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# Jets from black hole X-ray binaries: testing, refining and extending empirical models for the coupling to X-rays

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## ABSTRACT

In this paper we study the relation of radio emission to X-ray spectral and variability properties for a large sample of black hole X-ray binary systems. This is done to test, refine and extend – notably into the timing properties – the previously published 'unified model' for the coupling of accretion and ejection in such sources. In 14 outbursts from 11 different sources we find that in every case the peak radio flux, on occasion directly resolved into discrete relativistic ejections, is associated with the bright hard to soft state transition near the peak of the outburst. We also note the association of the radio flaring with periods of X-ray flaring during this transition in most, but not all, of the systems. In the soft state, radio emission is in nearly all cases either undetectable or optically thin, consistent with the suppression of the core jet in these states and 'relic' radio emission from interactions of previously ejected material and the ambient medium. However, these data cannot rule out an intermittent, optically thin, jet in the soft state. In attempting to associate X-ray timing properties with the ejection events we find a close, but not exact, correspondence between phases of very low integrated X-ray variability and such ejections. In fact the data suggest that there is not a perfect one-to-one correspondence between the radio, X-ray spectral or X-ray timing properties, suggesting that they may be linked simply as symptoms of the underlying state change and not causally to one another. We further study the sparse data on the reactivation of the jet during the transition back to the hard state in decay phase of outbursts, and find marginal evidence for this in one case only. In summary we find no strong evidence against the originally proposed model, confirming and extending some aspects of it with a much larger sample, but note that several aspects remain poorly tested.

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

## 1 INTRODUCTION

Accreting stellar-mass black holes in binary systems display different accretion 'states', characterized primarily by different X-ray spectral and variability properties (e.g. Nowak 1995; Homan et al. 2001; Homan & Belloni 2005, hereafter HB05; Remillard & McClintock 2006; Done, Gierlinski & Kubota 2007; Klein-Wolt & van der Klis 2008; Belloni 2009). Understanding empirically the relation of these states to the formation of powerful relativistic outflows, or jets, is a key goal for more detailed theoretical understanding of the coupled accretion–jet formation processes (e.g. Meier 2001; Livio, Pringle & King 2003; Ferreira et al. 2006). It also allows us to estimate the kinetic feedback to the ambient medium (e.g. Heinz & Sunyaev 2002; Fender, Maccarone & van Kesteren 2005), and to make direct comparisons with supermassive black holes in active galactic nuclei (AGN; e.g. Merloni, Heinz & di Matteo 2003; Falcke, Körding and Markoff 2004; Falcke & Biermann 2006; Körding, Jester & Fender 2006; Fender 2008).

In (Fender, Belloni & Gallo 2004, hereafter FBG04; see also Fender & Belloni 2004) we outlined a unified picture for the disc–jet coupling in black hole X-ray binaries, where 'disc–jet' should be taken as shorthand for the relation between the infall and outflow of matter around the compact object, in all its various proposed geometries (and 'disc' not taken to simply mean the optically thick, geometrically thin, variety of accretion flow). This was based primarily on the relation between X-ray and radio emission in four well-studied systems. In very brief summary, although we recommend the interested reader to read FBG04, the model's major components are as follows.

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(i) A steady, powerful, relatively low bulk velocity (bulk Lorentz factor $\Gamma \leq 2$) jet is always present in the canonical hard X-ray state.

(ii) As a source makes a hard to soft X-ray state transition, the jet becomes initially unstable and then produces a major flare which in some cases has been directly resolved into a major relativistic ejection event (with $\Gamma \geq 2$). The point at which this occurs in the X-ray hardness–intensity diagram (HID; see below) is referred to as the 'jet line'. The inferred origin for the flaring is internal shocking as this faster, transient jet runs into the pre-existing slower jet from the hard state.

(iii) Subsequently in the soft X-ray state the core jet is off, or at least much weaker.

(iv) In the soft to hard transition in the latter phases of the outburst the steady hard state jet reforms without a major flare (no slower jet in front to run into).

(v) In trying to understand these observational conclusions, it was suggested that the 'jet line' corresponded to the point at which an inwards-moving inner disc edge reached the innermost stable circular orbit (ISCO).

Empirical aspects of this model were confirmed for a different system in Corbel et al. (2004). In this paper we take a far larger sample of black hole X-ray binary outbursts and use them to test and refine the model of FBG04 in the context of X-ray spectral states. In addition, we extend the model by making for the first time a comprehensive attempt to include the X-ray short-time-scale variability properties of the systems.

## 2 DATA ANALYSIS

### 2.1 X-rays

The X-ray data presented in this paper were obtained with the Proportional Counter Array (PCA) onboard the *Rossi X-ray Timing Explorer* (*RXTE*). In our analysis we make extensive use of the HID as an indicator of the X-ray spectral state of a black hole binary in outburst. The HIDs presented here were taken from Homan et al. (in preparation). They were constructed from standard-2 mode data from the PCA. These data were corrected for background, but not for dead time (typically a few per cent). Averaged count rates were extracted for each observation in three bands: channel 20–40, 3–10 and 1–129, roughly corresponding to 9.5–17.0, 2.8–5.5 and 2–60 keV, respectively. The ratio of the count rates in first two bands was used as an indicator of the spectral hardness and the third band as the broad-band intensity. In case fast intensity or hardness variations were observed within an observation, the observation was split into two or more parts and hardness and intensity were calculated for each individual part.

In addition to HIDs we also studied the X-ray variability properties of all sources. Again, these data were taken from Homan et al. (in preparation). Power spectra were constructed from high-time-resolution data from the PCA, using most of the PCA energy range and following standard fast Fourier techniques (see e.g. Homan et al. 2005a for a detailed description). As a measure of the strength of the X-ray variability we extracted the rms-normalized power from the 0.01–64 Hz frequency range, for each observation (or observation segment).

### 2.2 Radio

Radio data presented in this paper were gathered exclusively from the literature, and references are provided in the brief descriptions for each outburst in Section 3.

## 3 RADIO FLARES AND EJECTION EVENTS IN THE CONTEXT OF OUTBURST EVOLUTION

As noted above, in the following analysis we use HID as an indicator of the X-ray spectral state of a black hole binary in outburst. This is the framework within which the analyses of FBG04, HB05 and others were also set. In the HID the vertical axis simply corresponds to X-ray count rate within some band, and the horizontal axis to the 'hardness', or ratio of counts measured in two narrower subbands, such that 'harder' spectra (those with a relatively higher proportion of high-energy to low-energy X-rays within the band) are on the right-hand side, and 'softer' spectra are on the left-hand side. Black hole and neutron star binaries (and maybe also white dwarfs) are known to demonstrate hysteresis in the tracks they trace in such diagrams during outburst, typically making hard to soft transitions at higher luminosities than the return soft to hard transition (FBG04; HB05; Koerding et al. 2008). Section 2.1 (above) gives the X-ray bands used for the hardness ratios in this paper.

In Fig. 1 we present HIDs for 14 outbursts from 11 different black hole X-ray binaries, annotated with symbols indicating times of radio detections, radio flares and times when the radio counterpart was undetectable. Note that we do not discriminate between levels of radio emission in these figures: it is either detected, a special case of which is the peak flux, or it is not. Nevertheless this is enough to give us a good test of the scenario presented in FBG04. In the following we describe the systems and their outbursts individually, in the order in which they are presented in Fig. 1. Note that while there are more *RXTE* data on black hole outbursts than those which are presented here, (i) these were all the outbursts for which we had useful X-ray and/or radio coverage, (ii) we are not aware of any other data set of results which contradict the empirical conclusions drawn here.

### 3.1 GRO J1655−40

This black hole binary is famous as the second known superluminal source in the galaxy (Hjellming & Rupen 1995; Tingay et al. 1995). The 1994 outburst with which these superluminal ejections were associated was not covered by *RXTE* (which was launched in 1995 December), but two subsequent outbursts, in 1996 and 2005, have been well covered in X-rays.

#### *3.1.1 1996*

Radio coverage of this outburst was poor, but comparing a Very Long Array (VLA) non-detection (<3 mJy) and a subsequent *MOST* detection at level of 55 ± 5 mJy (843 MHz) indicates that a radio flare (i.e. probable ejection event) occurred somewhere between 1996 May 20 and 28 (MJD 50223–50231). This radio flare occurred about half way in the transition between hard and soft X-ray states.

#### *3.1.2 2005*

The radio and *RXTE* coverage of this outburst was much better than in 1996. The source traces a clear pattern in the HID. Radio observations with the VLA were reported in Rupen, Dhawan & Mioduszewski (2005a,b,c,d,e,f,g,h). The relatively weak radio peak occurred during a phase of X-ray flaring during the hard to soft transition.

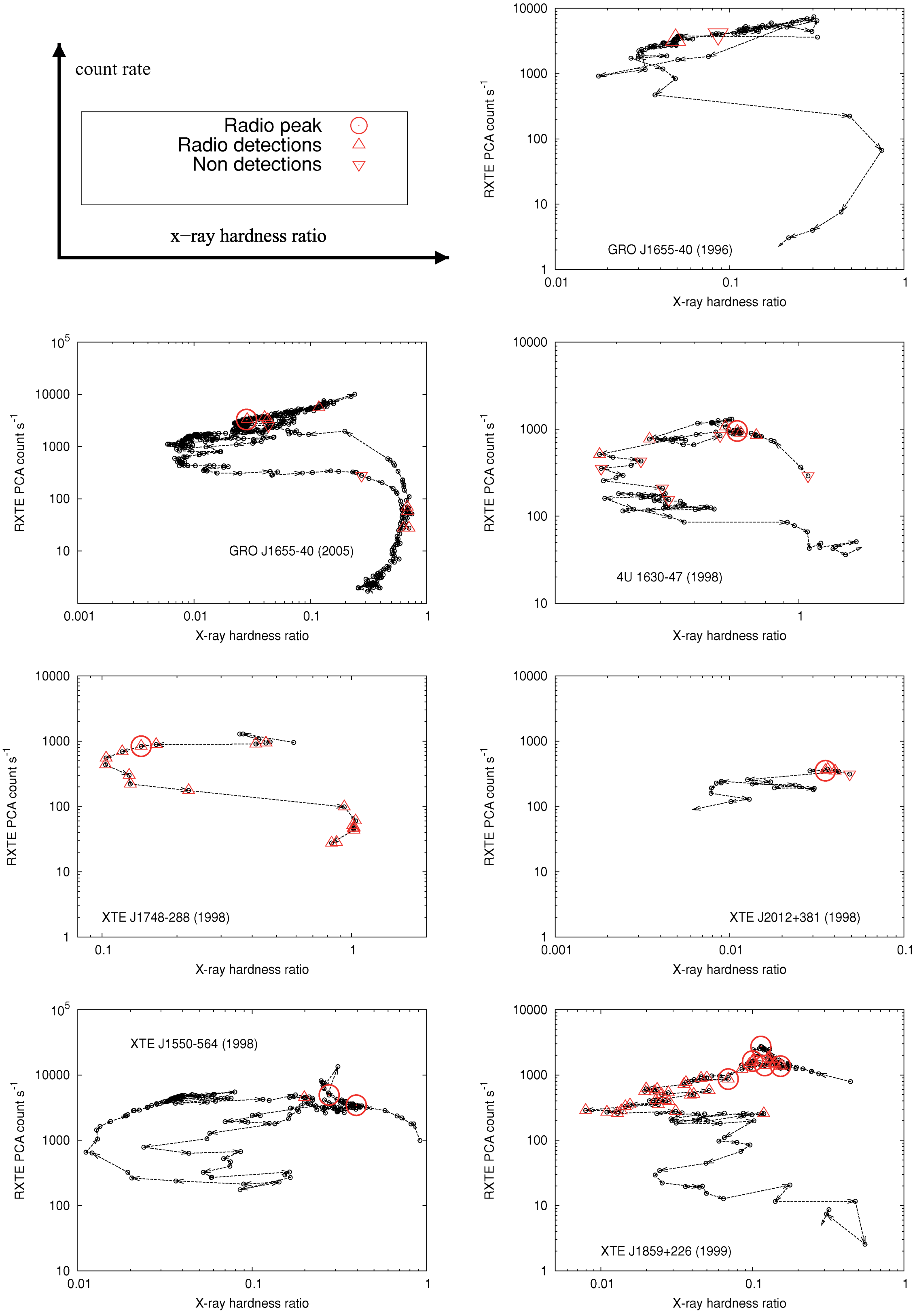

**Figure 1.** HIDs for black hole X-ray binary outbursts. The key at the top left indicates the symbols for radio detection, radio peak and radio upper limit, which are plotted on top of the HIDs at the location of the nearest *RXTE* X-ray observation, usually within 24 h. In some cases there are clear distinct radio peaks which probably correspond to individual ejection events, and so multiple radio peaks are indicated.

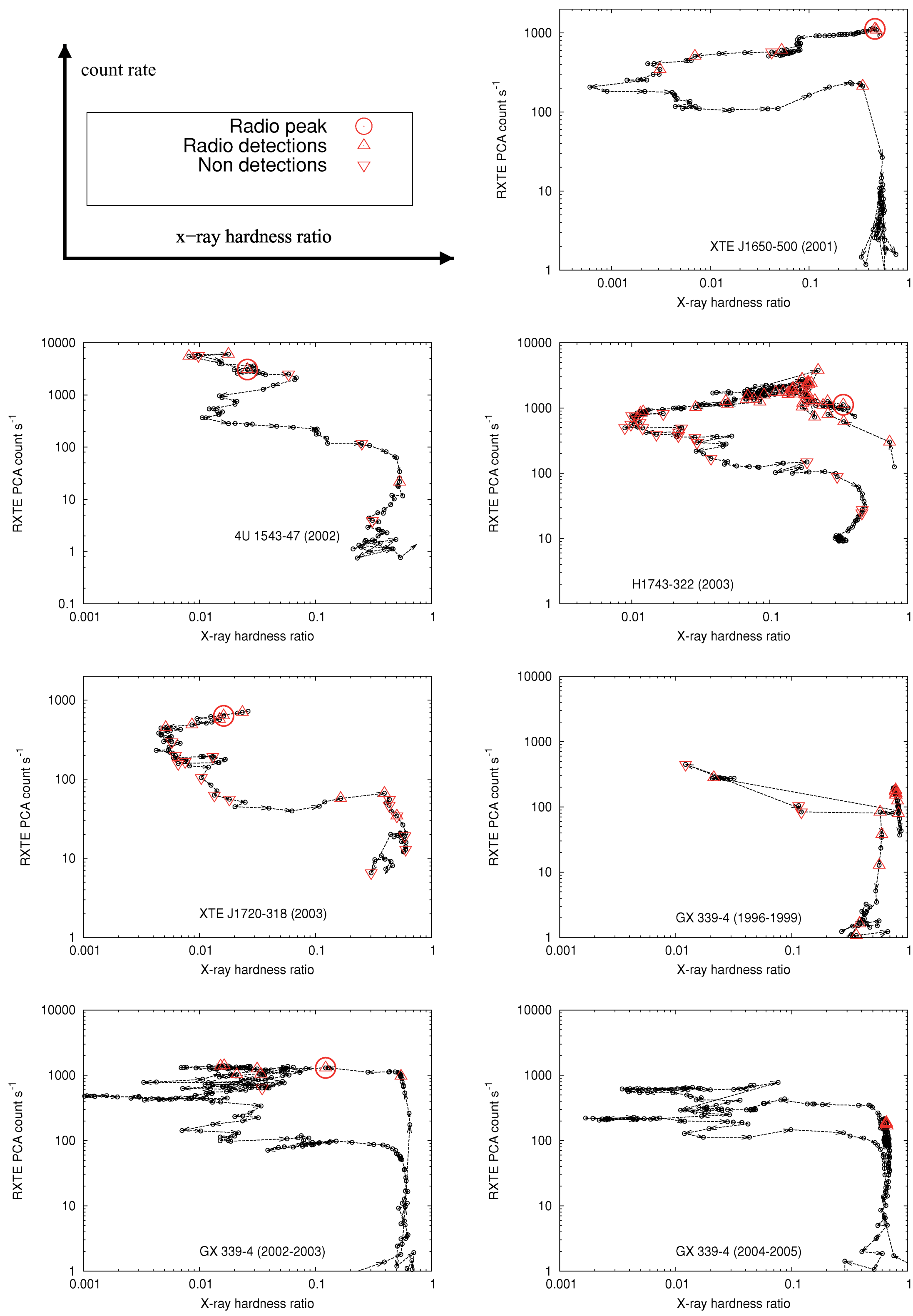

**Figure 1** – *continued*

### 3.2 4U 1630−47

The recurrent black hole transient 4U 1630−47 has undergone five outbursts between 1996 and 2005. The source has been identified with a weak radio counterpart (Hjellming et al. 1999) but is not always detected (Gallo et al. 2006). In Fig. 1 we present a HID for the 1998 outburst of the source, which has the best radio coverage (Hjellming et al. 1999). As with most sources, a jet has not been directly resolved in this source, so we can only rely upon the peak flux as an approximate indicator of an ejection event. This peak flux occurs about half way, in terms of relative X-ray spectral hardness, between the canonical hard and soft (or thermal dominant) X-ray states, around MJD 50861. By back-extrapolating the radio light curve, Hjellming et al. (1999) estimated a probably ejection date of ∼MJD 50851, 10 d earlier than this flare.

### 3.3 XTE J1748−288

This source underwent a bright and prolonged X-ray outburst with complex radio behaviour in 1998. Analysis of the radio flux and images has recently been undertaken in Brocksopp et al. (2007) and Miller-Jones et al. (in preparation). The peak radio flux is clearly during the hard to soft transition, but radio emission was essentially detected every time the source was observed throughout the entire period of the bright X-ray outburst. Observations with the VLA (Hjellming, Rupen & Mioduszewski 1998b; Hjellming et al. 1998c; Miller-Jones et al., in preparation) clearly show that a lot of this is due to resolved component which appear to interact with the environment and/or each other. Note that extrapolating the early proper motions of the resolved maps in Miller-Jones et al. (in preparation) indicates that the first ejection took place before the first X-ray observations, which may in principle have still been in the canonical low/hard state. The equally plausible alternative is that the initial proper motions were much higher, and the ejecta decelerated as they interacted with the interstellar medium (ISM; as in e.g. XTE J1550−564; Corbel et al. 2002).

### 3.4 XTE J2012+381

XTE J2012+381 is a black hole candidate X-ray transient that went into outburst in 1998 (e.g. Campana et al. 2002). The *RXTE* coverage is sparse. Hjellming, Rupen & Mioduszewski (1998a) and Pooley (1998) report on a weak but variable radio counterpart. The variability reported by Pooley (1998) may indicate an ejection around May 30 (MJD 50963).

### 3.5 XTE J1550−564

XTE J1550−564 is a fascinating source with a wealth of interesting properties in terms of its disc–jet coupling, including powerful, moving, X-ray jets (Corbel et al. 2002) and large loops in the HID (Fig. 1). Hannikainen et al. (2001) report very long baseline interferometry (VLBI) images of relativistic jets following a major flaring event around MJD 51078, with strong evidence for a secondary core ejection event around MJD 51080; Homan et al. (2001) report a bright, optically thin radio source around MJD 51248. These dates are indicated in Fig. 1. Note that there several unpublished radio observations of this outburst which may in the future shed some further light on the evolution of this outburst.

### 3.6 XTE J1859+226

XTE J1859+226 is a source for which there was both good X-ray and radio coverage around the brightest phases of the outburst (see e.g. Casella et al. 2004 for an X-ray study of the outburst). Radio data for this bright outburst are from Brocksopp et al. (2002), who noted five radio flare events in a sequence of declining strength (reminiscent of those seen in GRS 1915+105 e.g. Fender et al. 1999). All five radio flare events occur during a prolonged period of X-ray flaring around the middle of the hard to soft transition, with the strongest of these happening at the time of a local peak in the X-ray intensity. Fig. 2 presents a close-up of the HID around the time of these five flare events. All of these events occur around the same hardness, with the greatest outlier being revealed as associated with a brief and rapid hardening of the X-ray spectrum of total duration ≤1.8 d. This is explored in more detail in the discussion (see Fig. 2).

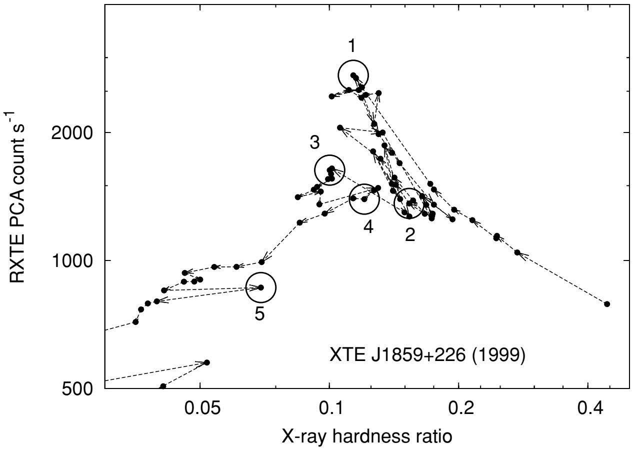

**Figure 2.** Closer inspection of the period of repeated flaring in XTE J1859+226 in 1999. Only the five flare peaks from Brocksopp et al. (2002) have been indicated, not all the radio detections (see Fig. 1). Arrows indicate the direction of motion in the HID; numbers indicate the sequence of events and correspond to those in fig. 4 of Brocksopp et al. (2002). All of the flare events are associated with a very similar X-ray colour. The apparent outlier at the softest colour (flare 5) is revealed to be associated with a very rapid (total duration ≤1.8 d) excursion to a harder state.

### 3.7 XTE J1650−500

Corbel et al. (2004) present a detailed discussion of the Australia Telescope Compact Array (ATCA) radio observations of this source during its 2001 outburst. The peak radio flux is detected close to the start of the hard to soft transition, although there is subsequently a lack of radio observations for 15 d and the true peak may have been missed. Subsequently the radio emission is found to be temporarily undetectable, but then to re-emerge in the soft state.

### 3.8 4U 1543−47

Park et al. (2004) and Kalemci et al. (2005) report in detail multiwavelength observations of this recurrent transient. In particular, Park et al. (2004) detected a rapidly rising radio flare on MJD 52443. During the decay of the outburst, radio emission is observed to reactivate by MJD 52487, a week after the MJD 52480 date that Kalemci et al. (2005) report for the soft to hard state transition, based on timing as well as spectral properties.

### 3.9 H1743−332

The 2003 outburst of this recurrent transient received excellent radio and X-ray coverage, as reported in McClintock et al. (2009). The HID reveals a peak in the radio emission near the start (i.e. hard side) of the hard to soft transition (as in XTE J1859+226 this is associated with a phase of X-ray flaring), with many more detections in the intermediate and initial soft states before a large number of upper limits in the later soft state and during the soft to hard transition.

### 3.10 XTE J1720−318

Brocksopp et al. (2005) report radio coverage of this outburst. The peak observed radio emission occurs around MJD 52655, at which point the source is already in a rather soft state. Subsequently there are a number of non-detections in the soft state. Brocksopp et al. (2005) also report that the radio emission in this source appears to switch back on between MJD 52715 and 52728 (increasing by a factor of at least 2 despite a more or less steady level of X-ray emission), with two further detections at comparable levels. This may be the best case to date for the reactivation of the jet during the soft to hard transition (see further discussion below).

### 3.11 GX 339−4

GX 339−4 has been a key source in our understanding of the relation between X-ray luminosity/states and radio emission (e.g. Hannikainen et al. 1998; Fender et al. 1999; Corbel et al. 2000, 2003; Gallo et al. 2004). This is due in part to its regular bright excursions and very clear hysteretical tracks in the HID (e.g. Belloni et al. 2005; HB05; Belloni 2009).

#### *3.11.1 1996–1999*

This was the outburst which clearly established the dramatic decrease in the X-ray–radio ratio during soft X-ray states. Radio observations are reported in Fender et al. (1999) and, more comprehensively, in Corbel et al. (2000). No clear bright radio flare was observed, although Fender et al. (1999) report a brief period of optically thin radio emission arising between MJD 50828 and 50840. The comparison of *RXTE* All-Sky Monitor (ASM) and Burst and Transient Source Experiment (BATSE) X-ray data with the radio monitoring clearly indicates the suppression of the radio emission in the soft state, although the poor *RXTE* PCA coverage means that this is not so clear in the figure presented here.

#### *3.11.2 2002–2003*

The 2002–2003 outburst provided a clear and precise detection of a radio flare and subsequent large-scale jet (Gallo et al. 2004). That this flare occurred during the hard to soft transition was already established in FBG04, and is shown again in Fig. 1. Once again the flare occurred about half way through the transition from hard to soft X-ray states. Subsequent radio brightenings were thought to be associated with the formation of shocks in the large-scale jet, something which may account for radio emission in the soft state in several of the other systems.

#### *3.11.3 2004–2005*

The 2004–2005 outburst of GX 339−4 did not receive much radio coverage, with Miller et al. (2006) publishing the only radio detection. However, the X-ray coverage was excellent, so it is worth presenting.

## 4 THE MOMENT OF MAJOR EJECTION IN THE HARDNESS–INTENSITY DIAGRAM

In the scenario of FBG04, the major ejection event in a black hole transient outburst occurs during the hard to soft state transition. In all cases presented in Fig. 1 the radio flare and/or resolved ejection event occurs between the brightest hard state and the transition to the soft state, in the 'intermediate states' of HB05. This confirms this aspect of the FBG04 model, with a much broader sample.

However, it is important to note that several systems, e.g. XTE J1550−564, XTE J1859+226, H1743−322, show extended periods of strong X-ray flaring during the hard to soft transition, and that it is *these* phases which seem to be associated with the brightest radio flares. Our archetypal varying black hole, GX 339−4, it seems, is actually a notable exception to this pattern, in showing a relatively smooth hard to soft transition without phases of strong X-ray flares.

Nevertheless, we can ask some naive questions and see where they lead; for example does the radio flaring always occur at the same hardness? It is hard to compare the evolution of different sources with different hardness ranges. In comparing different sources with similar absorption (GX 339−4 and XTE J1650−500) we find no evidence for ejections always occuring at the same hardness. Timing studies (see below) or comparison to the disc fraction luminosity diagram (Körding, Jester & Fender 2006; Dunn et al. 2008a) may provide clearer comparisons between different systems. In addition, to further refine the connection in the future we will need high angular resolution and/or high frequency radio/mm/infrared (IR) observations in order to avoid uncertainty associated with initially large optical depths.

We may also study in detail the hardness evolution of a single source when there is evidence for multiple ejection events. Fig. 2 highlights the region of the HID for XTE J1859+226 in which it seems that five discrete ejection events occurred (Brocksopp et al. 2002). The first four events occur in a narrow range of hardness $0.1 \leq H \leq 0.2$. The fifth event, which in Fig. 1 looks like something of an outlier, is revealed in Fig. 2 to be associated with a rapid (total duration $\leq$1.8 d) excursion back to a harder X-ray state. So, these data support the suggestion that the all five flare events occur when the source is in a very similar spectral state. Are all the events associated with hard to soft transitions (i.e. left to right motion in the HID)? This is harder to say. Certainly most seem to be associated with some change in direction or (two-dimensional) excursion, but the motion during this period is so fast that it is very hard to tell. Note that Casella et al. (2004) find that this region of the HID is very rich in strong quasi-periodic oscillations (QPOs), and provide more details of the QPO phenomenology.

The study of GX 339−4 reported in Belloni et al. (2005) implies that the lower luminosity outburst of GX 339−4 in 2004–2005 made the 'hard intermediate state' (HIMS) to 'soft intermediate state' (SIMS) transition at a larger hardness ratio than the outburst in 2002–2003. This conclusion was reached based on X-ray spectral and timing properties. If the moment of major ejection is associated with this transition, then the 'jet line' may be diagonal, or more complex, in the HID (see discussion later). It is also worth reminding the reader that while we do not discuss this source specifically here, the large number of events observed from the powerful jet source GRS 1915+105 (Fender & Belloni 2004) are all, to our knowledge, consistent with the patterns described in FBG04 (see also Soleri, Belloni & Casella 2008 for the association of type B QPOs with ejection events in this source).

## 5 X-RAY VARIABILITY AS AN INDICATOR OF EJECTION EVENTS

A complementary view of X-ray binary states and state transitions is provided by studying the X-ray variability of such sources, typically on time-scales of mHz to kHz, via Fourier power spectra (for recent reviews see Remillard & McClintock 2006; van der Klis 2006; Klein-Wolt & van der Klis 2008; Belloni 2009). These X-ray timing properties were not considered, however, in anything but the simplest sense in the model of FBG04. It has since been noted by several authors that the sharpest transition in the combined spectral and temporal classification of states is a sharp transition in timing properties between the SIMS and the HIMS (e.g. Belloni et al. 2005; Casella, Belloni & Stella 2005; Klein-Wolt & van der Klis 2008). Following the model presented in FBG04, several authors have speculated that there may be a close link between the sharp X-ray timing state transition and major relativistic ejection events (e.g. Ferreira et al. 2006; Klein-Wolt & van der Klis 2008). In the following we will explore the possibility that properties of the rapid X-ray variability may be a better indicator of ejection events than the energy spectrum.

In many cases analysis of rapid variability is a question of detailed fitting to X-ray power spectra, and of often subjective interpretation. Homan et al. (in preparation) have identified 'zones' of significantly and rapidly reduced X-ray rms variability, which occur in the intermediate X-ray states (see Belloni et al. 2005 for a clear example in the case of GX 339−4). In fact, the transition from the HIMS to the SIMS, the most dramatic change in timing properties, is well indicated (in some interpretations, *defined*) by a dramatic drop in the integrated X-ray rms variability. This drop in rms variability is often, but not exclusively (as far as the data currently reveal) associated with 'type B' QPOs as defined by Casella et al. (2005). Characteristic X-ray power spectra throughout a hard to soft state change in GX 339−4 are presented in Fig. 3 (alphabetical order corresponds to temporal order), and their corresponding temporal and hardness–rms diagrams (HRDs) presented in Figs 4 and 5 (power spectra over the preceding 30 d, for GX 339−4, are presented in Klein-Wolt & van der Klis 2008). Power spectra 'c', 'd' and 'e' correspond to the low-rms zone; the dramatic transition from the strongly variable power spectrum 'b' to the low-rms zone in 'c' takes place in $\leq 26$ h (in fact the transition has been observed to be as rapid as $\leq 32$ s; e.g. Casella et al. 2004). It is worth noting that immediately following these zones and phases with very strong QPOs (e.g. power spectrum 'd') the power spectrum returns to the band-limited noise shape which it had in the HIMS prior to the zone. This would seem to set some limit on the connection between the hard state noise and the jet launching mechanism, given that the jet properties appear to change dramatically following the major flare event (jet is suppressed and/or becomes optically thin; see next section). Klein-Wolt & van der Klis (2008) make a similar point in that frequencies associated with QPOs and other features in X-ray power spectra appear to evolve quite smoothly in frequency across the intermediate state transitions, at the same time that the jet appears to flare and then disappear. Note that the low-rms zones are sometimes 'filled in' in the HRDs (Fig. 5) during the hard to soft return state transition.

In the following section we study in detail the radio flux density, X-ray hardness (colour) and X-ray rms variability in detail for three outbursts: XTE J1550−564 (1998), XTE J1859+226 (1999) and GX 339−4 (2002). This is our first detailed and quantitative attempt to connect the sharp timing transitions with the exact moment of major relativistic ejection. In Fig. 4 we present radio flux density, X-ray rms and X-ray hardness against time for these three outbursts, and in Fig. 5 we plot the points of major radio ejection (radio flares; exactly equivalent to the points of peak radio flux in Fig. 1) in the rms versus colour diagram (see also Belloni et al. 2005 for the rms versus colour diagram for GX 339−4). In addition, in both sets of figures we indicate, with inverted open triangles, the times at which type B QPOs have been observed. Taken together, Figs 4 and 5 indicate a connection between X-ray spectral and timing

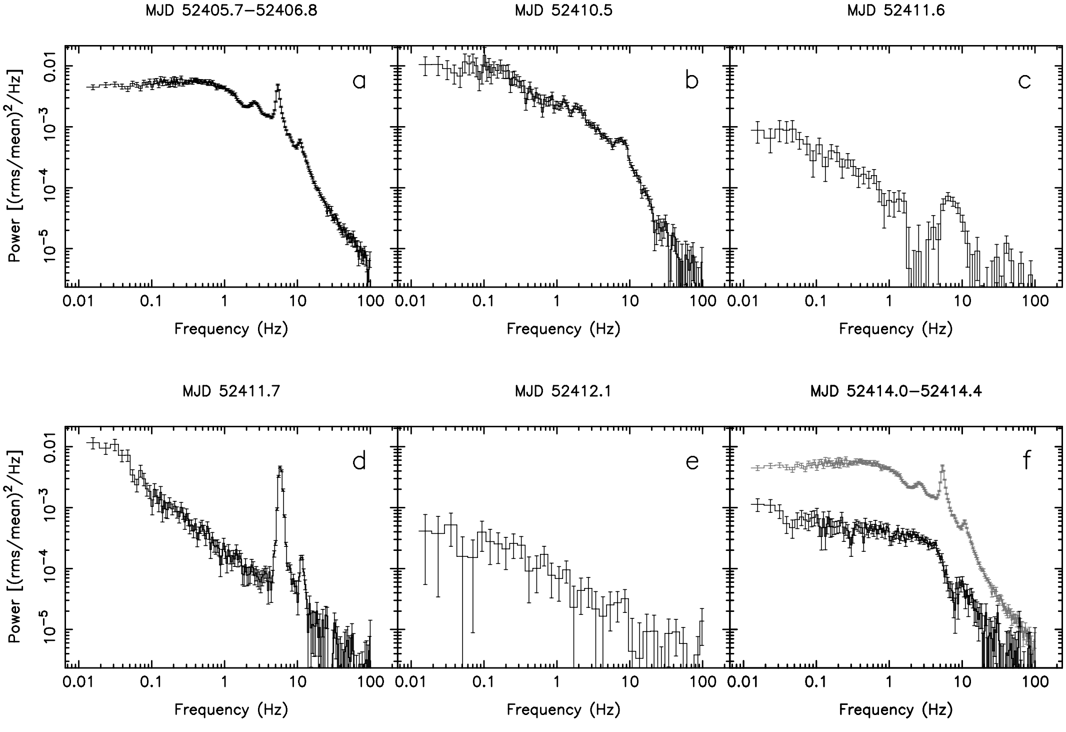

**Figure 3.** Detailed evolution of the X-ray power spectra of GX 339−4 before and after the radio flare and subsequent low-rms 'zone' in the 2002/2003 outburst. The epochs corresponding to the letters are also indicated in Figs 4 and 5. The power spectrum from panel (a) is replotted for reference in panel (f).

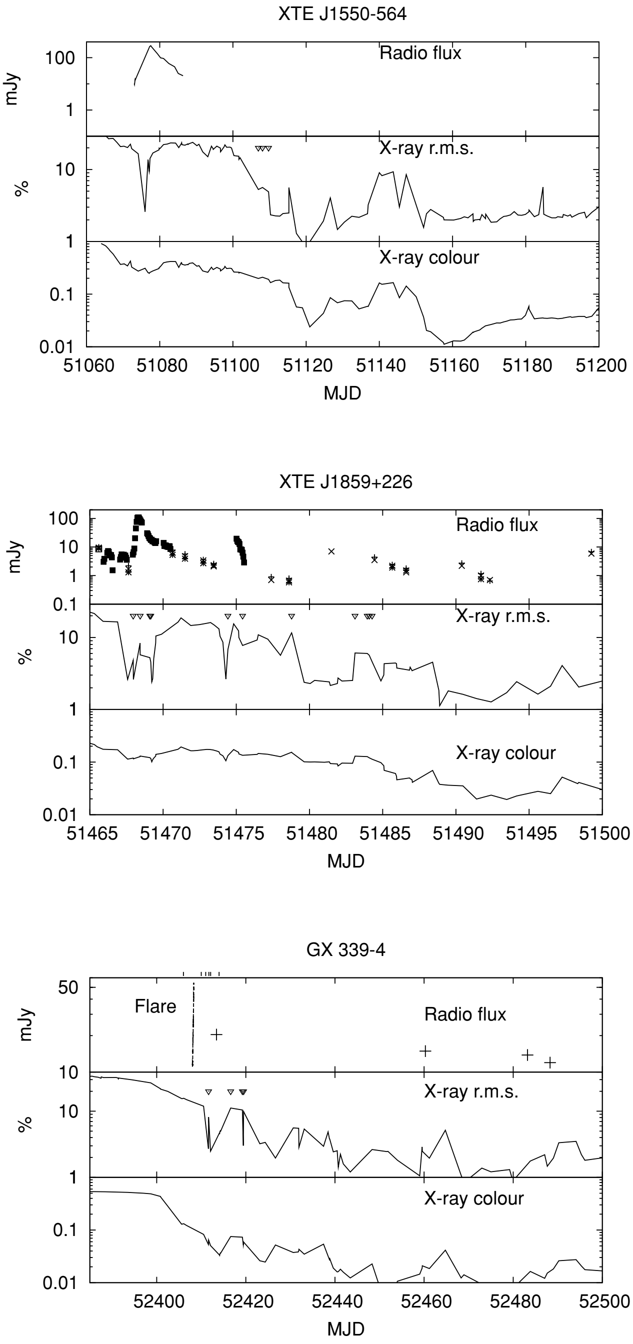

**Figure 4.** Evolution of radio flux density, (log) rms variability and (log) X-ray colour with time for the major outbursts of three black hole transients. Inverted open triangles in the rms panels indicate times when type B QPOs were observed. In XTE J1550−564 the major radio flare occurs just after a very sudden drop in X-ray variability (which itself corresponded to a very strong flare in total X-ray flux). In GX 339−4 the one observed bright radio flare occurs days before the clearest dip in the X-ray variability; the sequence of small ticks at the top of the figure indicates the epochs of the six power spectra presented in Fig. 3. In XTE J1859+226 a sequence of radio flares appear roughly correlated with drops in rms variability superposed on a declining trend which seems well matched to the softening X-ray colour. An alternative view of these events, in the hardness–rms plane, is presented in Fig. 5.

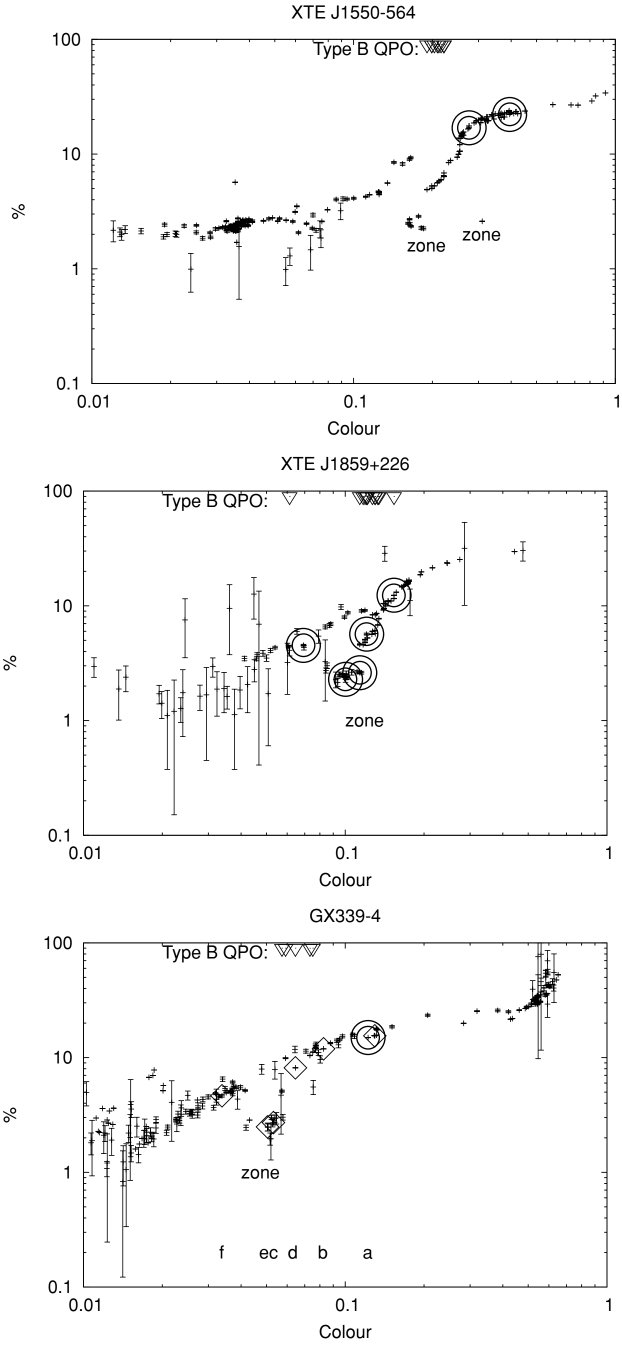

**Figure 5.** HRDs for the three transients investigated in detail in Fig. 4, with moments of radio flares indicated by the concentric rings. In the case of GX 339−4, the locations in the diagram of the six power spectra presented in Fig. 3 are indicated by diamonds, and the sequence indicated by the letters towards the lower edge of the figure. Inverted open triangles indicate the presence of type B QPOs.

changes and points of major ejection which looks promising at first but may weaken under closer inspection. We note that we only have coverage of the full transition from canonical hard to soft states in a subset of the outbursts presented in Fig. 1; in most cases this is due to the X-ray coverage having missed the initial hard state. Russell & Fender (2007) note that the time-scale from suppression of the optical/IR flux (probably indicating the beginning of the state transition) to radio flaring is typically 7–12 d.

### 5.1 XTE J1550−564

In the case of XTE J1550−564, the major radio flare and relativistic jets reported in Hannikainen et al. (2001) seem to be clearly associated with a very strong dip in the integrated X-ray rms, which corresponded to a major ∼six Crab X-ray flare. The X-ray peak occurs on MJF 51075−6, and the radio peak on 51078, consistent with the optical depth–evolution of a powerful ejection (e.g. van der Laan 1966; see also Discussion). The X-ray power spectrum at this peak showed a very strong drop in rms, with a prominent ‘type C’ (Sobczak et al. 2000; Casella et al. 2005) and possibly a weaker ‘type B’ QPO (Belloni et al., in preparation; not indicated in Figs 4 and 5 as a confirmed detection). Spectral fits, combined with a clear peak in the frequency of the low-frequency QPO at ∼13 Hz, suggest that for a transient phase the disc *may* reached a local minimum in radius, although there are certainly alternative explanations (see e.g. Sobczak et al. 2000). Note that type C QPOs are sometimes observed to reach higher frequencies (in both this and other sources) and so even if the disc did reach a local minimum in radius, there is no strong case that this was at the ISCO (this is of some importance compared to the suggestion in FBG04 that major ejections take place when the disc reaches the ISCO). Regardless of the precise details, the disc component was clearly very luminous and very hot at this point (comparable, briefly, to GRS 1915+105), and the event is strongly implicated in the production of a very powerful jet which was still observable accelerating electrons to TeV energies in the ISM some 4 yr later (Corbel et al. 2002). However, it is important to note that the drop in rms variability during this, and other, zones cannot be ascribed solely to dilution of the signal by a non-variable disc component. Taking this bright event as an example, both the disc and power-law components increased in luminosity by a factor of ∼3, whereas the rms variability dropped by a factor of ∼10. This event is clearly significantly harder than the later, broader, zone of reduced rms (Fig. 5).

### 5.2 XTE J1859+226

In XTE J1859+226 the sequence of five radio flare events appears to be well correlated with local minima in both X-ray timing and colour. The HRD clearly shows that all five reported events occurred around the reduced rms zones. Casella et al. (2004) report the evolution of the timing properties throughout this outburst in some detail.

### 5.3 GX 339−4

In GX 339−4 the strong radio flare reported by Gallo et al. (2004) clearly occurs around the end of the rapid X-ray colour change, but clearly *before* the zone of reduced X-ray rms. This is very important measurement: unless we have missed a major radio event (which is possible given the poor radio coverage in most cases) then the radio ejection in GX 339−4 began at least 2 d before the strong X-ray timing state transition, and also before the appearance of ‘type B’ QPOs (Casella et al. 2005) which have also been suggested to be associated with ejections (e.g. Soleri et al. 2008). The timing behaviour during this outburst is summarized in Belloni et al. (2005).

## 6 RADIO EMISSION IN THE SOFT STATE

In a large number of the outbursts presented in Fig. 1, there is clearly some radio emission, at least initially, in the soft X-ray states which generally follow the radio flare/ejection event. It is unfortunate that the large number of upper limits to the radio emission during the 1996–1999 soft state of GX 339−4 (Fender et al. 1999; Corbel et al. 2000) were not accompanied by intensive *RXTE* PCA monitoring, and so are not represented here. Nevertheless, some systems clearly show a lack of radio emission in the soft state once the large flare has faded (see e.g. 4U 1630−47, H1743−322, XTE J1720−318 in Fig. 1).

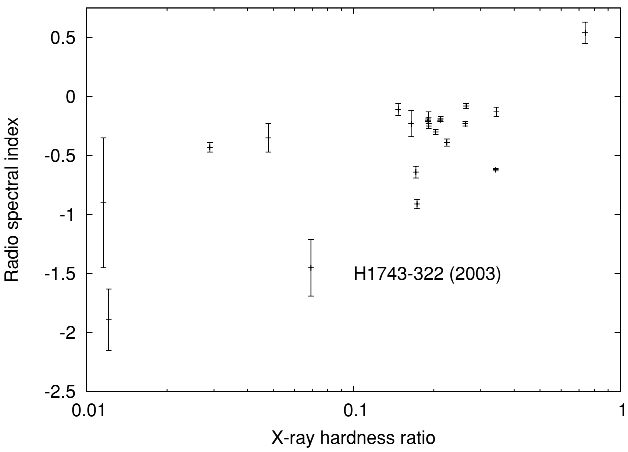

**Figure 6.** Radio spectral index as a function of X-ray colour for H1743−322, based on the observations reported in McClintock et al. (2009). There is a clear trend for more negative spectral indices, indicating optically thin emission, in softer states. This is consistent with, but not proof of, the suggestion that in the soft state radio emission is associated with spatially extended jets and shocks, and not with the core.

What are we to make of the radio detections in the soft state, given that the current paradigm is that the jet is suppressed in this state? There seem to be two alternatives.

I. The core jet *is* strongly suppressed, and the radio emission is associated with rebrightenings at shocks as the jet propagates away from the binary.

II. The core jet, in some cases, remains on, at least for a while, in the soft state.

We note that scenario I – radio brightening which images reveal to be displaced from the binary core – has been directly observed in several cases (e.g. Corbel et al. 2002; Gallo et al. 2004). In this scenario, the radio emission we observe in the soft state should in most cases have an optically thin radio spectrum, in contrast to the flat radio spectrum associated with the hard state (Fender 2001). In Fig. 6 we plot the radio spectral index for observations of H1743−322 as a function of X-ray hardness, which support a trend towards more negative spectral indices, indicative of a lower optical depth, with decreasing hardness. In addition such emission should be observed to monotonically fade as the ejecta expand in the surrounding medium. Occasional rebrightenings and spectral flattenings can be associated with shocks, whether internal or external.

Scenario II – the existence, sometimes, of a powerful jet from the core in the soft state – cannot be ruled out, but seems to be the more complex solution, requiring explanations for why the jet spectrum has switched to optically thin, and why it only happens sometimes.

We conclude that the scenario I, which agrees with the current paradigm of a suppressed (‘quenched’) core jet in the soft state is more likely, although scenario II cannot be ruled out. In order to test this further, sensitive high-resolution (VLBI) and/or high-frequency (mm/IR) observations are required throughout an outburst. Note that the near-IR evidence for suppression of the jet in the soft state (Homan et al. 2005a; Russell et al. 2007) clearly supports the case that the flat-spectrum jet is suppressed, and therefore that the jet power is significantly reduced (whether the jet emission is suppressed at all frequencies or just becomes optically thin).

## 7 WHEN DOES THE STEADY JET REACTIVATE – IS THE ‘JET LINE VERTICAL’?

It is clear from many radio observations (e.g. Tananbaum et al. 1972; Fender et al. 1999; Corbel et al. 2000, 2002; Gallo, Fender & Pooley 2003) that the radio emission from black hole X-ray binary systems (BHXRBs) reactivates when the sources transition back to the hard state following a period in a softer state. In FBG04 it was suggested (speculatively) that there may be a vertical ‘jet line’ for each HID (and maybe each source). In harder states than this jet line a steady jet would be produced, and in softer states the jet suppressed. Transition across the jet line from harder to softer states (i.e. right to left) would result in a radio flare (due to internal shocks as jet velocity increased), whereas the transition from soft to hard (left to right; at lower luminosity) would simply produce the reactivation of the (flat spectrum) jet without a large flare.

It seems clear that the jet does remain on until at least the moment of the radio flare, i.e. in the HIS, during the overall hard to soft transition (see Fig. 1; also Corbel et al. 2004; FBG04). However, data testing the reactivation of the hard state steady jet during the soft to hard transition has been hard to come by.

### 7.1 GX 339−4: the jet line does not seem to be vertical

Comparison of the 1996–1999 and 2002–2003 outbursts of GX 339−4 indicates that upper limits to the jet flux have been measured, in 1999, at almost exactly the same hardness ratio where the major radio flare was observed in 2002. This is shown in some detail in Fig. 7. Note that there may be some uncertainties associated with comparing colours at different epochs due to changes in the response of the *RXTE* PCAs.

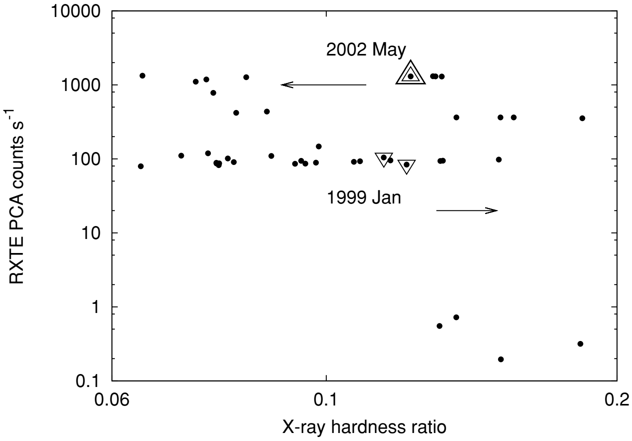

**Figure 7.** Varying radio response at the same hardness in GX 339−4. In the 2002–2003 outburst the source was detected at a steady level of ∼12 mJy before flaring to >40 mJy. Earlier observations, in January 1999, placed sub-mJy upper limits on the radio flux at the same hardness. The arrows indicate the general direction of motion in the HID at the time of the observations: in 1999 the source was returning to the hard state; in 2002 it was transiting from hard to soft.

The upper limits to the radio flux density in 1999 are clearly also, however, at much lower X-ray count rates. Could this be an explanation for the non-detection? The upper limits of ≤0.2 mJy were obtained at a count rate of ∼80 counts $s^{-1}$. The ∼12 mJy steady detection and subsequent flare were observed at a much higher count rate, of ∼1300 counts $s^{-1}$. Combining these two results, a relation between radio and X-ray fluxes steeper than $F_{\mathrm{radio}} \propto F_{\mathrm{X}}^{1.4}$ would be required to account for the non-detection in 1999. This is of course far steeper than the $F_{\mathrm{radio}} \propto F_{\mathrm{X}}^{\sim 0.7}$ relation of Corbel et al. (2002) for this and other (Gallo et al. 2003) sources in the hard state. A +1.4 index is in fact as expected for jets from a radiatively efficient accretion flow (e.g. Heinz & Sunyaev 2003; see Migliari & Fender 2006 for the possible case of such an index for neutron stars) and so this is not quite ruled out. Nevertheless, it seems likely that this combination of observations implies that a vertical ‘jet line’, implying a one-to-one correspondence between X-ray hardness and core jet properties, does not exist. Of course there is no a priori reason to assume a vertical jet line, but since this is what was sketched in FBG04 we need to address this point.

As noted in Corbel et al. (2000), the first redetection of GX 339−4 after the recovery of the jet at the end of the 1999–2000 outburst does have an unusually optically thin spectrum.

### 7.2 XTE J1720−318: reactivation of the jet?

The single best example of jet reactivation in the HIS appears to be the 2003 outburst of XTE J1720−318 (see Fig. 1). In this outburst the peak radio flux appears to occur at a hardness ratio of $0.01 \leq H \leq 0.02$. During the soft to hard transition no radio emission is detected to typical upper limits of 0.2–0.4 mJy to a hardness of ∼0.02, but radio emission is detected at a hardness of $0.1 \leq H \leq 0.2$ 15 d later. This is clearly softer than the hardest spectral state which seems to exist at $H \geq 0.3$ and in which the source remains in a further 30+ observations over 120 d. In total there is a period of 69 d between radio detections of the source. Two further detections are made as the source settles back into the hardest spectral state.

Fig. 8 plots the evolution of the XTE J1720−318 in the radio–X-ray plane, with approximate indications of X-ray state and also the correlation of Gallo, Fender & Pooley (2003) plotted. If we

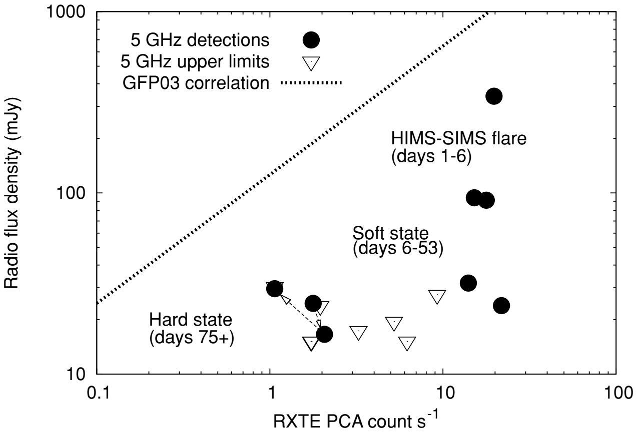

**Figure 8.** Radio detections of XTE J1720−318 in the radio–X-ray plane, compared to the overall hard state correlation from Gallo, Fender & Pooley (2003). The source is always below the relation (caveat distance uncertainties) but appears to move back towards the relation during reactivation on the lower hard-intermediate branch of the HID (see Fig. 1), after a long period of non-detection in the soft state.

compare the flux at this radio reactivation with the $L_{\rm radio}$–$L_{\rm X}$ relation presented in Gallo, Fender & Pooley (2003) and Gallo et al. (2006), we find that the source is rather radio quiet both in outburst and in the hard state (as noted already by Gallo 2007). However, the radio reactivation does seem to bring the source closer to the Gallo, Fender & Pooley (2003) correlation.

## 8 DISCUSSION

In all cases investigated here – 14 major outbursts compared to the three studied in FBG04 – the highest radio flux density occurred during the hard to soft state transition near the start (and peak) of the outburst. This seems to confirm the FBG04 assertion that major ejections occur during the evolution from spectral energy distributions (SEDs) dominated by a combination of corona plus jet, to those dominated by an optically thick disc-like component. However, it has also become apparent that in many systems the bright radio flare is associated with a phase of X-ray flaring which is nowhere near as evident in our archetypal system, GX 339−4. In some cases, e.g. XTE J1550−564, the disc can appear to become extremely hot and physical changes are not well mapped by the standard colours in the HID (as is the case for GRS 1915+105).

A key issue which arises in discussing the results compiled above is how robust an indicator is the X-ray hardness of the physical state of the accretion flow? We may wish to compare the physical conditions of the accretion flow at the moment of major ejection in different systems, or compare the moments of jet flare and subsequent suppression, with the moment of jet 're-ignition' on the lower branch. In fact it is clear that on the lower (later) branch of the outburst, at the same hardness (of course dependent on the energy ranges used for the hardness ratio), the disc fraction can be very different than on the upper (earlier) branch. Dunn et al. (2008b) present the relation between X-ray hardness and disc (≡ power law) fraction (their fig. 3, right-hand panel), illustrating the rather complex relation between a given hardness ratio and the ratio of the disc and power-law components. Based on this discussion, it is clear that the 'jet line', *if it corresponds to a comparable ratio of power law to thermal components in the X-ray spectrum*, should not be vertical in the HID (as sketched in FBG04) nor simply diagonal (as sketched in Klein-Wolt & van der Klis 2008) but rather more complex. Disc fraction luminosity diagrams (Körding, Jester & Fender 2006; Dunn et al. 2008a) or some other prescription for describing the evolution of physical components, rather than colours, may be required to make further progress here.

An interesting comparison case is Cyg X-1, where state transitions occur in both directions at essentially the same luminosity (∼2 per cent Eddington). This suggests that if there really is any physical connection between the disc–power-law ratio and the presence or absence of a jet, it could be tested here.

It is somewhat disappointing at first to find that there appears to be no one-to-one relation between abrupt changes in the rapid X-ray variability properties, as measured in Fourier power spectra, and the major radio ejection events. Both phenomena clearly happen around the same time, but the case of GX 339−4 (and possibly also XTE J1550−564), in which the radio ejection appears to occur more than a day before the rms-drop 'zone' appears to rule out a direct causal connection. We have briefly investigated the possible association between ejections and different types of QPO (following the classification of Casella et al. 2005) but the lack of a clear causal link with zones of low rms also rules out a one-to-one link between QPOs and ejections. In particular it had been suggested (e.g. Soleri et al. 2008) that the type B QPO might be associated with ejections, but the observation in GX 339−4 of a flare *prior* to the appearance of these QPOs does not support this idea. Before we discuss further, some caveats are worth restating however.

(i) As noted in FBG04, in the phase between the brightest canonical hard state and the brightest ejection, there seems to be a phase of instability in the jet, resulting in some flaring and rapid changes in spectral index. When combined with the poor radio sampling much of our conclusions are based upon, this remains a clear possibility for the case of GX 339−4 – i.e. there was an even larger flare which we missed.

(ii) There are at least two forms of delay which will act to make the radio emission appear later than the 'trigger' X-ray event. Optical depth effects (well understood since e.g. van der Laan 1966) will have this effect, as will the delay required for two 'shells' to collide in the event that radio emission is generated by internal shocks (e.g. Kaiser, Spruit & Sunyaev 2000; Jamil, Fender & Kaiser 2008). These delays are empirically observed in X-ray binaries to range from minutes to days depending on the luminosity of the event and the observing frequency.

However, if these caveats are not relevant, then we are forced to conclude that the major ejection events have an imprecise connection to the X-ray 'timing state' and possibly also to the spectral state. In fact it is not clear how tight is the relation between the two definitions of states (see discussions in e.g. HB05; Remillard & McClintock 2006; Klein-Wolt & van der Klis 2008). This may imply that the jet, and maybe also the X-ray radiation are common 'symptoms' of some other change, but not themselves causally connected. The bottom line is that current radio coverage is simply not sufficient to pin down the moment of ejection to any specific part of the complex X-ray transitions we have learned about via *RXTE*.

## 9 CONCLUSIONS

In FBG04 we presented a first attempt at a unified picture for the radio–X-ray coupling in black hole X-ray binaries. This picture was based upon the study of four black hole systems, presenting one outburst each (one oscillation event in the case of GRS 1915+105). One of the main conclusions of the paper was that relativistic ejections are associated with the high-luminosity hard to soft X-ray state transition which occurs near the beginning of most outbursts. In this paper we have investigated a far larger sample of black hole X-ray binary outbursts observed by *RXTE* for which there is at least some radio coverage. In all cases we find that the peak of the radio emission, which is almost certainly associated with a discrete relativistic ejection event (although there will be some delay between ejection and radio peak), to be associated with the overall hard to soft state transition, but we cannot pin down some specific phase in the intermediate states. This confirms the result of FBG04; however, we also note that in several systems the radio flare/ejection event is associated with phases of X-ray flaring which are not so evident in the most-studied source, GX 339−4.

We also find that in a large number of cases there is significant radio emission in the soft state, where we have previously asserted (Fender et al. 1999; FBG04) that the jet is suppressed or 'quenched'. It seems that in all cases this radio emission is consistent with having an origin in jet–ISM interactions far from the black hole, with the core radio emission indeed switched off. The evidence for this comes in the form of optically thin radio spectra and (usually) monotonic decays in radio flux in the soft state, as well as the fact that in several sources the radio emission is indeed strongly suppressed in the soft state. However, uncertainty about exactly when

**Table 1.** A brief tabular summary indicating aspects of the FBG04 model which have been tested, some empirical with interpretation, some mostly interpretation and some new, in this work.

| Empirical aspect | Interpretation | Comments |
|---|---|---|
| Major radio flare during hard to soft transition | Major ejection | *Confirmed*; additional X-ray flaring noted in some systems; in one system five radio flares occur around same hardness |
| Reactivation of radio emission on return hard branch | Reactivation of jet (without flare) | *Unclear*; only one useful example |
| No radio emission in soft state | Jet ‘off’ in soft state | *Consistent but not proven*; detections of (optically thin) radio in soft state; jet may be off (‘remnant’ radio) or intermittent |
| Low/hard state jet slower ($\Gamma \leq 2$) jet than subsequent powerful transient jet ($\Gamma \geq 2$) | Leads to internal shocks | *Unclear*; low/hard state jet velocity remains untested |
| Correspondence of power spectral changes with ejections | Ejection of corona? | *Unclear*; clear correspondence on time-scales of days but causal link not demonstrated |
| *Other aspects* | Jet power large | *Confirmed*; many further studies appear to support this |
| | Varying inner disc radius at transitions | *Unclear*; changes of order 10s of $R_G$ cannot be excluded |
| | Powerful ejection when disc reaches ISCO | *Unclear*; some evidence against (e.g. XTE J1550−564) |

the jet production mechanism shuts off remains, and is unlikely to be resolved by flux monitoring observations with relatively low angular resolution instruments such as ATCA and the VLA – higher resolution VLBI and/or higher frequency observations, preferably simultaneous with X-ray observations, are going to be necessary to make progress.

The reactivation of the core jet in the HIS was predicted in FBG04 but there remains little direct evidence for this, and it may well be that the core jet does not reactivate until the canonical hard state is reached. The one tentative identification of a HIS reactivation is the case of XTE J1720−318, where a weak radio source appears during the transition back to the hard state, but before the canonical hard state has been reached. More radio observations of the decay phases of outburst are required to investigate this further.

We have also attempted to extend our description of the X-ray properties beyond just X-ray colours, but also to variability properties. The bright intermediate states during which we have clearly established the relativistic ejections take place are also well known to be associated with the presence of strong QPOs, which generally rise in frequency as the hard to soft transition progresses (Klein-Wolt & van der Klis 2008 and references therein). In particular, we compared zones of anomalously low X-ray rms variability, which are associated with transitions between ‘hard intermediate’ and ‘soft intermediate’ states, with the times of radio ejection events. These zones are *not* simply associated with ‘disc dilution’ of the variability signal, but by some as yet unexplained reduction in the degree of variability of the hard X-ray component; they are also often associated with type B QPOs. In all cases where the data were good enough to measure both, the radio flares and rms drops are coincident within a few days. In the case of XTE J1859+226, there are hints that a sequence of five radio flares is associated with a corresponding number of rms variability drops, superposed on a general decline in the rms towards the soft state. An obvious speculation would be that the radio flares are associated with the ejection of the same coronal material which is responsible for much of the variability (as suggested previously by e.g. Rodriguez, Corbel & Tomsick 2003; Vadawale et al. 2003; FBG04; see also Rodriguez & Prat 2008). However, in the case of GX 339−4 it appears that a strong radio flare event took place more than a day *before* the X-ray rms drop, contrary to expectations for such a scenario. Therefore, at present it is uncertain whether the radio flares and rms drops are simply independent symptoms of some other underlying process, or that perhaps every dip is indeed causally connected to a subsequent flare, but that our radio coverage is so poor that we are missing most flares. Given the lack of a clear one-to-one relation between the rms decreases and jet ejections, it was clear that we would not (at this time) find a clear connection between the presence of certain types of QPO and ejections.

We furthermore note that some aspects of the FBG04 model, both empirical and interpretational, remain untested. Key amongst these is the continued lack of a good measure of the speed of the jet in the hard state. As noted in FBG04, and originally in Gallo, Fender & Pooley (2003) and Heinz & Merloni (2004), the relatively narrow range in normalizations of the disc–jet coupling in the hard state of different black hole X-ray binaries implies a narrow range of velocities for such jets. Although we (still) favour a lower velocity, we are still lacking the single good measurement of the velocity of a hard state jet in order to test this. Measuring the velocity of a steady-state jet, relatively low power, jet will however require imaginative methods. The proposed internal shock model suggested by a strong velocity differential, may still be tested independently for black hole binaries as begun recently by Jamil et al. 2008 (see also e.g. Peér & Casella 2009). Several of the interpretational aspects of the FBG04 model also remain untested, or even controversial. Primary amongst these is whether or not the inner disc radius really decreases in the hard to soft state transition. Several works (e.g. Miller et al. 2006; Rykoff et al. 2007) argue against this interpretation, while others support it sometimes using the same data (e.g. Gierlinski, Done & Page 2008; Cabanac et al. 2009). Table 1 summarizes which components of the model have been tested by this study, and what aspects have been added.

A key deficit in our understanding of the ‘disc–jet’ coupling in these systems arises not from the lack of observations of the accretion flow (i.e. X-rays), but from observations of the jet (radio, IR), particularly in comparison to studies of AGN, where there are a vast number of radio observations. The next generation of radio facilities (e.g. Fender 2008) will greatly improve on our coverage in this area, with daily (maybe more frequent) radio observations of all active X-ray sources. It is to be hoped that there will be an equivalent or descendent of *RXTE* around in that time to provide the necessary X-ray coverage.

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