± 0.050                                 |                |        |            |
| **Low-magnetic field accreting ms X-ray pulsars** |
| SAX J1808.4-3658 | S-OUTB | 0.14 | 0.8 ± 0.18 | 2.5 | GSG99,Z01,R02,R05 |
| S-OUTB | 1.82 | 0.44 ± 0.06 | 2.5 |            |
| S-OUTB | 0.56 | 0.44 ± 0.07 | 2.5 |            |
| IGR J002914+5934 | S-OUTB | 0.62 | 1.5 ± 0.3 | < 3? | G05,P04 |
| **Z-type NSs** |
| Sco X-1 | ASM mean | 253.80 | 10 ± 3 | 2.8 | FH00,P89,C76,BFG97 |
| GX 17+2 | ASM mean | 12.90 | 1.0 ± 0.3 | 14 | FH00,P89,P88,JN04 |
| GX 349+2 | ASM mean | 14.39 | 0.6 ± 0.3 | 5 | FH00,C91,C97 |
| Cyg X-2 | ASM mean | 10.75 | 0.6 ± 0.2 | 13.3 | FH00,P89,H00,C797,JN04 |
| GX 5-1 | ASM mean | 20.36 | 1.3 ± 0.3 | 9.2 | FH00,P89 |
| GX 340+0 | ASM mean | 8.54 | 0.6 ± 0.3 | 11 | FH00,P93 |
| GX 13+1 | PCA mean | 18 | 1.8 ± 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 |

Refs: 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, Mioduszewski & Dhawan 2004; MF05=Migliari & Fender 2005, in prep.; 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, Stappers & Getts 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; P88=Penninx et al. 1988; CP91=Cooke & Ponman 1991; CS97=Christian & Swank 1997; H90=Hjellming et al. 1990; C79=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.

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. (2003), and the X-ray flux calculated from simultaneous RXTE/ASM (2-10 keV) daily-averaged observations.

**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 GHz 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 Reynolds et al. (1998) and the distance in Kuulkers et al. (2003) and references therein.

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

**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 × 10$^{19}$ cm, larger than the binary stars separation (Chakrabarty & Morgan 1998). In Table 1 we show radio flux
densities reported in Gaensler et al. (1998) and the estimated distance from in’t Zand et al. (2001). Rupen et al. (2002 and 2005) reported radio detections at 8.5 GHz during the X-ray outbursts on 2002 October 16 and on 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/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 ~ 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_H = 4 × 10^{21} cm^{-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 α = −0.6.

2.4 Other high-magnetic field NS XRBs

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. VLA observations at 8.5 GHz did not detect the radio counterpart with a 3σ upper limit of 0.039 mJy. In Table 1 we report the distance from Negeruela & 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 Dec 14, 2004. The mean radio flux is from Fender & Hendry (2000). Note that, even though the classification of GX 13+1 as either 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 J1550-566, RX J339-4, V4641 Sgr, Cyg X-1 and XTE J1748-228] from Fender et al. (2004 and references therein). We used the values for distance and radio and X-ray luminosities listed in Table 1 in Fender et al. 2004; the radio flux densities at 5 GHz has been converted to flux densities at 8.5 GHz, assuming a radio spectral index α = −0.6, and the fraction of X-ray Eddington luminosity at the peak of the outburst in the very-high state has been converted to 2-10 keV luminosity, assuming that the latter is 80% of the bolometric flux (see §2.7).

2.7 Persistent BH XRBs

For clarity, we plot in Fig. 2 only GX 339-4 as a sample of BH XRBs in hard state (for a complete sample of BH XRBs see Gallo et al. 2003). We used fluxes form 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 in 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-fit model parameters for the PCA-HETXT energy spectra to create a simulated spectrum with expec. 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 HETGS (MEG) response matrix and ancillary file to extend the range below 3 keV, down to 0.5 keV, 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 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. (2004). The conversion to Eddington units is given dividing the bolometric luminosity by 1.3 × 10^{38} (M/M_⊙) erg/s, where M=1.4 M_⊙ for all the NSs, while for the BHs we used the masses listed in Table 1 of Fender et al. (2004). The bolometric luminosity will be F_{2-10} = F_{bol} × ξ, where we used ξ=0.2 for BHs in the hard state, ξ=0.8 for BHs during X-ray outbursts, ξ=0.4 for atoll sources in the hard state, ξ=0.7 for atoll sources in the soft state and ξ=0.8 for Z sources: the actual L_{2-10 keV}/L_{bol} ratio of the single observations are always within 10% of these ξ 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 Γ = 0.66 ± 0.07 (where L_R ∝ L_X^{Γ}).

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 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 av-
Figure 2. Radio (8.5 GHz) luminosity as a function of X-ray (2-10 keV) luminosity of NS XRBs: atoll sources in 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 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 X-ray binaries and the radio upper limits) with a slope of $\Gamma \sim 0.7$ (see §3.1).

Atoll sources steadily in soft state (filled stars) have been detected in radio. This is contrary to what 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 neutron star 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 hard state (as in persistent and transient BHs; see Fender et al. 2004).

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 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 millisecond X-ray pulsars is presented in Migliari, Fender & van der Klis (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 NS are significantly fainter in the radio band than ‘normal’ atoll sources, when at relatively low (< $10^{-2}$ Eddington) luminosities.

### 3.2 Neutron stars vs. 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 black holes related exclusively to the properties of the accretion flow, or also to some property unique to black holes? Clearly we may attempt to address this question by comparing the X-ray : radio coupling in NS XRBs with that of BH in XRBs, and AGN.

Observationally, there are clear qualitative similarities in the disc-jet coupling between neutron stars and black holes (see Fig.4 and Fig.5):

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

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

- The neutron stars in the hard state appear to show a steeper dependence of $L_R$ on $L_X$, also with a lower normalisation in $L_R$.
- The neutron stars do not appear to show anywhere near as much suppression of radio emission in steady soft states as the black holes.

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 $\sim 10^{-4}$ for the observations in the hard state only (i.e. GX 339-4 vs. 4U 1728-34 and Aql X-1) and $\sim 10^{-5}$ using the whole sample. This indicates 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' \(\langle L_R \propto M^{1.8}\rangle\); Merloni et al. 2004), the neutron stars remain stubbornly less radio-loud than the black holes for a given X-ray luminosity. Bolometric corrections are however 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. 2004) have already shown that the (often accepted) ‘escape velocity’ paradigm, which states that the jets’ velocity 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 BHs are not necessary for the production of relativistic jets. However, characteristics proper 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 low/hard / hard-atoll states. Comparison of the fits to the NS and BH samples indicates that at $L_X \sim 0.02$, the ratio of radio luminosities is $\sim 30$. As noted in Migliari et al. (2004), assuming a scaling $L_R \propto L_X^{1.4}$ this indicates that neutron star jets are about one order of magnitude less powerful than black hole 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 $L_{radio} \propto L_X^n$) 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 $L_R \propto L_X^{1.4}$, we get

- **BH** $L_J \propto L_X^{0.5}$
- **NS** $L_J \propto L_X$

where the quadratic relation for the black holes was already presented in Fender, Gallo & Jonker (2003). The linear relation between jet and X-ray powers in the NS sample implies that neutron star 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 $\dot{m}$ which is different in the two samples, as we shall outline below.

Assuming that the relation between $L_J$ and 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 black holes, we arrive at

- **BH** $L_J \propto L_X^{0.5} \propto \dot{m}$

This is exactly the prescription presented in Fender, Gallo & Jonker (2003) for jet-dominated states in X-ray binary 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 a ‘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 normalisations of $A_{\text{steady,BHC}} = 0.1$, $A_{\text{steady,NS}} = 0.01$ (where $L_J = A \times L_X^{1/4}$; Fender, Gallo & Jonker 2003; Fender, Maccarone & van Kesteren 2005). The value of $A_{\text{steady,BHC}} = 0.1$ corresponds to equipartition between jet and X-ray powers at around the soft $\to$ transition luminosity of $L_X,_{\text{trans}} \sim 0.02$. This is a larger normalisation than the conservative lower limit presented in Fender, Gallo & Jonker (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 X-ray binaries (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, Gallo & Jonker (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).

However, the result that for the BH \(L_X \propto \dot{m}^2\) is generically indicative of \textit{radiatively inefficient} accretion in the black hole 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, since 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 black hole 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 normalized accretion configurations, the jet-dominated scenario and the event horizon are not yet been detected in the radio band, their upper limits (the low-\(\dot{m}\) case) are very different. Estimates of the jet power normalized accretion configurations, the jet-dominated scenario and the event horizon are still consistent with upper limits to date are shown in Fig. 2), are still consistent with 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 / 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 general accepted idea that very high-magnetic fields at the surface of the NSs inhibit the production of \textit{steady} jets (while a large amount of energy can be extracted from magnetic fields to power extremely energetic transient jets, as e.g. in the case of the magnetar SGR 1806-20; Gaensler et al. 2005; Cameron et al. 2005). However, besides theoretical arguments, actual observational proves 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 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 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. Up-coming 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 \(L_\nu\) Lorentzian component of the power spectrum in NSs and the \(L_\nu\) Lorentzian component in the BH GX 339-4 are: \(L_{\nu} \propto \nu_{\text{h}}^{1.30\pm0.10}\) and \(L_{\nu} \propto \nu_{\text{u}}^{1.37\pm0.02}\).

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 2004 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 & Mendez 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 \(\nu_{\text{h}}\) and \(\nu_{\text{h}}\) in atoll sources: the best-fit power-law is \(\nu_{\text{h}} \propto \nu_{\text{a}}^{-2.43\pm0.03}\) (van Straaten, van der Klis & Wijnands 2005). In jet models, the total power of a steady compact jets is related to the radio power as \(L_{\nu} \propto \nu_{\text{h}}^{1.30\pm0.10}\) (Blandford & Königl 1979; Falcke & Biermann 1996; Markoff, Falcke & Fender 2001).

A linear relation between \(L_{\nu}\) 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 hard X-ray state (see above). If this scaling is correct, \(\nu_{\text{h}}\) in NSs and \(\nu_{\text{h}}\) in BHs scale about linearly with \(\dot{m}\). Using the \(\nu_{\text{h}} \propto \nu_{\text{a}}^{-2.43\pm0.03}\) empirical correlation and \(L_{\nu} \propto \nu_{\text{h}}^{1.30\pm0.10}\) found in atoll NSs, we obtain a relation that link about quadratically the upper kHz QPO frequency (possible indicator of the inner disc radius) and the mass accretion rate: \(\dot{m} \propto \nu_{\text{a}}^{2.16\pm0.20}\).

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 black holes in a three-dimensional space where the variables are the mass of the black hole, 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 disk and jet in black holes 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. (2004) developed a sketch-model which shows how the accretion disc properties (as traced in X-rays) are connected to the jets 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 [very-high state 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 (associ-
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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 from the radio core. Sco X-1 has been observed for 56 hr on June 11-13, 1999 (MJD 51340 – 51342.5) 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 Fig. 3 and Fig. 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 Z sources’ observations (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 51340 to MJD 51342.5 (Fig. 3c,d and Fig. 4a,b in Fomalont et al. 2001). From Table 1 and Fig. 1 of Bradshaw et al. (2003) we know that Sco X-1 is mainly in the HB on MJD 51340, in the NB on MJD 51341 and in the FB on MJD 51342.

- On MJD 51340 (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.
- On MJD 51340 (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. 1999; Gallo et al. 2003; see Fender et al. 2004), 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. 2004]. Around MJD 51341.5, the flux in the core decreases while the source is in the FB, to increase again in correspondence of the FB-to-NB transition. We do not have a 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 51342, a transient jet activity associated with the FB-to-NB state change as well is a plausible scenario.
- On MJD 51342 (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 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.

![Figure 6](image-url)
All the other coordinated X-ray/radio observations of Z sources (Fenninx 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 September 1, 1989, the source was in a ‘very hard’ state, i.e. at the bottom right of the HID track in our Fig. 5 (with the lowest \( \dot{m} \)), where the compact jet was possibly still not very powerful. On September 4, 1989, 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, that 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. \( L_X \lesssim 0.02L_{\text{Edd}} \)), 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-rays 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 disk 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) Neutron star X-ray binaries are definitely less ‘radio loud’ than black hole X-ray binaries. 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 black holes’ fundamental plane 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) Contrary 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 neutron stars have another channel for producing radio emission.

v) The slope of the power-law correlation in the hard state of BHs is \( \sim 0.7 \), while for NSs 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 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 black holes originate in a radiatively inefficient flow, independent of whether the ‘missing’ energy escapes to infinity in an outflow or crosses a black hole 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: \( \dot{m} \propto \nu_{\text{QPO}}^{-2} \).

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 millisecond 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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