Mon. Not. R. Astron. Soc. **355,** 1105–1118 (2004) doi:10.1111/j.1365-2966.2004.08384.x

Towards a unified model for black hole X-ray binary jets

R. P. Fender,[1★] T. M. Belloni[2★] and E. Gallo[1★]

[1]*Astronomical Institute 'Anton Pannekoek', University of Amsterdam, and Center for High Energy Astrophysics, Kruislaan 403, 1098 SJ Amsterdam, the Netherlands*

[2]*INAF – Osservatorio Astronomico di Brera, Via E. Bianchi 46, I-23807 Merate, Italy*

Accepted 2004 September 6. Received 2004 August 26; in original form 2004 July 2

ABSTRACT

We present a unified semiquantitative model for the disc–jet coupling in black hole X-ray binary systems. In the process we have compiled observational aspects from the existing literature, as well as performing new analyses. We argue that during the rising phase of a black hole transient outburst the steady jet known to be associated with the canonical 'low/hard' state persists while the X-ray spectrum initially softens. Subsequently, the jet becomes unstable and an optically thin radio outburst is always associated with the soft X-ray peak at the end of this phase of softening. This peak corresponds to a 'soft very high state' or 'steep power-law' state. Softer X-ray states are not associated with 'core' radio emission. We further demonstrate quantitatively that the transient jets associated with these optically thin events are considerably more relativistic than those in the 'low/hard' X-ray state. This in turn implies that, as the disc makes its collapse inwards, the jet Lorentz factor rapidly increases, resulting in an internal shock in the outflow, which is the cause of the observed optically thin radio emission. We provide simple estimates for the efficiency of such a shock in the collision of a fast jet with a previously generated outflow that is only mildly relativistic. In addition, we estimate the jet power for a number of such transient events as a function of X-ray luminosity, and find them to be comparable to an extrapolation of the functions estimated for the 'low/hard' state jets. The normalization may be larger, however, which may suggest a contribution from some other power source such as black hole spin, for the transient jets. Finally, we attempt to fit these results together into a coherent semiquantitative model for the disc–jet coupling in all black hole X-ray binary systems.

Key words: accretion, accretion discs – black hole physics – ISM: jets and outflows – X-rays: binaries.

1 INTRODUCTION

Relativistic jets are a fundamental aspect of accretion on to black holes on all scales. They can carry away a large fraction of the available accretion power in collimated flows which later energize particles in the ambient medium. The removal of this accretion power and angular momentum must have a dramatic effect on the overall process of accretion. In their most spectacular form they are associated with supermassive black holes in active galactic nuclei (AGN) and with γ-ray bursts (GRBs), the most powerful and explosive engines in the Universe respectively. However, parallel processes, observable on humanly accessible time-scales, are occurring in the accretion on to black holes and neutron stars in binary systems within our own Galaxy.

The current observational picture of X-ray binary jets is most simply put as follows: In the low/hard state, which exists typically below a few per cent of the Eddington luminosity $L_{\rm Edd}$ (e.g. Maccarone 2003; McClintock & Remillard 2004), there is a 'compact' self-absorbed jet that manifests itself as a 'flat' (spectral index $\alpha \sim 0$ where $\alpha = \Delta\log S_\nu/\Delta\log\nu$) or 'inverted' ($\alpha \geqslant 0$) spectral component in the radio, millimetre and (probably) infrared bands (e.g. Fender 2001b; Corbel & Fender 2002). The radio luminosity of these jets shows a strong, non-linear correlation with X-ray luminosity (Corbel et al. 2003; Gallo, Fender & Pooley 2003) and has only been directly spatially resolved in the case of Cyg X-1 (Stirling et al. 2001), although the 'plateau' jet of GRS 1915+105 is phenomenologically similar and has also been resolved (Dhawan, Mirabel & Rodríguez 2000; Fuchs et al. 2003). The suggestion that such steady, compact jets are produced even at very low accretion rates (Gallo et al. 2003; Fender, Gallo & Jonker 2003) has recently received support in the flat radio spectrum observed from the 'quiescent' transient V 404 Cyg at an average X-ray luminosity

★E-mail: rpf@science.uva.nl (RPF); belloni@merate.mi.astro.it (TMB); egallo@science.uva.nl (EG)

$L_X \sim 10^{-6}$ L_{Edd} (Gallo, Fender & Hynes 2004b). During steady 'soft' X-ray states, the radio emission, and probably therefore jet production, is strongly suppressed (Tananbaum et al. 1972; Fender et al. 1999b; Corbel et al. 2001; Gallo et al. 2003).

Additionally there are bright events associated with transient outbursts and state transitions (of which more later), which are often directly resolved into components displaying relativistic motions away from the binary core (e.g. Mirabel & Rodríguez 1994; Hjellming & Rupen 1995; Fender et al. 1999a), not only in the radio but also – at least once – in the X-ray band (Corbel et al. 2002). These events typically display optically thin (synchrotron) radio spectra ($\alpha \leqslant -0.5$). Both kinds of jets are clearly very powerful and coupled to the accretion process. See Mirabel & Rodríguez (1999) and Fender (2004) for a more thorough review of the observational properties of X-ray binary jets.

In this paper we attempt to pin down as accurately as possible the moment at which the major radio outburst occurred and relate this to the X-ray state at the time. We subsequently compare this with the X-ray state corresponding to the lower-luminosity steady jets, to the evolution of transient outbursts, and to the velocity and power associated with each 'type' of jet, in order to draw up a framework for a unified model of black hole X-ray binary jet production.

Several black hole systems are investigated in this paper, and in addition we compare these with the neutron star systems Cir X-1 and Sco X-1. The data relating to the radio flares, jet Lorentz factors (if measured), corresponding X-ray luminosities, estimated distances and masses, are summarized in Table 1.

2 THE SAMPLE: FOUR BLACK HOLES UNDERGOING JET FORMATION

Is there a signature in the X-ray light curve of an outbursting source that indicates when the relativistic jet is launched? In the following we investigate radio and X-ray light curves of four black hole binaries, i.e. GRS 1915+105, GX 339−4, XTE J1859+226 and XTE J1550−564, undergoing state transitions in order to investigate this point.

2.1 X-ray data analysis

For XTE J1550−564, XTE J1859+226 and GX 339−4, we extracted the background-subtracted PCA count rate, using PCU2 only, for each available *RXTE* observation relative to the first part of the outburst considered. For each observation, we also produced an X-ray colour (or hardness ratio) by dividing the background-subtracted count rates in the 6.3–10.5 keV band by those in the 3.8–6.3 keV band. For GRS 1915+105, given the much shorter time-scales involved, we analysed a single observation (see Section 2.2.1), producing a PCA light curve at 1 s resolution from all PCUs summed together, and an X-ray colour curve at the same time resolution. The energy bands used for the colour, 15.2–42.3 and 2.1–5.9 keV, were different. The reason for this is that the thermal disc component in GRS 1915+105 is considerably higher than in other systems (see Fender & Belloni 2004): using the same energy bands results in the harder C state having a softer colour than the softer B state. The use of a harder energy band for the numerator ensures that the thermal disc component does not strongly contaminate it.

In order to estimate in a homogeneous way the source luminosity at peak of the outburst for XTE J1550−564, XTE J1859+226 and GX 339−4, we extracted *RXTE* PCA + HEXTE spectra from the public archive corresponding to the peak flux in the PCA band. Spectra were created from PCU2 data (3–25 keV) for the PCA and from cluster A data (20–200 keV) for HEXTE, using FTOOLS 5.3. The spectra were corrected for background and deadtime effects. A 0.6 per cent systematic error was added to the PCA to account for residual calibration effects. We fitted the spectra with the standard phenomenological model for these systems, consisting of a cut-off power law (CUT-OFF), a disk blackbody (DISKBB), and a Gaussian emission line between 6 and 7 keV, all modified by interstellar absorption. The actual models might be more complex, but we are interested in the determination of the flux only, so that the presence of additional components like iron absorption edges does not change our results significantly. The reduced χ^2 values were between 1.3 and 1.5. From the best-fitting models for each source, in order to estimate the bolometric flux, we computed the unabsorbed flux of the disc blackbody component in the 0.001–100 keV range

Table 1. Parameters for the X-ray binary systems and selected jet events discussed in this paper; the last two sources contain accreting neutron stars, the rest black hole candidates. The first three columns give the source name, distance and mass of the accretor. Columns 4–9 give the date, rise time, peak radio flux, constraints on bulk Lorentz factor, estimated jet power and corresponding estimated X-ray power for jet production events. The final column gives references.

Source	d (kpc)	M ($M_\odot$)	Date (MJD)	Δt (s)	$S_{5\,GHz}$ (mJy)	Γ	L_J (Edd)	$L_{X,VHS}$ (Edd)	Ref.[a]
GRS 1915+105 (flare)	11	14	50 750	43 200	320	$\leqslant$1.4	0.6	1.1	F99
GRS 1915+105 (osc.)	11	14	many	300	50	$\geqslant$2	0.05	1.1	F99
GRO J1655−40	3.5	7	49 580	43 200	2000	$\geqslant$1.7	1.0	0.1	HR95
XTE J1859+226	6	7	51 467	21 600	50	?	0.2	0.2	B02
XTE J1550−564	6	9	51 077	43 200	130	$\geqslant$2	0.3	0.5	W02
GX 339−4	8	7	52 408	19 800	55	$\geqslant$2.3	0.3	0.07	G04
V4641 Sgr	8	9	51 437	43 200	420	$\geqslant$9.5	0.8	4	Hj01, Or01
Cyg X-1	2.5	10	53 055	2000	50	?	0.02	∼0.05	P04
XTE J1748−288	8.5	7	50 980	172 800	530	$\geqslant$2.7	1.9	∼0.1	B04
Cir X-1	6	1.4	51 837	43 200	20	$\geqslant$15	0.6	∼0.7	F04
Sco X-1	2	1.4	many	3600	15	$\geqslant$3.2	0.02	∼1	F02

[a]References: F99 = Fender et al. (1999a); HR95 = Hjellming & Rupen (1995); B02 = Brocksopp et al. (2002); W02 = Wu et al. (2002); G04 = Gallo et al. (2004a); Hj01 = Hjellming et al. (2000); Or01 = Orosz et al. (2001); P04 = Pooley (2004); B04 = Brocksopp et al. (in preparation); F04 = Fender et al. (2004); F02 = Fomalont et al. (2001a,b).

and that of the power-law component in the 2–100 keV range. For GRS 1915+105, given the much shorter time-scales involved for the short oscillations, we applied the procedure outlined above to the *RXTE*/PCA + HEXTE data of the observation of 1997 October 25, the last one before the launch of the major jet observed with MERLIN (Fender et al. 1999a). In order to approximate the flux evolution from the count-rate light curves, we applied to all preceding and following observations the count rate to flux conversion factor obtained from the peak. By comparison with published flux values for XTE J1550−564 (Sobczak et al. 2000), this proved to be a reasonable approximation for our purposes.

Much of the following discussion is based upon the association of radio emission with the X-ray 'states' of different sources. We will use the following abbreviations throughout this paper: the 'low/hard' state as 'LS'; the 'high/soft' state as 'HS'; and the 'very high' or 'intermediate' states as 'VHS/IS'. In fact, as we shall discuss further (see also Belloni et al., in preparation; Homan & Belloni 2004), the VHS/IS is not a single state but has both 'hard' (as used to describe the X-ray spectrum) and 'soft' varieties.

Note that recently McClintock & Remillard (2004) have proposed a modification to this classification scheme in which the LS is referred to as the 'hard' state and the HS as the 'thermal dominated state', while revised definitions are introduced for the VHS/IS states. While we retain the 'classical' definitions of states, we discuss later on how these correspond to the revised state definitions of McClintock & Remillard.

2.2 Individual sources

2.2.1 GRS 1915+105

GRS 1915+105 has long been a key source in our understanding of the disc–jet coupling in X-ray binary systems (see Fender & Belloni 2004 and references therein). In the context of this study, it is interesting because its X-ray state never seems to reach the 'canonical' LS or HS but instead switches between 'hard' (state 'C' of Belloni et al. 2000) and 'soft' (states 'A' and 'B') VHS/IS states (see also Reig, Belloni & van der Klis 2003). It has clearly been established in this source that phases of hard (C) X-ray emission lasting more than a few hundred seconds are associated with radio events, and that when the source is only in soft (A, B) states there is no radio emission (Klein-Wolt et al. 2002). In the context of this work its importance is therefore in establishing that state changes 'within' the VHS/IS can produce radio outbursts without requiring any 'contact' with the canonical LS or HS. Fig. 1(a) presents the light curve of a typical 'oscillation' event in which the source makes a transition from state C to state A/B. The data correspond to the *RXTE* observation of 1999 June 14 (class ν); time zero is 01:00:40 UT. These oscillation events can occur in very long sequences and are generally associated with sequences of synchrotron oscillations which are almost certainly from the jets (e.g. Klein-Wolt et al. 2002).

2.2.2 GX 339−4

GX 339−4 is also a key source in our understanding of the disc–jet coupling in X-ray binaries (Fender et al. 1999b; Corbel et al. 2000, 2003; Gallo et al. 2003; Belloni et al. 2004), albeit one that varies on time-scales considerably longer than in GRS 1915+105. Recently, a clear bright optically thin radio flare was observed from this source, and subsequently found to be associated with a relativistic ejection event (Gallo et al. 2004a). The light curve, corresponding to the first part of the 2002/2003 outburst (Belloni et al. 2004), presented in Fig. 1(b) shows many similarities with that of GRS 1915+105 (Fig. 1a) in the X-ray band, with a rising hard (in this case the canonical LS) state softening shortly before a soft VHS/IS peak. Subsequently, both sources show a drop in the X-ray flux and then a slow recovery to even higher levels. Compared to GRS 1915+105 we see that the softening of the X-ray state began a few days *before* the radio flare, which seems to correspond to the VHS/IS peak near the *end* of the softening. However, the key thing we learn from GX 339−4 compared to GRS 1915+105 is that the major radio event is also associated with the state transition, something that is not unambiguous in GRS 1915+105. In this context it is interesting to note that the rise and decay time-scales of the radio oscillation events in GRS 1915+105 are comparable to the durations of both the hard VHS/IS and soft VHS/IS states (since the source is in general 'oscillating' between the two). However, in GX 339−4 we see that this is clearly not the case, and that the transient radio event is associated with a specific and very limited instant in time.

2.2.3 XTE J1859+226

XTE J1859+226 (Fig. 1c) is a more 'traditional' transient than either GRS 1915+105 or GX 339−4, and underwent a bright outburst in 1999 (Wood et al. 1999; Markwardt, Marshall & Swank 1999; Brocksopp et al. 2002; Casella et al. 2004). It showed an initial LS peak during the rise to outburst, which preceded the subsequent soft peak by several days. This allows us to separate the LS and VHS/IS peaks (which was impossible for GRS 1915+105 and still difficult for GX 339−4) and to identify which is associated with the radio event. The radio data used in Fig. 1(c) are from Brocksopp et al. (2002).

This source peaked in hard X-rays (see BATSE light curve in Brocksopp et al. 2002) about a week before the soft peak. The X-ray state between the two peaks can be formally described as a 'hard VHS/IS' which is gradually softening. The optically thin radio event is clearly associated not with the peak of the LS, after which the X-ray spectrum starts to soften, but with the VHS/IS peak, which seems to occur just at the end of the spectral transition. Note also that some radio emission persists after the LS peak, into the VHS/IS (further discussion below).

2.2.4 XTE J1550−564

XTE J1550−564 (Fig. 1d) is another bright transient which has undergone several outbursts in recent years. The data analysed here correspond to the brightest one, in 1998/1999 (see Sobczak et al. 2000; Homan et al. 2001; Remillard et al. 2002). This outburst was associated with a very strong optically thin radio event subsequently resolved into a radio (Hannikainen et al. 2001) and, most spectacularly, an X-ray jet moving relativistically (Corbel et al. 2002). The radio data plotted in Fig. 1(d) are from Wu et al. (2002) and Hannikainen et al. (in preparation).

As in XTE J1859+226, the LS and VHS/IS peaks are clearly separated in time, in this case by approximately two weeks. Cursory inspection of Fig. 1(d) clearly indicates that the optically thin jet is launched at the time of the VHS/IS peak, which occurs, again, just at the end of the X-ray spectral transition. Once more, as in XTE J1859+226, we also note low-level radio emission between the LS and VHS/IS peaks.

3 JETS AS A FUNCTION OF X-RAY STATE: NEW PERSPECTIVES

Based upon the investigation we have performed, we are better able to associate the characteristics of the radio emission

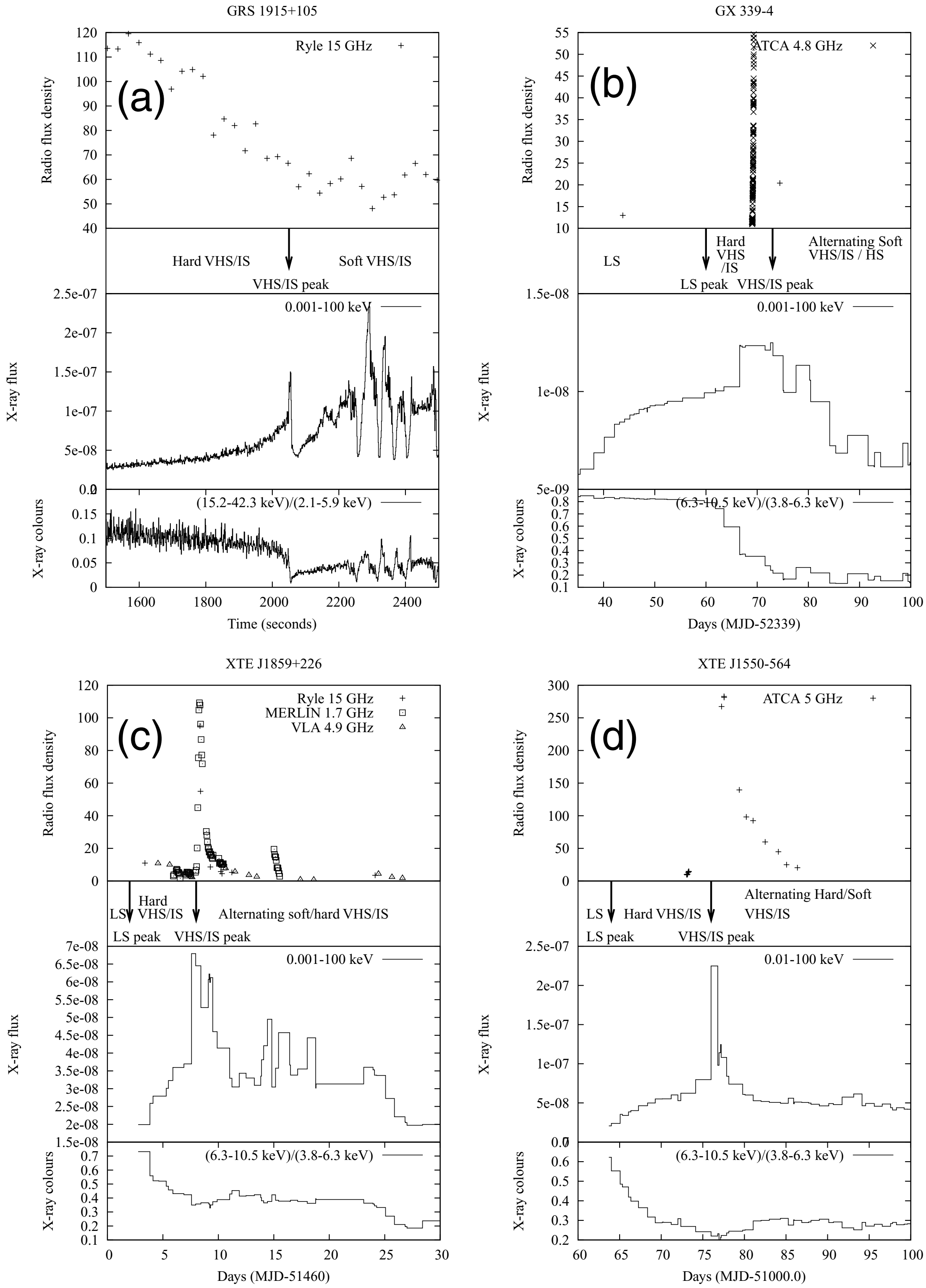

Figure 1. Radio and X-ray light curves, X-ray colours and X-ray state classifications during periods around transient jet formation, for four black hole (candidate) X-ray binaries. In GRS 1915+105 the canonical LS or HS are never reached; in GX 339−4, XTE J1859+226 and XTE J1550−564 the delay between the canonical LS peak and subsequent VHS/IS peak ranges from a few days to two weeks. Nevertheless, in all four cases the radio flare occurs at the time of the VHS peak, indicating a clear association between this, and not the previous LS, and the major ejection. The units of the X-ray flux are erg s^{-1} cm^{-2}.

as a function of X-ray state, and therefore to probe the details of the jet–disc coupling. While the previously established pattern,

(i) LS = steady jet,

(ii) HS = no jet,

remains valid, additional information has clearly come to light about the details of jet formation in the VHS/IS during transient outbursts.

3.1 Persistence of the steady jet in the 'hard' VHS/IS

It has by now been established for several years that the canonical LS is associated with persistent flat- or inverted-spectrum radio emission which probably arises in a self-absorbed, self-similar outflow (Fender 2001b). This radio emission is correlated with the X-ray emission as $L_{\rm radio} \propto L_{\rm X}^{b}$ where $b \sim 0.7$ with a small apparent range in normalizations for several different systems (Corbel et al. 2003; Gallo et al. 2003) [see also Fender et al. (2003) and Jonker et al. (2004) for further discussions and implications].

While the HS was known to be associated with a dramatic decrease in the radio emission (e.g. Tananbaum et al. 1972; Fender et al. 1999b; Gallo et al. 2003), it was not well known how the radio emission behaved in the VHS/IS. Fender (2001a) suggested, based upon GRS 1915+105, that the VHS/IS was associated with unstable, discrete ejection events. Corbel et al. (2001) reported that, 11 d after a transition to the VHS/IS, the radio emission from XTE J1550−564 was reduced ('quenched') by a factor of 50 compared to the previous LS.

However, it is clear from Fig. 1 that some radio emission persists beyond the end of the canonical LS, before the outburst. Some of the best data available are those of XTE J1859+226 (Brocksopp et al. 2002), which are plotted in Figs 1(c) and 2. For at least 3 d following the LS peak, while the X-ray spectrum is softening, the radio emission is persistent, with an approximately flat spectrum. Furthermore, the radio luminosity remains consistent with the universal relation of Gallo et al. (2003); this is demonstrated in the left panels of Fig. 2. In fact, inspecting fig. 3 of Gallo et al. (2003) we can see that, in the case of Cyg X-1, the turnover in the radio emission occurs *after* there has already been some softening of the X-ray emission, implying also that the compact jet persists into the 'hard VHS/IS'. Based on a recent study of XTE J1650−500, Corbel et al. (2004) have also concluded that the steady jet may persist beyond the initial softening of the canonical LS. The importance of this is that there is clearly *not* a one-to-one relation between the behaviour of the radio emission and the X-ray states as currently defined (this will be discussed more later).

3.2 Changes in the jet radio spectrum *prior* to the outburst

Following the persistence of the steady LS-like radio emission into the hard VHS/IS, the data indicate that a change in the radio emission does occur prior to the radio flare. In brief, it appears that the radio emission starts to become more variable, with a peaked or (more) optically thin spectrum shortly before the radio flare. We present the evidence for this from the following four key sources under study here.

3.2.1 GRS 1915+105

Given that, in GRS 1915+105, (i) we are typically observing radio emission from the *last* state transition, and (ii) the transition period between the 'hard' and 'soft' VHS/IS is very rapid, it is not possible to investigate this effect for the oscillation-type events in this source. However, the effect is seen in the monitoring of the plateau state and subsequent radio flares as reported in Fender et al. (1999a). As noted in that work (see also discussion in Klein-Wolt et al. 2002), major radio ejections (which were directly resolved) followed the plateau. Thus, as in the other sources, a transition from the 'hard' to the 'soft' VHS/IS (as GRS 1915+105 rarely, if ever, reaches the canonical LS or HS) resulted in a major ejection. However, the data also reveal that the radio spectrum started to change *prior* to the first major ejection event. This is presented in Fig. 2.

In fact the radio spectrum is already 'optically thin' a couple of days before the flux starts rising, reaching a mean value of −0.6 on MJD 50 750, the day before the flare. The change in the radio spectrum occurs around the time that the spectrum starts to soften dramatically towards the 'soft' VHS/IS.

3.2.2 GX 339−4

The detailed radio light curve of GX 339−4 around the time of the major radio flare is reported in Gallo et al. (2004a). During the first 2 h of observations on MJD 52 408, immediately prior to the rise of the radio flare, the spectral index seems to vary from flat to more optically thin ($\alpha \sim -0.2$) and back to flat. Even though the error bars are relatively large, this is consistent with rapid variability of the radio spectrum outflow structure prior to the radio flare.

3.2.3 XTE J1859+226

In this source, over the 4 d prior to the flare on MJD 51 467.5, the radio spectrum changes from flat ($0.037 \geqslant \alpha \geqslant -0.030$) to more optically thin ($\alpha = -0.237$ on MJD = 51 467); see Fig. 2 (lower panels). On this date, the radio spectrum is measured over seven frequencies: fig. 5 of Brocksopp et al. (2002) shows that the actual spectrum, even though overall optically thin, is peaked around 3 GHz (i.e. flat inverted till 3 GHz and optically thin above), indicating that a structural change in the outflow has occurred prior to the flare.

3.2.4 XTE J1550−564

The radio coverage of the outburst of XTE J1550−564 as presented in Fig. 1(d) is reported in Wu et al. (2002). However, further measurements presented in Hannikainen et al. (in preparation) indicate that on MJD 51 073, some 4.5 d prior to the flare, there was rapid spectral variability. This included a transition from a peaked to an optically thin spectrum, and back to a peaked spectrum again, on a time-scale of less than half a day.

3.3 Association of the outburst with the soft VHS/IS peak

Many – perhaps all – sources that undergo an X-ray outburst have a bright hard state during the rising phase (e.g. Brocksopp et al. 2002; Maccarone & Coppi 2003; Yu et al. 2003; Yu, van der Klis & Fender 2004). We know that hard X-ray states correspond to phases of powerful jet production, and that the relativistic ejections tend to occur around the time of X-ray state transitions, and that soft states do not seem to produce jets (see Fender 2004, for a review).

What was difficult to tell from investigation of the most-studied sources like GRS 1915+105 and GX 339−4 was to what part of the state transition sequence the optically thin jet formation corresponded. The above examples appear to give a clear answer: the optically thin radio jet is produced at the VHS/IS peak, which occurs at or near the end of the X-ray spectral softening. We note that this is consistent with the suggestion of Mirabel et al. (1998) that the 'spike' in the X-ray light curve of GRS 1915+105 corresponded to the trigger point for the optically thin radio event, although, as we have seen, in the case of GRS 1915+105 there are many ambiguities that cannot be resolved by studying this source in isolation.

Fig. 3 presents the hardness–intensity diagrams (HIDs) for three of the four sources presented in Fig. 1, with the point corresponding

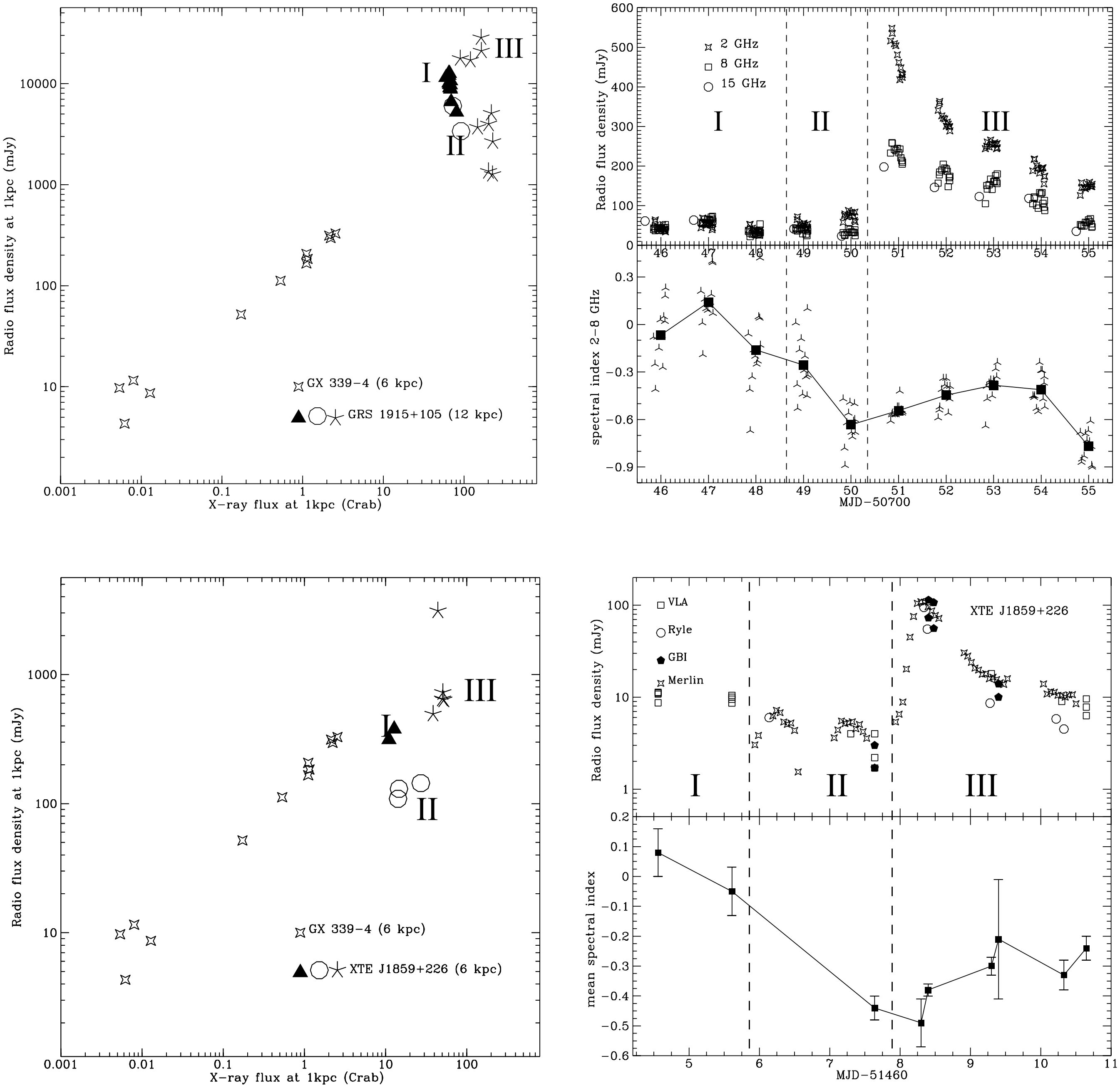

Figure 2. Behaviour of radio emission immediately prior to optically thin flare events. The upper left panel shows data for the GRS 1915+105 plateau reported in detail in Fender et al. (1999a); the lower left panel shows the outburst of XTE J1859+226 reported in Brocksopp et al. (2002) and also Fig. 1 herein. The right-hand panels show in detail the radio light curves and fitted spectral indices over this period, and are separated for each source into three phases. The location of these phases in the radio luminosity versus X-ray luminosity ($L_{\rm radio}$–$L_{\rm X}$) plane (Gallo et al. 2003) is indicated in the left-hand panels [the X-ray luminosity is calculated from the *RXTE* ASM, as in Gallo et al. (2003), and is therefore much less accurate than the fluxes presented in Fig. 1]. Initially, while still in a 'hard' VHS/IS, both sources display optically thick radio emission which lies close in the $L_{\rm radio}$ –$L_{\rm X}$ plane to the mean relation for LS black hole X-ray binaries, as marked out by the data for GX 339−4 (Gallo et al. 2003). Subsequently, the radio emission seems to become more erratic and occasionally optically thin.

most clearly to the time of the major radio flare indicated with a circle. In these HIDs the canonical LS corresponds to a nearly vertical branch on the right-hand side of the diagram, seen here only for GX 339−4; the horizontal right-to-left motion exhibited by these sources is characteristic of a transition from a 'hard' to a 'soft' VHS/IS (Belloni 2004; Belloni et al. 2004; Homan & Belloni, in preparation). Furthermore, the X-ray intensity has been converted to an Eddington-fraction luminosity, based upon the distance and mass estimates given in Table 1. It is clear that in all cases the radio flare occurs when the sources are in the VHS/IS, having significantly softened from the LS prior to the event, and with a X-ray luminosity in the range 10–100 per cent Eddington.

It is worth revisiting the result of Corbel et al. (2001) in which XTE J1550−564 was found to be radio-quiet while in the VHS/IS.

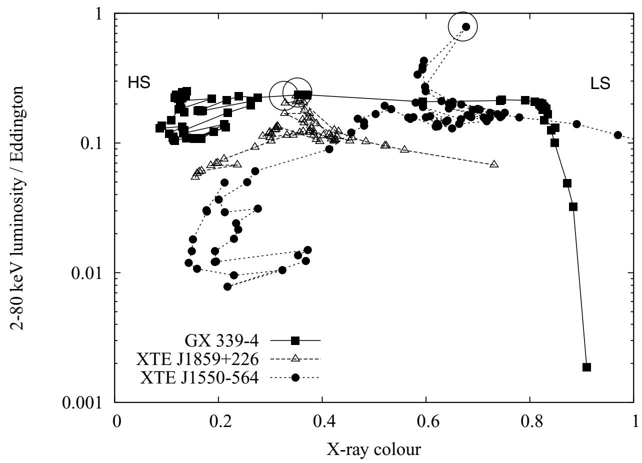

Figure 3. Combined X-ray hardness–intensity diagram (HID) for GX 339−4, XTE J1859+226 and XTE J1550−564. The X-ray fluxes plotted in Figs 1(b)–(d) have been scaled to Eddington-ratioed luminosities using the distance and mass estimates given in Table 1. Note that ejections in GX 339−4 and XTE J1859+226 occur at almost exactly the same colour and X-ray luminosity. Most of the data points correspond to varying degrees of the VHS/IS, and not the canonical LS (to the right) or HS (to the left).

An inspection of the X-ray data indicates the following: The first radio observation, which resulted in an optically thin detection, was made within a day or two of the soft VHS/IS peak. The second observation, resulting in an upper limit only, was several days late, in the middle of the soft VHS/IS phase. Thus these observations are consistent with the picture presented here, namely that the optically thin radio flare occurs at the soft VHS/IS peak, and in the subsequent soft VHS/IS phase the core radio emission is suppressed.

Corbel et al. (2004) report a detailed study of the radio emission from the black hole transient XTE J1650−500 (plus a phenomenological comparison with XTE J1859+226 and XTE J1550−564) in which the canonical LS and HS, as well as various 'degrees' of VHS/IS, were observed. Specifically they conclude that the steady LS jet may persist into the 'hard' VHS/IS, and that the optically thin radio flare is associated with the soft VHS/IS peak (although they use the state definitions of McClintock & Remillard 2004). These results seem to be consistent with the conclusions we have drawn (more quantitatively) about the association of X-ray states and jet production.

3.4 Variation of accretion disc radius with state

It is widely accepted that a geometrically thin, optically thick, accretion disc extends close to the black hole in 'soft' X-ray states and is 'truncated' at larger radii in 'harder' X-ray states (e.g. Esin, McClintock & Narayan 1997; McClintock & Remillard 2004, and references therein). While the absolute values of the radii obtained from X-ray spectral fits may be severely underestimated (e.g. Merloni, Fabian & Ross 2000a), large changes in the fitted radii are likely to be due to real changes in the location of the brightest X-ray-emitting region. Specifically, we have the following for the four sources under detailed consideration here.

3.4.1 GRS 1915+105

The 'dip-flare' cycles of GRS 1915+105, such as those presented in Fig. 1(a), are well known to be associated with apparent changes in the fitted accretion disc radius (e.g. Belloni et al. 1997; Fender & Belloni 2004, and references therein). During the 'soft VHS/IS' (states A/B) the fitted inner disc radius reaches a stable, low, value and is considerably larger in the 'hard VHS' (state C).

3.4.2 GX 339−4

Spectral fits over the period focused on in Fig. 1(b) indicate a fitted inner disc radius that decreased dramatically at the point of spectral softening (Zdziarski et al. 2004; Nespoli 2003). This low value of the fitted inner radius remained stable for an extended period (>100 d) until the return to the canonical LS.

3.4.3 XTE J1859+226

To our knowledge, detailed spectral fits over the entire outburst of XTE J1859+226 have not been published. However, both the general X-ray spectral and timing evolution and the preliminary fits reported by Markwardt (2001) indicate a similar pattern to other X-ray binaries. Hynes et al. (2002) discuss the post-outburst evolution of the accretion disc in XTE J1859+226, but note that the absolute value of the inner disc radius cannot be well constrained, and so it is hard to use their results to compare with those earlier in the outburst.

3.4.4 XTE J1550−564

Sobczak et al. (2000) fitted disc radii to over 200 spectra of XTE J1550−564 during the entire 1998–1999 outburst. They found that at the peak of the outburst ('soft VHS') the fitted disc radii varied a lot but were in general very (unrealistically) small. Subsequently, in the canonical HS state the disc radius remained relatively small and stable over ∼100 d.

3.5 The alternative state definitions of McClintock & Remillard

We can summarize these connections between X-ray state and radio emission within the framework of the revised definitions of McClintock & Remillard (2004). This is presented in Table 2. Two significant points are worth noting:

(i) In the framework of McClintock & Remillard, it may be exactly the point of the transition to the SPL that corresponds to the radio ejection event.

(ii) In the same framework, there appear to be both 'jet on' and 'jet off' phases associated with the same state 'intermediate' label.

Table 2. Comparison of the 'classical' X-ray states, and those of McClintock & Remillard (2004), with the radio properties as discussed in detail in the text. 'VHS/IS' corresponds to 'very high state/intermediate state' and 'SPL' stands for 'steep power law'.

'Classical' states	McClintock & Remillard	Radio properties
low/hard state (LS)	hard state	steady jet
'hard' VHS/IS	intermediate state	steady jet
'hard' → 'soft' VHS/IS	intermediate → SPL	radio flare
'soft' VHS/IS	intermediate/SPL	no jet
high/soft state (HS)	thermal dominant	no jet

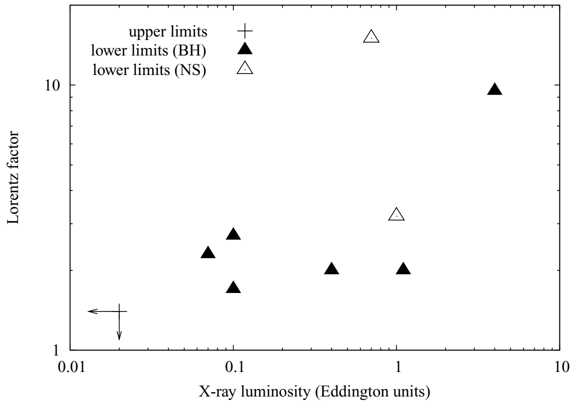

Figure 4. Limits on jet Lorentz factors as a function of the estimated bolometric X-ray luminosity at the time of jet launch. The arrows in the lower left of the figure indicate the condition that jets in the general LS state have $v \leqslant 0.8c$. The rest of the symbols are lower limits only to the Lorentz factors from individual black hole (filled symbols) and neutron star (open symbols) X-ray binaries; the data are listed in Table 1.

Point (i), already suggested by McClintock & Remillard (2004), has been noted as likely also by Corbel et al. (2004). However, considering point (ii), it appears that the new definitions have both advantages and disadvantages.

4 INCREASING VELOCITY AS A FUNCTION OF X-RAY LUMINOSITY AT LAUNCH

A further key component for the model towards which we are progressing is the variation of jet velocity with X-ray luminosity/state. The empirical evidence clearly points to an increase of jet velocity with X-ray luminosity, at least in the sense of a step up from mildly relativistic velocities in the LS to significantly relativistic velocities resulting from outbursts at a significant fraction of the Eddington limit. Table 1 presents a compilation of estimated jet Lorentz factors as a function of the X-ray luminosity at launch. In fact, with the exception of the upper limit for the LS sources (see below), these are all based upon observed proper motions in spatially resolved radio maps and are therefore only lower limits (see Fender 2003). These data are plotted in Fig. 4. Note that a higher Lorentz factor in transient jets associated with outbursts is further supported by the much larger scatter in the $L_{\rm radio}$–$L_{\rm X}$ plane compared to the LS sources (Gallo et al. 2003).

The measured spread to the radio/X-ray correlation in LS black hole X-ray binaries was interpreted by Gallo et al. (2003) in terms of a distribution in Doppler factors and used to infer an upper limit $\Gamma \lesssim 2$ to the bulk velocity of compact jets. The value of the spread as it appears in Gallo et al. is mainly determined by the two data sets for which the correlation extends over more than three orders of magnitude in X-ray luminosity, namely V 404 Cyg and GX 339−4. Obviously, errors in the distance estimates to these systems will introduce a further source of scatter to the correlation. While V 404 Cyg is (reasonably well) known to lie at ~3.5 kpc (Wagner et al. 1992), the distance to GX 339−4, and hence its luminosity, remain uncertain. Recent works (Hynes et al. 2004; Zdziarski et al. 2004) have significantly revised the lower limit of 4 kpc (Zdziarski et al. 1998) adopted in Gallo et al. (2003), placing GX 339−4 at a distance larger than 6 kpc. In particular, Hynes et al. (2004) discuss the possibility that the system could even be located on the far side of the Galaxy, at ~15 kpc. In fact, any value between 6 and 15 kpc has the effect of lowering the final spread to the radio/X-ray correlation by shifting GX 339−4 closer to V 404 Cyg, resulting in a more stringent upper limit on the jet bulk Lorentz factor. A minimum distance to GX 339−4 of 6 kpc reduces the measured spread by a factor of 1.6, requiring an outflow bulk velocity smaller than $0.7c$. This sets a new upper limit of $\Gamma_{\rm radio} \lesssim 1.4$ to the average bulk Lorentz factor of LS black hole X-ray binary jets; in fact, the distance to GX 339−4 would have to be larger than 15 kpc before the spread exceeds again the value obtained for 4 kpc. As discussed in Gallo et al. (2003), the above arguments are formally valid in the case of radio beaming combined with isotropic X-ray emission, but if X-rays are moderately beamed [$v_{\rm X} \sim 0.3c$, as suggested by, for example, models of dynamical coronae (Beloborodov 1999), the conclusions remain essentially unchanged.

However, Heinz & Merloni (2004) argue that the spread around the correlation can only really be used, in the absence of additional information, to constrain the *range* in jet velocities, and not the absolute values. Based upon their arguments, it remains likely that the bulk Lorentz factor of the LS jets is $\Gamma \sim 1$ but it is not a formal requirement. Based upon an analysis of the normalizations for GX 339−4 and V 404 as estimated in Gallo et al. (2003), they conclude that the Lorentz factors of the two sources differ by no more than a factor of 2. Given the ‘universality’ – within about one order of magnitude – of the correlation presented in Gallo et al. (2003), this in turn implies that independent measurement of the Lorentz factor of a jet in the LS would apply to all LS sources. In the discussion that follows, we shall continue to assume that the Lorentz factor of the steady jets is $\Gamma \leqslant 2$ but note that it is not proven.

What is not clear from these data is whether the velocity is a simple ‘step’ function of the X-ray luminosity at launch, or rather a smoother function. As discussed in Fender (2003) a broad range in Γ will, in most circumstances, produce approximately the same proper motions. For the simple unified model discussed in this paper, either (‘step’ or smooth function) interpretation is sufficient. The key factor is that the jets associated with the VHS/IS peak are probably more relativistic than those in the LS which generally precedes it.

5 RADIO EMISSION AND JET POWER

It is also crucial to estimate the jet power as a function of X-ray luminosity/state. In the following we present simplified expressions for the power in both optically thick and optically thin jets, in Eddington units, as a function of observable radio and X-ray emission.

5.1 The low/hard state optically thick jet

In Fender et al. (2003) it was argued that the total jet power $L_{\rm J}$, in the absence of significant advection, was related to the accretion luminosity $L_{\rm X}$ as follows:

$$L_{\rm J} = A_{\rm steady} L_{\rm X}^{0.5},$$

where $A_{\rm steady} \geqslant 6 \times 10^{-3}$ (the normalization is referred to simply as A in Fender et al. 2003).

Studies of the rapid variability from the ‘hard’ transient XTE J1118+480, which remained in the LS throughout its outburst, have supported the idea that the optical emission may originate in an outflow and not reprocessed emission from the disc (Merloni, Di & Fabian 2000b; Kanbach et al. 2001; Spruit & Kanbach 2002; Malzac, Merloni & Fabian 2004). Detailed modelling of the correlated variability by Malzac et al. (2004) has resulted in a normalization of the jet/outflow power which corresponds to $A_{\rm steady} \sim 0.3$ in the above formalization, which would imply that all LS sources are jet-dominated. For now we shall take this as the largest likely value of $A_{\rm steady}$ [see also Yuan, Cui & Narayan (2004), who estimate a value for the radiative efficiency for the jet in XTE J1118+480 that lies between the lower limit of Fender et al. (2003) and the estimate of Malzac et al. (2004)].

5.2 The optically thin jets

The power associated with the production of optically thin jets can be calculated from the peak luminosity and rise time of the event, adapting the minimum energy arguments of Burbidge (1956, 1959), as follows:

$$L_{\rm J} = 20\Delta t^{2/7} L_{\rm radio}^{4/7} M^{-3/7} = 2\times10^{-5}\,\Delta t^{2/7} d^{8/7} S_{5\,\rm GHz}^{4/7} M^{-1},$$

where $L_{\rm J}$ is the mean power into jet production (in Eddington units), Δt is the rise time of the event (in seconds), $L_{\rm radio}$ is the peak radio luminosity of the event at 5 GHz (in Eddington units), d is the distance (in kpc), $S_{5\,\rm GHz}$ is the peak radio flux density at 5 GHz (in mJy), and M is the black hole mass (in solar units). The equation assumes an emitting plasma with volume corresponding to $4\pi(\Delta t c)^3$, a filling factor of unity, negligible energy in protons, and a spectral index of $\alpha = -0.75$. See Longair (1994) for a fuller discussion.

In addition, since we have argued above that the bulk Lorentz factor is considerably higher for the transient jets underlying these optically thin outbursts, we need to compensate for the resultant Doppler effects. Fender (2001b) demonstrated that it is much more likely, for significantly relativistic jets, that the jet power is underestimated than overestimated, and introduced a correction factor $F(\Gamma, i) = \Gamma\delta^{-3}$, where δ is the relativistic Doppler factor associated with bulk Lorentz factor Γ (the correction includes the kinetic energy of bulk flow). For $2 \leqslant \Gamma \leqslant 5$ the mean value of $F(\Gamma, i)$ averaged over cos (i) is $\sim$50. We adopt this value as an additional (upward) correction to the power of the optically thin jets. Comparison of the formula given above with specific examples more carefully considered, e.g. the 1997 ejections from GRS 1915+105 reported by Fender et al. (1999a), indicate this to be a reasonable correction. As discussed earlier, however, we have no clear upper limit on Γ associated with these events, and the correction could be much larger. For example, for $2 \leqslant \Gamma \leqslant 7$ the mean value of $F(\Gamma, i)$ is $\sim$160, and for $2 \leqslant \Gamma \leqslant 10$ it is $\sim$575.

In Table 1 we list in columns 8 and 9 the estimated optically thin radio powers during the flare events, $L_{\rm J}$, and the corresponding peak 'soft VHS/IS' X-ray luminosity, $L_{\rm X,VHS}$, both expressed as Eddington fractions. These values are plotted against each other in Fig. 5, and compared with the functions for the steady/LS jets as outlined above, for both the Fender et al. (2003) lower limit and the Malzac et al. (2004) estimate.

A best-fitting power law to the data for the transient events is of the form

$$L_{\rm jet} = A_{\rm trans} L_{\rm X}^{0.5\pm0.2},$$

where the fitted value is $A_{\rm trans} = (0.4 \pm 0.1)$. Note that, since for the transient jets $L_{\rm X} \sim 1$, this indicates near equipartition of $L_{\rm X}$ and $L_{\rm J}$ around the time of such events.

The index of the fit, 0.5 ± 0.2, is comparable to that derived for the LS, namely $L_{\rm jet} \propto L_{\rm X}^{0.5}$ (Fender et al. 2003). The value of the normalization, $A_{\rm trans}$, is much larger than the conservative value for the steady jet normalization $A_{\rm steady}$ estimated in Fender et al. (2003, see above). However, it is only $\sim$50 per cent larger than the value of $A_{\rm steady}$ implied by the results of Malzac et al. (2004). Were such a large value to be valid for the LS, it would imply that black hole X-ray binaries are likely to be jet-dominated below $L_{\rm X} = A_{\rm steady}^2 \sim 0.1\,L_{\rm Edd}$. Since most sources do not strongly exceed this Eddington ratio while in a 'hard' X-ray state (see e.g. Figs 3 and 5), it implies that *only* in the HS and 'soft' VHS/IS and states, when the jet is suppressed, is the X-ray luminosity dominant over the jet (see also the discussion in Malzac et al. 2004). Put another way, for such a large normalization, whenever the jet is on, it is the dominant power output channel.

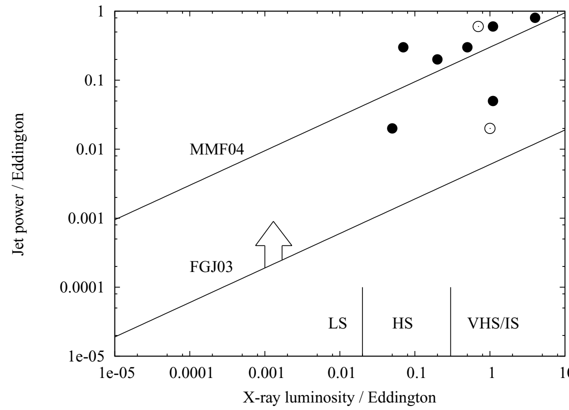

Figure 5. Comparing estimated jet power in the steady/LS and transient/VHS/IS states. Note that the uncertainties on the estimated jet powers are large, *at least* one order of magnitude. The solid line marked FGJ03 indicates the lower limit to the steady jet power in the LS as estimated by Fender et al. (2003). The line marked MMF04 indicates the same function with the larger normalization as calculated by Malzac et al. (2004). The solid points indicate the estimates of jet power for the transient events listed in Table 1. It is interesting to note that the data are therefore compatible with the MMF04 relation at all X-ray luminosities. If the steady LS jet power is lower, nearer to the lower limit indicated by the FGJ03 function, then there may be a step up in jet power for the transient events. A very approximate indication of the regimes typically corresponding to the different X-ray states is indicated at the bottom of the figure. The power estimates for the two neutron star sources, Sco X-1 and Cir X-1, are indicated by open symbols.

5.3 Some caveats

Note that there are very large uncertainties remaining in the estimation of both $A_{\rm steady}$ and $A_{\rm trans}$. The functions used for the power of the steady jets are based upon essentially one detailed example (XTE J1118+480) and extrapolated to other sources via the 'universal' $L_{\rm radio} \propto L_{\rm X}^{0.7}$ relation (although estimates from a handful of other sources are also compatible). While this approach may well be appropriate, spectral changes – in particular the location of the optically thin break in the synchrotron spectrum – could strongly affect the variation of $L_{\rm J}$ as a function of $L_{\rm X}$, and more work needs to be done in the future.

In the case of the power function for the transient jets, we have in fact more independent measurements, but those measurements themselves probably have a greater associated uncertainty. Underestimation of $L_{\rm J}$ can clearly arise due to deviations from equipartition, a lack of knowledge of the high-frequency extension of the synchrotron spectrum, and a possible underestimate of the bulk Lorentz factor. Overestimation of $L_{\rm J}$ could arise due to overestimation of the synchrotron-emitting volume (i.e. a filling factor $f < 1$ or injection/acceleration of particles into a confined jet).

5.4 A single function or a step up in jet power?

Nevertheless, it is notable that a single power-law relation could be plotted through both the steady LS and transient VHS/IS functions, and that the normalization of such a single function would be close to that estimated by Malzac et al. (2004), i.e. $A_{\rm steady} \sim A_{\rm trans} \sim 0.3$.

If there is not a single function, then it seems that the transient VHS/IS jets are somewhat more powerful as a function of $L_{\rm X}$ than an extrapolation of the steady LS jets function. This suggestion is strengthened by our argument, below, that the optically thin events are likely to arise in internal shocks which do not dissipate 100 per cent of the available kinetic energy. If real, this effect may be due to temporarily increased efficiency of jet production in the inner disc, or to the transient addition of a new power source, namely the black hole spin (e.g. Blandford & Znajek 1977; Punsly & Coroniti 1990; Livio, Ogilvie & Pringle 1999; Meier 1999, 2001, 2003; Koide et al. 2002). Nevertheless, we consider the similarity in both gradient and normalization of the two jet functions to be remarkable. We note that, for the model outlined in this paper to be tested against higher-mass (intermediate or supermassive) black holes, a further mass term would be required for both expressions (see Heinz & Sunyaev 2003; Merloni, Heinz & di Matteo 2003; Falcke, Körding & Markoff 2004). However, for the X-ray binaries where the range in mass is likely to be $\leqslant 2$, this is not important at the current level of accuracy.

6 INTERNAL SHOCKS

The arguments given above clearly indicate that, as the X-ray luminosity of the accreting source increases, then so does the velocity of the outflow (although whether this is in the form of a step, or other functional form, is as yet unclear). Since most, probably all, outbursting sources have followed a path in which they have become monotonically brighter in a hard state before making a transition to a soft state, this tells us that a shock should form in the previously generated 'steady' jet as the faster-moving VHS/IS jet catches up and interacts with it. This internal shock is therefore a natural origin for the optically thin events observed at the beginning of X-ray transient outbursts. Internal shocks have previously been proposed for active galactic nuclei (AGN) (e.g. Rees 1978; Marscher & Gear 1985; Ghisellini 1999; Spada et al. 2001) and γ-ray bursts (GRBs) (e.g. Rees & Meszaros 1994; Van Paradijs, Kouveliotou & Wijers 2000, and references therein). Indeed in the context of X-ray binaries an internal-shock scenario has already been discussed previously for GRS 1915+105 by Kaiser, Sunyaev & Spruit (2000), Vadawale et al. (2003) and Turler et al. (2004), and their ideas have significantly inspired this work.

Rees & Meszaros (1994) spelled out the basis for such 'internal shocks' in the context of GRBs. They assumed that two 'blobs' of equal mass but differing Lorentz factors were ejected such that the later ejection had the higher Lorentz factor. This component, if moving along precisely the same trajectory as the original component, will collide with it. Assuming conservation of energy and momentum, it was shown that up to 40 per cent of the total kinetic energy could be released in this shock.

The formulation for the efficiency of energy release, ϵ, as presented in Rees & Meszaros (1994), corresponds to the case in which both blobs have Lorentz factors $\Gamma_{1,2} \gg 1$. We have repeated their approach, but considered instead the (less simple) case in which the first blob is at most only mildly relativistic ($\Gamma_1 < 2$). In Fig. 6 we plot the internal shock efficiency for two cases:

(a) The blobs have the same total energy, fulfilling the criterion that $\Gamma_1 M_1 = \Gamma_2 M_2$ (where M is the mass of the blob). This corresponds to the situation in which the jet power does not increase significantly, while the Lorentz factor does.

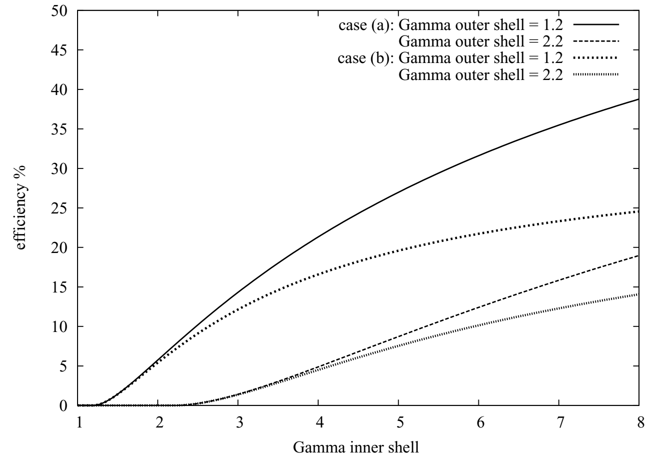

Figure 6. Efficiency of energy release for the collision of two shells, where the outer shell is only mildly relativistic (bulk Lorentz factor, BLF) $\Gamma < 2$, under the assumption of conservation of momentum and energy. Case (a) corresponds to the case of two blobs with equal total energy (i.e. $\Gamma_1 M_1 = \Gamma_2 M_2$), in which case the jet power has not increased. Case (b) corresponds to the case of the same mass but increased Lorentz factor, i.e. an increase in jet power by a factor $\Gamma_2 - \Gamma_1$. This can be considered a (highly oversimplified) approximation to the collision of a relativistic VHS/IS jet (inner shell) with the preceding steady LS jet (outer shell).

(b) The blobs have equal mass. This corresponds to a genuine increase in jet power by a factor $\Gamma_2 - \Gamma_1 \sim \Gamma_2$. This corresponds to the maximum efficiency for the internal shock (e.g. Spada et al. 2001).

For the kind of values estimated for transient jets, efficiencies in the range 5–40 per cent are expected. For a total jet power of $P_{\rm J}$, the power in the shock (i.e. available for particle acceleration) will be $P_{\rm shock} \leqslant \epsilon P_{\rm J}$. The remaining jet power $(\epsilon - 1)P_{\rm J}$ is associated with the kinetic energy of the merged shells and should eventually be dissipated via interactions with the ambient medium.

Of course, this is a highly oversimplified approximation of the true circumstances as the jet increases in velocity. Nevertheless, it illustrates that the internal shock produced by a transient (as it is subsequently shut down in the soft state) acceleration of the jet from $\Gamma \sim 1$ to $\Gamma \lesssim 10$ could produce dissipation in an internal shock with an observed energy release comparable (within the order-of-magnitude uncertainty) to that estimated for the steady jet prior to the acceleration. If, as seems likely, $A_{\rm trans} \geqslant A_{\rm steady}$, then the more efficient shock scenario (b) (Fig. 6) is more likely, and the total jet power, and not just velocity, has significantly increased. Beloborodov (2000) discusses in further detail the high radiative efficiencies that may be obtained in the internal shock model.

The internal shock scenario is also attractive as an explanation for why the same radio flux at a given radio frequency for a given source can be sometimes optically thin and sometimes optically thick. Consider GRS 1915+105, where in the plateau states a flux density of ∼40 mJy at 15 GHz may be associated with an optically thick spectrum, and later a comparable flux density with optically thin rising phases of oscillation events (e.g. Fender et al. 1999a). If the particle acceleration all occurred at the base of a jet with an approximately fixed structure, this is hard to explain. However, it follows naturally from a scenario where the optically thin events are associated with internal shocks occurring at a much larger distance from the dense inner jet.

Note that it is the radiation resulting from the energy liberated by the internal shock that we have measured in order to estimate the jet power in Section 5. However, since our estimates of the bulk Lorentz factor must be based upon observations of the post-shock plasma, then the true jet power must be larger by a factor ϵ^{-1}. Since $0.05 \lesssim \epsilon \lesssim 0.45$ in the above simplification, this may imply that the underlying jet power is actually a further order of magnitude larger for the transient jets. In this case a single function corresponding to both the LS and VHS/IS jets seems less likely.

As discussed in Vadawale et al. (2003), the strength of the shock is likely to be related to the amount of material lying in the path of the faster 'VHS/IS' jet. They discussed this in the context of GRS 1915+105, where the strength of 'post-plateau jets' (Klein-Wolt et al. 2002) is shown to be correlated with the total X-ray fluence of the preceding 'plateau' (which was presumably a phase of slower jet production). Generalizing this phenomenon to other X-ray transients, it provides a natural explanation for why, although there are often multiple radio flaring events, the first is invariably the strongest.

7 TOWARDS A UNIFIED MODEL

Based upon the key generic observational details assembled above, we have attempted to construct a unified, semiquantitative, model for the disc–jet coupling in black hole X-ray binaries. A simplified version of the model specific to GRS 1915+105 has been presented in Fender & Belloni (2004). The model is summarized in Fig. 7, which we describe in detail below. The diagram consists of a schematic X-ray hardness–intensity diagram (HID) above a schematic indicating the bulk Lorentz factor of the jet and inner accretion disc radius as a function of X-ray hardness. The path of a typical X-ray transient is as indicated by the solid arrows. The four sketches around the outside of the schematics indicate our suggestions as to the state of the source at the various phases i–iv, described below:

(i) Sources are in the low-luminosity LS, producing a steady jet whose power correlates as $L_{\rm jet} \propto L_{\rm X}^{0.5}$ (ignoring any mass term). This phase probably extends down to very low luminosities ('quiescence').

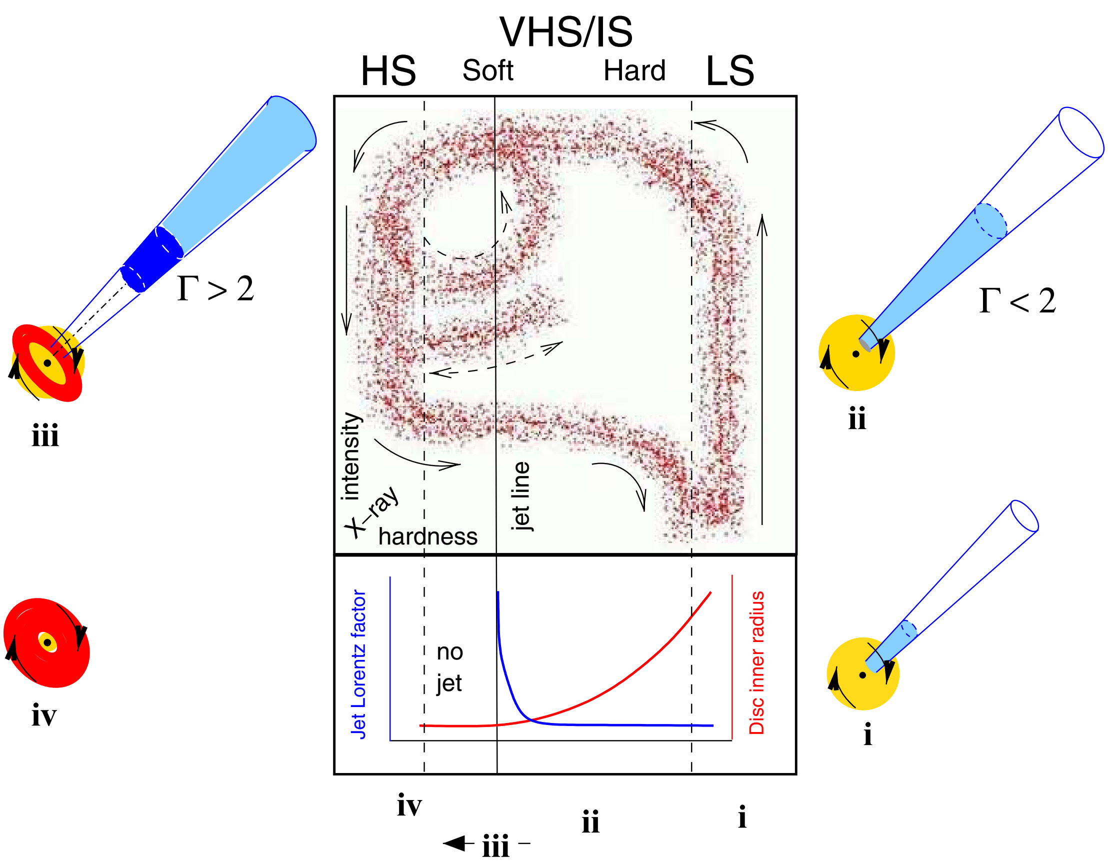

Figure 7. A schematic of our simplified model for the jet–disc coupling in black hole binaries. The upper central box panel represents an X-ray hardness–intensity diagram (HID); 'HS' indicates the 'high/soft state', 'VHS/IS' the 'very high/intermediate state', and 'LS' the 'low/hard state'. In this diagram, X-ray hardness increases to the right and intensity upwards. The lower panel indicates the variation of the bulk Lorentz factor of the outflow with hardness – in the LS and hard VHS/IS the jet is steady with an almost constant bulk Lorentz factor $\Gamma < 2$, progressing from state i to state ii as the luminosity increases. At some point – usually corresponding to the peak of the VHS/IS – Γ increases rapidly, producing an internal shock in the outflow (state iii) followed in general by cessation of jet production in a disc-dominated HS (state iv). At this stage fading optically thin radio emission is only associated with a jet/shock which is now physically decoupled from the central engine. As a result the solid arrows indicate the track of a simple X-ray transient outburst with a single optically thin jet production episode. The dashed loop and dotted track indicate the paths that GRS 1915+105 and some other transients take in repeatedly hardening and then crossing zone iii – the 'jet line' – from left to right, producing further optically thin radio outbursts. The sketches around the outside illustrate our concept of the relative contributions of jet (blue), 'corona' (yellow) and accretion disc (red) at these different stages.

(ii) The motion in the HID, for a typical outburst, has been nearly vertical. There is a peak in the LS after which the motion in the HID becomes more horizontal (to the left) and the source moves into the 'hard' VHS/IS. Despite this softening of the X-ray spectrum, the steady jet persists, with a very similar coupling, quantitatively, to that seen in the LS.

(iii) The source approaches the 'jet line' (the solid vertical line in the schematic HID) in the HID between jet-producing and jet-free states. As the boundary is approached, the jet properties change, most notably its velocity. The final, most powerful, jet has the highest Lorentz factor, causing the propagation of an internal shock through the slower-moving outflow in front of it.

(iv) The source is in the 'soft' VHS/IS or the canonical HS, and no jet is produced. For a while following the peak of phase iii, fading optically thin emission is observed from the optically thin shock.

Following phase iv, most sources drop in intensity in the canonical HS until a (horizontal) transition back, via the VHS/IS, to the LS. Some sources will make repeated excursions, such as the loops and branches indicated with dashed lines in Fig. 7, back across the jet line, However, with the exception of GRS 1915+105, the number of such excursions is generally $\leqslant 10$. When crossing the jet line from right to left, the jet is reactivated but there is (generally) no slower-moving jet in front of it for a shock to be formed; only motion from left to right produces an optically thin flare (this is a prediction). Subsequently the motion back towards quiescence is almost vertically downwards in the HID.

The model as outlined above has many similarities with the scenarios described by Meier (1999, 2001, 2003), who has approached the problem from a more theoretical point of view. Meier (2001) has suggested that in low-luminosity states the jet is powered by a modification of the Blandford & Payne (1982, 'BP') mechanism taking into account frame dragging near a rotating black hole (Punsly & Coroniti 1990, 'PC'). This 'BP/PC mechanism' can extract black hole spin by the coupling of magnetic field lines extending from within the ergosphere to outside of it. Meier (2001) further suggests that during phases of very high accretion the Blandford & Znajek (1977, 'BZ') mechanism may work briefly. This may be associated with a 'spine jet', which is considerably more relativistic than the 'sheath jet' produced by the BP/PC mechanism. Note that the power of the jets as given in Meier (2001, 2003) is about linearly proportional to the accretion rate; in the formulation of Fender et al. (2003) this corresponds to the 'jet-dominated state' (see also Falcke et al. 2004).

We can revisit the scenarios of Meier (1999, 2001, 2003) in the light of our compilation of observational results and steps towards a unified model. In the faint LS (phase i in Fig. 7), is the jet formed by the BP or BP/PC mechanism? Given that the jet may be formed at relatively large distances from the black hole in such states, there may not be any significant influence of the black hole spin on the jet formation process. However, it is also likely that in such states the jet formation process is not occurring within thin discs, as is the basis of the BP mechanism, but rather in a geometrically thick flow (see also e.g. Blandford & Begelman 1999; Meier 2001; Merloni & Fabian 2002).

As the accretion rate increases, the power of this disc–jet will increase and the geometrically thin accretion disc will propagate inwards. During this phase the jet formation process may migrate from BP $\rightarrow$ BP/PC. However, the suggestion that the most relativistic jets are formed by the BZ process seems at odds with the observation of significantly relativistic outflows from two neutron star systems (Fomalont, Geldzahler & Bradshaw 2001a,b; Fender et al. 2004). In a related work, the results of Yu et al. (2004) indicate that the subsequent evolution of X-ray transient outbursts is approximately determined *before* the soft VHS/IS peak, in both neutron star and black hole systems. This suggests that already by the time of the LS peak we can estimate the size of the ejection event that is to follow, and is a further indication that the study of neutron stars will shed important light on the physics of jet formation in black hole systems.

7.1 Ejected disc or ejected corona?

It is interesting to compare the sequence of events we have outlined as being responsible for ejection events with the interpretation most commonly put forward when the disc–jet coupling in GRS 1915+105 was first observed. In this source, oscillations, on time-scales of tens of minutes, between hard (state 'C' $\equiv$ hard VHS/IS) and soft (states 'A' and 'B' $\equiv$ soft VHS/IS – see Fig. 1a) were associated with cycles of disc 'emptying' and refill (e.g. Belloni et al. 1997). When the relation to ejection events (Pooley & Fender 1997; Eikenberry et al. 1998; Mirabel et al. 1998) was discovered, it was suggested that the 'disappearance' of the inner disc was directly related to its (partial) ejection (see also Feroci et al. 1999; Nandi et al. 2001). The following sequence of events was envisaged:

(i) Thin disc extends close to black hole (soft state).
(ii) Inner disc is ejected, resulting in
disappearance of inner disc $\rightarrow$ transition to hard state, synchrotron event.
(iii) Refill of disc $\rightarrow$ return to soft state.

However, Vadawale et al. (2003) argued that it was the 'corona' that was subsequently ejected as the disc moved in, again specifically for the case of GRS 1915+105. Rodriguez, Corbel & Tomsick (2003) have also suggested, in the case of XTE J1550−564, that it is coronal, and not disc, material that is ejected prior to radio outburst

It is clear that if the model we have outlined in this paper is correct, the 'disc ejection' scenario is unlikely to exist for any black hole X-ray binary. Specifically, it is the transition *towards* the soft state (that is, the 'refill' of the inner disc) that causes the ejection event. Therefore, if we are to consider the ejection of mass, it is more likely the 'corona' (or whatever form the accretion flow has in the harder states) and not the 'disc' that is ejected.

8 CONCLUSIONS

We have examined the observational properties of the jets associated with black hole X-ray binary systems. The key observations can be summarized as follows:

(i) *The radio–X-ray coupling*: We have established that the steady radio emission associated with the canonical LS persists beyond the softening of the X-ray spectrum in the 'hard' VHS/IS. At the end of the transition from 'hard' to 'soft' VHS/IS, usually associated with a local maximum in the X-ray light curve, a transient radio outburst occurs. The radio emission is subsequently suppressed until the source X-ray spectrum hardens once more. Some sources may repeatedly make the transition from 'hard' to 'soft' VHS/IS and back again, undergoing repeated episodes of steady and transient jet formation.

(ii) *Jet velocities*: We have argued that the measured velocities for the transient jets, being relativistic with $\Gamma \gtrsim 2$, are significantly larger than those of the steady jets in the LS, which probably have $\Gamma \lesssim 1.4$.

(iii) *Jet power*: We have furthermore established that our best estimates of the power associated with the transient jets are compatible with extrapolations of the functions used to estimate the power in the LS (albeit with a relatively large normalization).

Essentially equivalent conclusions about the radio–X-ray coupling have been drawn by Corbel et al. (2004). Putting these observational aspects together, we have arrived at a semiquantitative model for jet production in black hole X-ray binaries. We argue that, for X-ray spectra harder than some value (which may be universal or vary slightly from source to source), a steady jet is produced. The power of this jet correlates in a non-linear way (approximately given as $L_{\rm J} \propto L_{\rm X}^{0.5}$) with the X-ray luminosity. As the X-ray luminosity increases above ∼1 per cent of the Eddington rate, the X-ray spectrum begins to soften. Physically this probably corresponds to the heating of the inner edge of the accretion disc as it propagates inwards with increasing accretion rate. Initially the jet production is not affected. As the disc progresses inwards the jet velocity increases. As it moves through the last few gravitational radii before the innermost stable circular orbit (ISCO), the Lorentz factor of the jet rises sharply, before the jet is suppressed in a soft disc-dominated state. The rapid increase in jet velocity in the final moments of its existence results in a powerful, optically thin, internal shock in the previously existing slower-moving outflow.

The inner disc may subsequently recede, in which case a steady jet is re-formed, but with decreasing velocity and therefore no internal shocks. If the disc once more moves inwards and reaches the 'fast jet' zone, then once more an internal shock is formed. In fact, while jets are generally considered as 'symptoms' of the underlying accretion flow, we consider it possible that the reverse may be true. For example, it may be the 'growth' of the steady jet (for example, via buildup of magnetic field near the ISCO/black hole) that results in the hardening of the X-ray spectrum, perhaps via the pressure that it exerts on the disc to push it back, or simply via Comptonization of the inner disc as it spreads (for further discussions, see e.g. Nandi et al. 2001; Tagger et al. 2004).

In the context of the nature and classification of black hole 'states', these states, whether 'classical' or as redefined by McClintock & Remillard (2004), do not have a one-to-one relation with the radio properties of the source. It seems that, as far as the jet is concerned, it is 'on' – albeit with a varying velocity – if the disc does not reach 'all the way in', which probably means as far as the ISCO. The dividing 'jet line' on the HID (Fig. 7) may also correspond, at least approximately, to a singular switch in X-ray timing properties (Belloni et al. 2004; Homan & Belloni 2004) [see also once more the discussion in McClintock & Remillard (2004)] and may be the single most important transition in the accretion process. Further study of the uniqueness of the spectral and variability properties of sources at this transition point should be undertaken to test and refine our model.

Finally, given that Merloni et al. (2003) and Falcke et al. (2004) [see also Heinz & Sunyaev (2003) and Maccarone, Gallo & Fender (2003)] have recently demonstrated quantitatively the scaling of radio–X-ray coupling across a range of $\gtrsim 10^7$ in black hole mass, it is obviously of great interest to see if the model we are working towards for the coupling of accretion and jet formation in black hole binaries may also be applied to AGN. In addition, detailed modelling of the internal shock scenario is required to see if the coupling, as outlined above, really could allow us to predict radio light curves from X-ray, and vice versa. These two areas should be the next steps forward.

ACKNOWLEDGMENTS

RPF would like to thank many people for useful discussions related to the ideas presented here, including Catherine Brocksopp, Annalisa Celotti, Stephane Corbel, Jeroen Homan, Peter Jonker, Marc Klein-Wolt, Tom Maccarone, Dave Meier, Simone Migliari, Jon Miller and Felix Mirabel. We thank the referee, Andrea Merloni, for thoughtful and detailed comments on the paper.

REFERENCES

Belloni T., 2004, Nucl. Phys. B Proc. Suppl., 132, 337
Belloni T., Mendez M., King A. R., van der Klis M., van Paradijs J., 1997, ApJ, 488, L109
Belloni T., Klein-Wolt M., Mendez M., van der Klis M., van Paradijs J., 2000, A&A, 355, 271
Beloborodov A. M., 1999, ApJ, 510, 123
Beloborodov A. M., 2000, ApJ, 539, L25
Blandford R. D., Begelman M. C., 1999, MNRAS, 303, L1
Blandford R. D., Payne D. G., 1982, MNRAS, 199, 883
Blandford R., Königl A., 1979, ApJ, 232, 34
Blandford R., Znajek R. L., 1977, MNRAS, 179, 433
Brocksopp C. et al., 2002, MNRAS, 331, 765
Burbidge G. R., 1956, Phys. Rev., 103, 264
Burbidge G. R., 1959, ApJ, 129, 849
Casella P., Belloni T., Homan J., Stella L., 2004, A&A, in press
Corbel S., Fender R. P., 2002, ApJ, 573, L35
Corbel S., Fender R. P., Tzioumis A. K., Nowak M., McIntyre V., Durouchoux P., Sood R., 2000, A&A, 359, 251
Corbel S. et al., 2001, ApJ, 554, 43
Corbel S., Fender R. P., Tzioumis A. K., Tomsick J. A., Orosz J. A., Miller J. M., Wijnands R., Kaaret P., 2002, Sci, 298, 196
Corbel S., Nowak M. A., Fender R. P., Tzioumis A. K., Markoff S., 2003, A&A, 400, 1007
Corbel S., Fender R., Tomsick J. A., Tzioumis A. K., Tingay S., 2004, ApJ, in press (astro-ph/0409154)
Dhawan V., Mirabel I. F., Rodríguez L. F., 2000, ApJ, 543, 373
Eikenberry S. S., Matthews K., Murphy T. W. Jr, Nelson R. W., Morgan E. H., Remillard R. A., Muno M., 1998, ApJ, 506, L31
Esin A. E., McClintock J. E., Narayan R., 1997, ApJ, 489, 865
Falcke H., Biermann P. L., 1996, A&A, 308, 321
Falcke H., Körding E., Markoff S., 2004, A&A, 414, 895
Fender R. P., 2001a, in Kaper L., van den Heuvel E. P. J., Woudt P. A., eds, Proc. ESO Workshop, Black Holes in Binaries and Galactic Nuclei, Garching, Germany, 1999 September. Springer, Berlin, p. 193
Fender R. P., 2001b, MNRAS, 322, 31
Fender R. P., 2003, MNRAS, 340, 1353
Fender R. P., 2004, in Lewin W. H. G., van der Klis M., eds, Compact Stellar X-ray Sources. Cambridge Univ. Press, Cambridge, in press (astro-ph/0303339)
Fender R., Belloni T., 2004, ARA&A, 42, 317
Fender R. P., Garrington S. T., McKay D. J., Muxlow T. W. B., Pooley G. G., Spencer R. E., Stirling A. M., Waltman E. B., 1999a, MNRAS, 304, 865
Fender R. et al., 1999b, ApJ, 519, L165
Fender R. P., Gallo E., Jonker P., 2003, MNRAS, 343, L99
Fender R., Wu K., Johnston H., Tzioumis T., Jonker P., Spencer R., van der Klis M., 2004, Nat, 427, 222
Feroci M., Matt G., Pooley G., Costa E., Tavani M., Belloni T., 1999, A&A, 351, 985
Fomalont E. B., Geldzahler B. J., Bradshaw C. F., 2001a, ApJ, 553, L27
Fomalont E. B., Geldzahler B. J., Bradshaw C. F., 2001b, ApJ, 558, 283
Fuchs Y. et al., 2003, A&A, 409, L35
Gallo E., Fender R. P., Pooley G. G., 2003, MNRAS, 344, 60

Gallo E., Corbel S., Fender R. P., Maccarone T. J., Tzioumis A. K., 2004a, MNRAS, 347, L52
Gallo E., Fender R. P., Hynes R. I., 2004b, MNRAS, submitted
Ghisellini G., 1999, Astron. Nachr., 320, 232
Hannikainen D. C., Campbell-Wilson D., Hunstead R., McIntyre V., Lovell J., Reynolds J., Tzioumis T., Wu, K., 2001, Ap&SS, 276, 45
Harmon B. A. et al., 1995, Nat, 374, 703
Harmon B. A., Deal K. J., Paciesas W. S., Zhang S. N., Robinson C. R., Gerard E., Rodríguez L. F., Mirabel I. F., 1997, ApJ, 477, L85
Heinz S., Merloni A., 2004, MNRAS, submitted
Heinz S., Sunyaev R. A., 2003, MNRAS, 343, L59
Hjellming R. M., Rupen M. P., 1995, Nat, 375, 464
Homan J., Wijnands R., van der Klis M., Belloni T., van Paradijs J., Klein-Wolt M., Fender R., Mèndez M., 2001, ApJS, 132, 377
Hynes R. I., Haswell C. A., Chaty S., Shrader C. R., Cui W., 2002, MNRAS, 331, 169
Hynes R. I., Steeghs D., Casares J., Charles P. A., O'Brien K., 2004, ApJ, 609, 317
Jonker P. G., Gallo E., Dhawan V., Rupen M., Fender R. P., Dubus G., 2004, MNRAS, 351, 1359
Kaiser C. R., Sunyaev R., Spruit H. C., 2000, A&A, 356, 975
Kanbach G., Straubmeier C., Spruit H. C., Belloni T., 2001, Nat, 414, 180
Klein-Wolt M., Fender R. P., Pooley G. G., Belloni T., Migliari S., Morgan E. H., van der Klis M., 2002, MNRAS, 331, 745
Koide S., Shibata K., Kudoh T., Meier D. L., 2002, Sci, 295, 1688
Levine A. M., Bradt H., Cui W., Jernigan J. G., Morgan E. H., Remillard R. A., Shirey R., Smith D., 1996, ApJ, 469, L33
Livio M., Ogilvie G. I., Pringle J. E., 1999, ApJ, 512, 100
Longair M. S., 1994, High Energy Astrophysics Vol. 2: Stars, the Galaxy and the Interstellar Medium. Cambridge Univ. Press, Cambridge
Maccarone T., 2003, A&A, 409, 697
Maccarone T. J., Coppi P. S., 2003, MNRAS, 338, 189
Maccarone T., Gallo E., Fender R. P., 2003, MNRAS, 345, L19
McClintock J. E., Remillard R. A., 2004, in Lewin W. H. G., van der Klis M., eds, Compact Stellar X-ray Sources. Cambridge Univ. Press, Cambridge, in press (astro-ph/0306213)
Malzac J., Belloni T., Spruit H. C., Kanbach G., 2003, A&A, 407, 335
Malzac J., Merloni A., Fabian A. C., 2004, MNRAS, 351, 253
Markwardt C., 2001, Ap&SS, 276, 209
Markwardt C. B., Marshall F. E., Swank J. H., 1999, IAU Circ. 7274
Marscher A. P., Gear W. K., 1985, ApJ, 298, 114
Marscher A. P., Jorstad S. G., Gomez J.-L., Aller M. F., Terasranta H., Lister M. L., Stirling A. M., 2002, Nat, 417, 625
Meier D. L., 1999, ApJ, 522, 753
Meier D. L., 2001, ApJ, 548, L9
Meier D. L., 2003, New Astron. Rev., 47, 667
Merloni A., Fabian A. C., 2002, MNRAS, 332, 165
Merloni A., Fabian A. C., Ross R. R., 2000a, MNRAS, 313, 193
Merloni A., Di Matteo T., Fabian A. C., 2000b, MNRAS, 318, L15
Merloni A., Heinz S., di Matteo T., 2003, MNRAS, 345, 1057
Miller J. M. et al., 2002, ApJ, 578, 348
Mirabel I. F., Rodríguez L. F, 1994, Nat, 371, 46
Mirabel I. F., Rodríguez L. F, 1999, ARA&A, 37, 409
Mirabel I. F., Dhawan V., Chaty S., Rodriguez L. F., Marti J., Robinson C. R., Swank J., Geballe T., 1998, A&A, 330, L9
Nandi A., Chakrabarti S. K., Vadawale S. V., Rao A. R., 2001, A&A, 380, 245
Nespoli E., 2003, MSc thesis, Milan
Orosz J. A. et al., 2001, ApJ, 555, 489
Paredes J. M., Marti J., Peracaula M., Pooley G., Mirabel I. F., 2000, A&A, 357, 507
Pooley G. G., 2004, ATEL 242
Pooley G. G., Fender R. P., 1997, MNRAS, 292, 925
Punsly B., Coroniti F. V., 1990, ApJ, 354, 583
Rees M. J., 1978, MNRAS, 184, 61
Rees M. J., Meszaros P., 1994, ApJ, 430, L93
Reig P., Belloni T., van der Klis M., 2003, A&A, 412, 229
Remillard R. A., Sobczak G. J., Muno M. P., McClintock J. E., 2002, ApJ, 564, 962
Rodriguez J., Corbel S., Tomsick J. A., 2003, ApJ, 595, 1032
Sobczak G. J., McClintock J. E., Remillard R. A., Cui W., Levine A. M., Morgan E. H., Orosz J. A., Bailyn C. D., 2000, ApJ, 533, 993
Spada M., Ghisellini G., Lazzati D., Celotti A., 2001, MNRAS, 325, 1559
Spruit H. C., Kanbach G., 2002, A&A, 391, 225
Stirling A. M., Spencer R. E., de la Force C. J., Garrett M. A., Fender R. P., Ogley R. N., 2001, MNRAS, 327, 1273
Tagger M., Varniere P., Rodriguez J., Pellat R., 2004, ApJ, 607, 410
Tananbaum H., Gursky H., Kellogg E., Giacconi R., Jones C., 1972, ApJ, 177, L5
Turler M., Courvoisier T. J.-L., Chaty S., Fuchs Y., 2004, A&A, 415, L35
Vadawale S. V., Rao A. R., Naik S., Yadav J. S., Ishwara-Chandra C. H., Pramesh Rao A., Pooley G. G., 2003, ApJ, 597, 1023
Van Paradijs J., Kouveliotou C., Wijers R. A. M. J., 2000, ARA&A, 38, 379
Wagner R. M., Kreidl T. J., Howell S. B., Starrfield S. G., 1992, ApJ, 401, L97
Wood A., Smith D. A., Marshall F. E., Swank J. H., 1999, IAUC 7274
Wu K. et al., 2002, ApJ, 565, 1161
Yu W., Klein-Wolt M., Fender R., van der Klis M., 2003, ApJ, 589, L33
Yu W., van der Klis M., Fender R., 2004, ApJ, 611, L121
Yuan F., Cui W., Narayan R., 2004, ApJ, submitted (astro-ph/0407612)
Zdziarski A. A., Poutanen J., Mikolajewska J., Gierlinski M., Ebisawa K., Johnson W. N., 1998, MNRAS, 301, 435
Zdziarski A. A., Gierlinski M., Mikolajewska J., Wardzinski G., Smith D. M., Harmon A. B., Kitamoto S., 2004, MNRAS, 351, 791

This paper has been typeset from a TEX/LATEX file prepared by the author.