Powerful jets from black hole X-ray binaries in Low/Hard X-ray states

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ABSTRACT

Four persistent (Cygnus X-1, GX 339-4, GRS 1758-258 and 1E 1740.7-2942) and three transient (GS 2023+38, GRO J0422+32 and GS 1354-64) black hole X-ray binary systems have been extensively observed at radio wavelengths during extended periods in the Low/Hard X-ray state, which is characterised in X-rays by a hard power-law spectrum and strong variability. All seven systems show a persistent flat or inverted (in the sense that $\alpha > \sim 0$, where $S_\nu \propto \nu^\alpha$) radio spectrum in this state, markedly different from the optically thin radio spectra exhibited by most X-ray transients within days of outburst. Furthermore, in none of the systems is a high-frequency cut-off to this spectral component detected, and there is evidence that it extends to near-infrared or optical regimes. Luminous persistent hard X-ray states in the black hole system GRS 1915+105 produce a comparable spectrum. This spectral component is considered to arise in synchrotron emission from a conical, partially self-absorbed jet, of the same genre as those originally considered for Active Galactic Nuclei. Whatever the physical origin of the Low/Hard X-ray states, these self-similar outflows are an ever-present feature. The power in the jet component is likely to be a significant ($\geq 5\%$) and approximately fixed fraction of the total accretion luminosity. The correlation between hard X-ray and synchrotron emission in all the sources implies that the jets are intimately related to the Comptonisation process, and do not have very large bulk Lorentz factors, unless the hard X-ray emission is also beamed by the same factor.

Key words: binaries: close – ISM:jets and outflows – radio continuum: stars – X-rays: stars

1 INTRODUCTION

Radio emission is often observed from X-ray binaries, particularly transient systems, and especially the black hole candidates. It is increasingly accepted that this radio emission is the radiative signature of jet-like outflows, some or all of which may possess relativistic bulk motions. Recent reviews may be found in Hjellming & Han (1995); Mirabel & Rodríguez (1999) and Fender (2000).

1.1 Black Hole X-ray states

The ‘Low/Hard’ X-ray state is one of five ‘canonical’ X-ray states, characterised by both spectral and timing behaviour at X-ray energies, observed from black hole X-ray binaries in our Galaxy (e.g. Tanaka & Lewin 1995; Nowak 1995; Mendez, Belloni & van der Klis 1998; Grove et al. 1998; Poutanen 1998). As discussed in Fender (2000), the relation of black hole X-ray state to radio emission can be summarised as in Table 1. In addition, transitions between states appear to produce discrete ejection events in both persistent and transient (where rapid state changes are observed as outbursts) systems (Hjellming & Han 1995; Kuulkers et al. 1999; Fender et al. 1999a,b, Fender & Kuulkers 2001).

The X-ray spectrum in the Low/Hard state is dominated by a power-law component which extends to $\gtrsim 100$ keV (Poutanen 1998 and references therein; but see also McConnell et al. 2000); any thermal (accretion disc) component contributes $\lesssim 20\%$ in the soft X-ray band ($\lesssim 10$ keV) and not at all in hard ($\gtrsim 10$ keV) X-rays. Modelling of the Low/Hard state favours an accretion disc which is truncated at some distance (typically inferred to be of order 100 Schwarzschild radii) from the central black hole, around which exists a Comptonising corona (Poutanen 1998). ‘Seed’
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photons Compton-upscattered by the corona produce the observed power-law spectral component; the apparent cut-off in the power-law component at $\sim 100$ keV is generally interpreted as evidence for a thermal distribution of hot electrons in the corona. The flow from the inner edge of the accretion disc appears to be radiatively inefficient and has been modelled as a two-temperature advection dominated accretion flow (ADAF; Narayan, Mahadevan & Quataert 1998 and references therein).

2 PERSISTENT X-RAY BINARIES IN THE LOW/HARD STATE

The persistent black hole X-ray binaries displaying the Low/Hard X-ray state are Cyg X-1, GX 339-4 and probably the Galactic Centre hard-X-ray sources 1E1740.7-2942 & GRS 1758-258 (e.g. Tanaka & Lewin 1995). LMC X-3 may also make transient, quasi-periodic excursions from the High/Soft to the Low/Hard X-ray state (Wilms et al. 2001), but is too distant for current radio telescopes to observe easily. We describe below the radio properties of these four sources; radio spectra and images are presented in Figs 1 & 2, additional information on the radio spectrum, optical flux and distance and presented in table 2.

Note that throughout this paper we refer to the spectral index, defined as $\alpha = \Sigma \log S_{\nu} / \Sigma \log \nu$, i.e. $S_{\nu} \propto \nu^{-\alpha}$. Sources with $\alpha \sim 0$ will be refer to as ‘flat spectrum’, those with $\alpha > 0$ as having ‘inverted’ spectra. Optically thin emission typically has $-1 \leq \alpha \leq -0.5$.

2.1 Cyg X-1

The radio flux from Cyg X-1 has been established to show a moderate degree of variability, with a mean flux density of $\sim 15$ mJy at cm wavelengths (Brocksopp et al. 1999 and references therein). The radio spectrum extends to mm wavelengths with a spectral index $\alpha \sim 0$ (Fender et al. 2000a). The radio emission is also modulated with a semi-amplitude of around 20%, at the 5.6-day orbital period (Pooley, Fender & Brocksopp 1999), probably as a result of free-free absorption in the dense stellar wind of the OB-type companion (Brocksopp et al. 1999). On longer (weeks to months) timescales the radio emission is correlated with soft- and hard-X-ray emission when the source is in the Low/Hard state (Brocksopp et al. 1999). There is strong but inconclusive evidence that during transitions to softer X-ray states the radio emission is suppressed, and flaring may occur around the time of state transition (Brocksopp et al. 1999 and references therein). Cyg X-1 probably lies at a distance of 2–3 kpc (Fender & Hendry 2000 and references therein). Fig 1(a) displays the mean radio-mm spectrum of Cyg X-1. Stirling et al. (1998, 2001) present evidence for an extended and collimated radio structure from Cyg X-1 on milliarcsecond scales, which is almost certainly a compact jet.

2.2 GX 339-4

GX 339-4 displays a slightly inverted ($\alpha \sim +0.1$) radio spectrum when in the Low/Hard (and maybe also ‘Off’) X-ray state (Corbel et al. 2000 and references therein), which may extend to near-infrared wavelengths (Corbel & Fender 2000). As in Cyg X-1, the radio emission is correlated with the soft- and hard-X-ray emission when in the Low/Hard X-ray state (Hannikainen et al. 1998b; Corbel et al. 2000) and probably also in the ‘Off’ state (Corbel et al. 2000). In the High/Soft X-ray state both the hard X-ray and radio emission from GX 339-4 are strongly suppressed; the source was undetectable at radio wavelengths throughout 1998 whilst in this state (Fender et al. 1999b). GX 339-4 probably lies at a distance of 2–4 kpc (Fender & Hendry 2000 and references therein). Fig 1(b) displays a typical radio spectrum for GX 339-4.

2.3 1E 1740.7-2942

The radio counterpart to the galactic centre hard X-ray source 1E 1740.7-2942 (Tanaka & Lewin 1995; also known as the ‘Great Annihilator’) consists of a compact core at the centre of extended double-sided jets (Mirabel et al. 1999; Mirabel 1994). The core radio emission appears to be correlated with X-ray emission (Mirabel et al. 1999, 1993). A small number of reported radio observations (e.g. Mirabel et al. 1999, 1993; Gray, Cran & Ekers 1992; Anantharamaiah et al. 1993; Martí 1993) repeatedly detect the core at 5 GHz, but a good multiple-frequency spectrum has yet to be reported. Several observations report two-point spectral indices, for example Mirabel et al. (1992, 1993) report 20–6 cm spectral indices of $\alpha > -0.2$ in 1989 March and $\alpha = -0.4 \pm 0.1$ in 1991 October. Gray et al. (1992) similarly conclude that the 20–cm spectral index of the core component (their source ‘A’) must be flatter than -0.36, based on VLA and ATCA observations in 1989–1991. Heindl, Prince & Grunsfeld (1994) further report that in 1989 March while the source was $\sim 0.4$ mJy at 5 GHz it was ‘undetected’ at 1.5 GHz, again implying a fairly flat or inverted spectrum. However, it is clear that for this source a well determined multi-frequency radio spectrum is desirable and, at present, lacking. In Fig 1(c) we indicate the mean 5 GHz flux density and the possible range of 1–9 GHz spectral indices inferred from the literature. Certainly the core does not have the steep, optically thin spectral index of $-0.8 \pm 0.1$ observed from the jet lobes/hotspots (Mirabel et al. 1992). Fig 2 shows a deep radio image of the core + jets radio structure of the system (from Mirabel & Rodriguez 1999). 1E 1740.7-2942 is assumed to lie at a distance of $\sim 8.5$ kpc, in the region of the galactic centre (e.g. Tanaka & Lewin 1995).

2.4 GRS 1758-258

GRS 1758-258 is another galactic centre hard X-ray source with very similar X-ray properties to 1E 1740.7-2942 (Tanaka & Lewin 1995; Lin et al. 2000). The radio counterpart is also a compact core with extended jet-like structures (Mirabel 1994). The compact core has a flat radio spectrum at cm wavelengths (Lin et al. 2000). Fig 1(d) shows a typical radio spectrum of the source; Fig 2 shows a deep radio image of the core + jets radio structure of GRS 1758-258 (from Martí et al. 1998). Like 1E 1740.7-2942, GRS 1758-258 is also assumed to lie in the galactic centre region (e.g. Tanaka & Lewin 1995) and so we assume a distance of $\sim 8.5$ kpc.
Table 1. The relation of radio emission to black hole X-ray state. VHS, IS, HS, LS and PL correspond to Very High State, Intermediate state, High (soft) state, Low (hard) state and Power Law, respectively.

| State    | X-ray properties                      | Timing              | Radio properties          |
|----------|---------------------------------------|---------------------|---------------------------|
| VHS / IS | Disc + PL in varying proportions      | 5–15% rms variability, QPOs | Radio suppressed by factor ≥ 25 |
| HS       | Disc ($kT \sim 1$ keV) + weak PL ($\alpha \sim -1.5$) | < 10% rms variability |                           |
| LS / Off | PL ($\alpha \sim -0.5$) dominated      | Up to 50% rms below $\sim 1$ Hz | Low level, steady, flat spectrum |

Figure 1. The flat radio(–mm) spectra of the four persistent Galactic black hole candidate X-ray binaries in the Low/Hard X-ray state. Solid bars indicate typical measurement uncertainties, dotted bars are estimates of the observed range of variability in the Low/Hard state. For 1E 1740.7-2942 the only repeated detections have been at 4.9 GHz; the range of inferred spectral indices from 1 – 9 GHz, from a limited number of observations have been indicated. See main text for references.

3 X-RAY TRANSIENTS IN THE LOW/HARD STATE

Only three X-ray transients have been observed to spend an extended period in the Low/Hard X-ray state during which time there was good coverage at radio wavelengths. Some systems, such as GRO J1716-249 ("Nova Oph 1993"), were observed at radio wavelengths during (probable) excursions in the Low/Hard state, but in these cases the state changes were so rapid and frequent that the radio emission was dominated by the major, discrete ejections and the presence (or not) of an underlying flat spectral component could not be tested. Distance estimates for these three systems are from Chen et al. (1997).

3.1 GS 2023+338 (V404 Cyg)

GS 2023+338 was first detected by the Ginga X-ray satellite in 1989 May (Makino 1989), and was a bright and unusual X-ray transient. Oosterbroek et al. (1997), in a study of the X-ray spectral and timing properties of this system, conclude that it stayed in the Low/Hard X-ray state throughout the outburst (see also Zycki, Done & Smith 1999a,b). The radio emission from this system was also unusual – a bright optically thin outburst (presumably associated with the rapid state transition at the start of the outburst) was followed by the emergence of ‘second stage’ emission with a flat/inverted radio spectrum (Han & Hjellming 1992; see Figs 3 and 5).

Han & Hjellming (1992) also report (amongst other things) rapid variability, possibly quasi-periodic, which appears, in hindsight, to be very much like the ‘radio QPO’ observed from GRS 1915+105 (Pooley & Fender 1997). Furthermore, the extremely well correlated radio : optical light curve (Han & Hjellming 1992) may be indicating the extension of the flat spectral component to optical wavelengths (just as the flat spectral component in GRS 1915+105 extends to at least near-infrared wavelengths; Fender & Pooley 1998, 2000 and references therein). Radio spectra of GS 2023+338 during the Low/Hard state is shown in Fig 3(a).

3.2 GRO J0422+32

GRO J0422+32 was discovered as a new, bright hard X-ray source by BATSE onboard CGRO in 1992 (Paciesas et al. 1992). According to Esin et al. (1998) GRO J0422+32 was at all times during its outburst in the low/hard X-ray state. Shrader et al. (1994) present the UV, optical and radio outburst data on this source. The radio observations reveal a flat radio spectrum which becomes more inverted as the out-
burst progresses. Shrader et al. (1994) and Hjellming & Han (1995) refer to this flat/inverted radio spectral component as ‘second stage’ radio emission, and note its similarity to that of GS 2023+338 (see above). Radio spectra of GRO J0422+32 in the Low/Hard X-ray state is presented in Fig 3(b).

3.3 GS 1354-64

This (recurrent) X-ray transient was discovered by Ginga in 1987 February (Makino 1987). However, it was the 1997 outburst which had the best coverage, and established that the system remained in the Low/Hard X-ray state (Revnivtsev et al. 2000; Brocksopp et al. 2001). During this outburst a radio counterpart to the system was detected for the first time (Fender et al. 1997c; Brocksopp et al. 2001). The radio spectrum of this system was observed to invert (ie. $\alpha > 0$) within 30 days of the initial detection, as the source persisted in the Low/Hard X-ray state (Fig 3(c); Brocksopp et al. 2001).

3.4 Transients in the Low/Hard state without good radio coverage

Miyamoto et al. (1993) show that during the decay phase of its outburst, the transient GS 1124-683 (‘Nova Mus 1991’) began a transition from the high/soft to low/hard X-ray states commencing around 1991 April 19 (MJD 48365) and being complete by 1991 June 13 (MJD 48420). Unfortunately there appear to be no radio observations during the Low/Hard state. For a discussion of the optically thin radio outbursts associated with the very high X-ray state in this source (Miyamoto et al. 1993), see Ball et al. (1995) and Kuulkers et al. (1999).

Esin et al. (1998) suggest that the transient GRO J1716-249 was in the low/hard X-ray state when bright in hard
Figure 3. Flat/inverted (i.e. spectral index $\alpha \geq 0$) radio spectra from three black hole X-ray transients during an extended period in the Low/Hard X-ray state. Note that all three sources appear to evolve from approximately flat to inverted radio spectrum on timescales of tens to hundreds of days.

X-rays (as observed with BATSE - Hjellming et al. 1996). However, the relatively sparse radio coverage and rapid, repeated state changes (Hjellming et al. 1996), each one presumably leading to a discrete ejection which evolved to an optically thin radio state, preclude us from looking for a flat spectral component associated with the low/hard X-ray state.

Mendez et al. (1998) show that GRO J1655-40 passed through the Low/Hard X-ray state on its way to ‘quiescence’ ($\equiv$ the ‘Off’ state?) at the end of its 1997 outburst. However, as this outburst had not shown the spectacular radio flaring associated with the 1994/1995 outburst(s), there was no radio coverage being undertaken at this time. Note that in a detailed study of the radio emission from GRO J1655-40 during the earlier outburst, Hannikainen et al. (2000) discern the presence of underlying flat-spectrum ‘core’ emission which is not highly polarised.

4 OTHER X-RAY TRANSIENTS

Generally speaking, most X-ray transients do not spend any extended period in the Low/Hard state during outburst, often transiting from quiescence/Off state to the High/Soft or Very High states and then fading rapidly away. Reviews of X-ray transient observational properties can be found in e.g. Tanaka & Lewin (1995) and Chen, Shrender & Livio (1997).

Of the 26 transients discussed in Chen et al. (1997), probably only GRS 2023+38 and GRO J0422+32 remained in the Low/Hard state through (most of) their outbursts. Esin et al. (2000) discuss the ‘typical’ outbursts of the bright transients GRS 1124-683 and A0620-00, illustrating the rapid transition to the Very High state and then the decline through the High, Intermediate and Low/Hard states back to quiescence ($\equiv$ ‘Off’ state). The jet source GRO J1655-40 was similarly observed to pass through the ‘canonical’ X-ray states during the decline from outburst peak (Mendez et al. 1998). In such cases of outbursts dominated by soft X-ray states, the radio emission is often dominated by one or more discrete ejection events, associated with the state transition and/or the Very High state. A detailed study of three systems is presented in Kuulkers et al. (1999 – note that the data in that paper on GS 1124-683 correspond to epochs before the Low/Hard state was entered); see also Hjellming & Han (1995). The radio spectra of these systems, dominated as it is by one or more discrete ejections, is typically optically thin (i.e. $\alpha \leq -0.5$) within a few days of the peak of the emission, sometimes temporarily inverting as a new component (which is initially optically thick) is ejected (e.g. Kuulkers et al. 1999). This is as a result of expansion of the ejecta to the point where self-absorption is no longer important (note that some transients show an optically thin rise also – see e.g. Hjellming et al. 1999 and references therein). These transient, optically thin outbursts are often much brighter at radio wavelengths than the flat spectral components under discussion here, but little is known about any high-frequency component.

It should be noted that the radio spectra of more unusual radio-bright X-ray sources such as Cyg X-3 and GRS 1915+105 also evolve towards an optically thin state following major outbursts (e.g. Hjellming & Han 1995; Fender et al. 1997a; Fender et al. 1999a), again presumably as the (discrete) ejecta expand sufficiently for internal self-absorption to become unimportant.

Fig 4 compares a sample of optically thin radio spectra from five X-ray transients (for further references see e.g. Hjellming & Han 1995, Fender & Kuulkers 2001) plus the unusual radio-jet X-ray binaries SS 433 and Cyg X-3 (data from Fender et al. 2000b and Fender et al. 1997b respectively for these two systems) with the seven flat-spectrum sources presented in Figs 1 and 4. Outburst dates, distance estimates and associated references are given in table 3; for
Table 3. A sample of optically thin radio outbursts from X-ray binaries. These are compared with the Low/Hard state sources in Fig 6.

| Source          | Outburst Date | Distance (kpc) | Ref     |
|-----------------|---------------|----------------|---------|
| SS 433          | 1999 May      | 3              | D98     |
| XTE J1748-288   | 1998 Aug      | 8.5            | –       |
| CI Cam          | 1998 May      | 2              | B99     |
| GRO J1716-249   | 1995 March    | 2.4            | C97     |
| GRO J1655-40    | 1994 Aug      | 3.2            | C97     |
| Cyg X-3         | 1994 Feb      | 8.5            | D83     |
| GS 1124-683     | 1991 Feb      | 5.5            | C97     |

Refs: D83 – Dickey (1983), C97 – Chen, Shrader & Livio (1997), D98 – Dubner et al. (1998), B99 – Belloni et al. (1999)

XTE J1748-288 we assume a distance of 8.5 kpc given its proximity to the galactic centre.

While this is not a completely comprehensive sample of data for optically thin events, it is probably representative of the range of luminosities observed in optically thin events (Cyg X-3 being the brightest radio source associated with an X-ray binary – see e.g. Fender & Kuulkers 2001).

Two things are immediately apparent:

(i) Spectra: the Low/Hard state sources all have flat or inverted radio (–mm) spectra, whereas the soft transients have optically thin spectra, most obviously at high frequencies.

(ii) Radio luminosity: the optically thin sources span a much larger range in radio luminosities than the Low/Hard state sources.

5 DISCUSSION: OBSERVATIONAL CHARACTERISTICS

It has been shown that, as well as the persistent systems Cyg X-1 and GX 339-4, and also probably 1E 1740.7-2942 and GRs 1758-258, X-ray transient black hole candidates also show a low-level, flat/inverted spectral component at radio wavelengths when in the Low/Hard X-ray state for any length of time. In this section we discuss the spectral form and extent, polarisation properties and degree of variability of the flat/inverted spectral components.

5.1 Spectral extent and evolution

As discussed in Fender et al. (2000) for the case of Cyg X-1, as yet no-one has found either high- or low-frequency cutoffs to the flat spectral component and as a result the energy associated with it is essentially unconstrained. However in Cyg X-1 the flat spectral component is overwhelmed by thermal emission from the OB-type companion star at wavelengths \( \lambda \leq 30\mu m \) (Fender et al. 2000). In the case of GRs 1915+105 (Fender & Pooley 1998,2000 and references therein), and possibly Cyg X-3 (Fender et al. 1996) and GX 339-4 (Corbel & Fender 2000) there is strong evidence that the flat spectral component extends to the near-infrared (K-band, 2.2\( \mu m \)), and hence has a much larger radiative luminosity (\( \geq 10^{36} \text{ erg s}^{-1} \) for GRs 1915+105) than could be anticipated from radio observations only. However, only one of these systems (GX 339-4) is in the canonical ‘Low/Hard’ X-ray state (the X-ray states of Cyg X-3 and GRs 1915+105 evade simple classification, although GRs 1915+105 may spend much of its time in something like the Very High State – Belloni 1998). Do the flat spectral components associated with the transients in the Low/Hard state also extend to the near-infrared or beyond?

Han & Hjellming (1992) report a very clear correlation between X-ray, optical and radio fluxes from GS 2023+38 during the decay following the outburst. The spectral evolution from radio–optical is illustrated in Fig 5. We assume an extinction in the optical R-band of 2.3 magnitudes (based on \( A_V = 3 \text{ mag} \) – Shahbaz et al. 1994; Rieke & Lebofsky 1985). The radio–optical spectrum can be fitted by a single power–law shortly after the emergence of the flat spectral component around MJD 47685. After that the radio spectrum inverts while the highest frequency (usually 14.9 GHz) radio flux densities closely track the dereddened optical flux. Such a strong correlation implies a common emission mechanism, and we suggest that in this case the optical flux during this phase of the decay was dominated by high-frequency synchrotron emission.

Why the radio spectrum should invert, without affecting the optical flux, if it is also synchrotron, may be due to free-free absorption from debris local to the system following the outburst (Zycki, Done & Smith 1999a,b do report a large and variable absorption component present in X-ray spectra following the outburst). In Appendix A it is shown that a simple model in which the intrinsic jet emission suffers foreground free-free absorption can be used to fit the data, but this is certainly an oversimplification of the true picture. Importantly, we cannot rule out varying internal synchrotron self-absorption, but evaluation of its significance would require modelling of the jet, which is beyond the scope of this work.

The radio spectra of GRO J0422+32 and GS 1354-64 are also observed to invert as the outburst declines (Fig 3), in a manner consistent with increasing low-frequency absorption. There is also evidence in both cases for an extension of the flat spectral component to the optical bands. Van Paradijs et al. (1994) discuss a flat spectral component from 10\( \mu m \) through to the optical band from GRO J0422+32, which they attribute to free-free emission, most probably from a disc-wind. Shrader et al. (1994) also note that the dereddened optical continuum of GRO J0422+32 rapidly evolves to a flat spectrum (\( \alpha \sim 0 \)) during the decay phase of the outburst. Finally, Brocksopp et al. (2001) also report evidence for correlated radio : optical emission from GS 1354-64.

In all three sources the spectrum from the highest radio frequency to the optical band is approximately flat (table 2). There seems to be no a priori reason why flux densities at radio and optical wavelengths should be comparable in the Low/Hard state, so there appears to be either a physical coupling, or coincidence.

Very few low-frequency (\( \nu < 1 \text{ GHz} \)) observations have been made of these systems, although in the case of GS 1354-64 the spectrum extends at least as low as 843 MHz (Brocksopp et al. 2001), as it does in GX 339-4 (Corbel et al. 2000 and references therein).
5.2 Polarisation

While there have been no reported measurements of linear polarisation from Cyg X-1, Corbel et al. (2000) report a low level of linear polarisation, of order 2%, from GX 339-4 in the Low/Hard X-ray state. The polarisation angle in this system has remained approximately constant (to within uncertainties of order $10^\circ$) over a period of $\geq 2$ yr, implying a fixed orientation of the magnetic field in this system (whether parallel or perpendicular to the jet axis is at present uncertain). Presumably this fixed axis corresponds to the rotation axis of the black hole and/or inner accretion disc (the latter is in fact probably slaved to the former). Han & Hjellming (1992) report a comparable level of linear polarisation from GS 2023+338 with a constant position angle over a period of $\sim 2$ months, again implying a relatively stable and fixed-orientation magnetic field structure within the jet.

5.3 Variability timescales

Rapid variability has been observed from the flat spectral component in Cyg X-1 (Brocksopp et al. 1999), GX 339-4 (Corbel et al. 2000), GS 2023+338 (Han & Hjellming 1992) and GRO J0422+32 (Shrader et al. 1994). Furthermore, there was a clear correlation between X-ray and radio emission in GS 2023+338 at least, implying an ongoing coupling between the accreting and outflowing matter. In this source the significant variability was observed on timescales of minutes, implying size scales of order $10^{12}$ cm ($< 10^6$ Schwarzschild radii for a $10\, M_\odot$ black hole).

In contrast some of the optically thin outbursts of other sources can be almost perfectly described by smooth power-law decays and show little rapid variability. Hjellming & Han (1995) show six examples of fits to optically thin events with simple ‘synchrotron bubble’ models. In such cases the decay of the radio emission arises due to adiabatic expansion losses, and so weaker radio emission is associated with increasingly large physical structures which display less and less variability on short timescales. Such events are also physically decoupled and observationally uncorrelated with the accretion disc emission following the dramatic events of the outburst. For example, 10 days after ejection, material travelling at $\sim 0.9c$ will be $> 10^{16}$ cm ($\equiv 1500$ A.U. $\equiv 10^{10}$ Schwarzschild radii) from the central black hole. The picture is not quite so simple however, as several transients whose radio emission is dominated by optically thin ejections sometimes briefly display inverted spectra (Knulkers et al. 1999). This is interpreted as the ejection of new components which are initially optically thick at radio wavelengths, but which rapidly become optically thin. Such multiple ejections of discrete blobs
has been directly observed in e.g. GRS 1915+105 (Mirabel & Rodríguez 1994; Fender et al. 1999a).

6 THE NATURE OF THE FLAT SPECTRAL COMPONENT

It has long been accepted that radio emission from X-ray binaries is synchrotron emission from material ejected from the system (Hjellming & Han 1995 and references therein). Such ejections, at relativistic bulk velocities, have been directly observed in several cases (Hjellming & Han 1995; Mirabel & Rodríguez 1999; Fender 2000 and references therein). However, a simple homogenous synchrotron-emitting source should exhibit a two component spectrum with a spectral index of +2.5 below some frequency at which self-absorption becomes significant, and α above this frequency (with a turnover within one decade in frequency). For a power-law distribution of electrons of the form \( N(E)dE \propto E^{-\beta}dE \), this optically thin spectral index is \( \alpha = (1 - \beta)/2 \). Observed optically thin spectral indices are typically in the range \(-1 \lesssim \alpha \lesssim -0.5\), corresponding to electron energy indices of \( 2 \lesssim p \lesssim 3 \). This range is approximately consistent with both simple theories of particle acceleration and the observed cosmic-ray energy index (Blandford & Eichler 1987).

The radio spectra observed from these black hole systems in the Low/Hard state is however quite different, showing a flat spectrum which probably extends to very high frequencies. Blandford & Königl (1979) showed, in a model developed for AGN, that a simple ‘isothermal’ conical jet can produce a flat spectrum even with an electron distribution \( N(E)dE \propto E^{-2}dE \). Reynolds (1982) explored in more detail the observed spectra from winds and jets with a variety of geometries, magnetic fields and energetics (see also Cawthorne 1991 for a review). Hjellming & Johnston (1991) and Falcke & Biermann (1996, 1999) have discussed the application of such models to X-ray binaries. Given that we recover the negative spectral index during major optically thin outbursts, some form of the partially self-absorbed conical jet model does seem the most likely origin of the flat spectral component in X-ray binaries also. In the simplest case, a flat spectrum implies a characteristic size scale at any frequency which is proportional to \( \nu^{-1} \). Thus if the flat spectra extend from radio to near-infrared or optical frequencies, this implies that the jet must be self-similar over the same range in physical size, i.e. \( \gtrsim 5 \) orders of magnitude. In Fender et al. (2000) it was noted that the flat spectral component observed from Cyg X-1 was much flatter than that observed from ‘flat spectrum’ AGN. This is primarily due to the high-frequency turnover, which occurs around the millimetre band for AGN (Bloom et al. 1994), not being observed for Cyg X-1 (or any other X-ray binary to date). As the highest-frequency emission will arise from the smallest physical scales for a conical jet or similar model, this lack of observed turnover in X-ray binaries is probably due to higher densities and/or magnetic fields in the accretion flow around a \( \sim 10M_\odot \) black hole as compared to the \( \gtrsim 10^6M_\odot \) black holes in AGN. If the turnover for the X-ray binaries transpires to be around the optical or near-infrared bands, this would imply an approximate empirical scaling of the high frequency cut-off, \( \nu_{\rm \text{HIGH}} \propto M_{\text{BH}}^{1/2} \).

Earlier interpretations of the flat radio spectra were very closely related to these conical jet models. The flat spectral components observed from GS 2023+338 and GRO J0422+32 have been referred to as ‘second stage’ radio emission (Hjellming & Han 1995), and it was suggested that they originate in a wind from the accretion disc through which the observer sees to different depths as a function of frequency (Hjellming & Han 1995). Furthermore it was suggested that the slowly-decreasing flux density was as a result of a decreasing physical size scale. Both a spherical wind and conical jet will have an electron density which falls as \( r^{-2} \) (for no pair processes), and will produce analogous spectra (Reynolds 1982). However, the direct observations of apparently collimated jets from Cyg X-1, 1E 1740.7-2942 and GRS 1758-258 provide strong evidence for a collimated geometry. Furthermore, the observed linear polarisation would not arise in a spherically symmetric source.

7 JET POWER

The radiative luminosity is the only quantity we can directly measure from the flat spectral component. As non-radiative (i.e. adiabatic expansion) losses are likely to dominate, this will be a very conservative lower limit on the power into the jet. The observed radiative luminosity of Cyg X-1 is \( \sim 2 \times 10^{36} \text{ erg s}^{-1} \) when observed up to 15 GHz in the radio band (for a distance of \( \sim 2 \text{ kpc} \)). However, as argued above, there is evidence that the flat spectral component extends across the millimetre and infrared bands to the near infrared or even optical bands. The same flat spectral component extending to the optical V-band will have a radiative luminosity of \( \sim 7 \times 10^{34} \text{ erg s}^{-1} \).

The ratio of observed (radiative) power, \( \eta \), to total internal jet power is likely to be \( \lesssim 5\% \), a figure based both on theory (Blandford & Königl 1979) and on observations of GRS 1915+105 (Fender & Pooley 2000). This is because the electrons lose energy primarily as a result of adiabatic
expansion, and not via synchrotron or inverse Compton processes (although above some cut-off frequency these radiative losses will dominate).

The power in such a jet can be estimated as

$$L_{\text{jet}} \gtrsim 10^{36} \left( \frac{d}{2 \text{ kpc}} \right)^2 \left( \frac{\nu_{\text{HIGH}}}{10^{14} \text{ Hz}} \right) \left( \frac{S_\nu}{15 \text{ mJy}} \right) \left( \frac{\eta}{0.05} \right)^{-1} F(\Gamma, i) \text{ erg s}^{-1}$$

where $\nu$ is the high-frequency cut-off to the flat spectral component, $S_\nu$ is the flux density (dereddened, if necessary) measured at that frequency, and $F(\Gamma, i)$ is an approximate correction factor for relativistic bulk motion (see below). The parameters have been scaled for Cyg X-1, with a high-frequency cut off around 3\mu m.

The observed X-ray luminosity of Cyg X-1 in the Low/Hard state is $\sim 3 \times 10^{37}$ erg s$^{-1}$ (Nowak et al. 1999; di Salvo et al. 2001). So, based on only the following assumptions:

(i) The flat spectral component extends to near-infrared / optical bands

(ii) The radiative efficiency of the jet is $\lesssim 5\%$

(iii) Relativistic beaming of the radio emission is not significant

it is concluded that the power in the jet, in the Low/Hard X-ray state, is $\gtrsim 5\%$ of the total accretion luminosity as observed in X-rays.

However, the third assumption is certainly worth considering more carefully, since observations of other X-ray binaries certainly have revealed evidence for outflows at relativistic velocities. The luminosity based on the above inequality can be significantly affected by bulk relativistic motions which will (a) Doppler shift the observed frequencies, (b) ‘Doppler boost’ the observed flux densities (aberration), and (c) add a significant amount of bulk kinetic energy to the power requirements.

For a flat ($\alpha = 0$) spectral component of flux density $S_\nu$ extending to frequency $\nu$, $L \propto \nu S_\nu$. For bulk motion at velocity $\beta$, the Lorentz factor is $\Gamma = (1 - \beta^2)^{-1/2}$ and corresponding relativistic Doppler factor $\delta = \left[ \gamma (1 - \beta \cos \theta) \right]^{-1}$. The transformation from the comoving to observer’s frames is $\nu_{\text{obs}} = \delta \nu_0$ and $S_{\nu_{\text{obs}}} = \delta^{k-\alpha} S_0$, where $k = 3$ for a single discrete component, and $k = 2$ for a simple jet emitting isotropically in its rest frame (Rybicki & Lightman 1979; Crawtherne 1991); therefore $L_{\text{obs}} = L_0 \delta^{3-k-\alpha}$. Assuming $\alpha = 0$ and $k = 2$ (observationally $k$ is found to be near 2 than 3 for GRS 1915+105 – Mirabel & Rodriguez 1994; Fender et al. 1999a), $L_0 = L_{\text{obs}} \delta^{-3}$. In addition, taking into account bulk relativistic motion, the total jet power must be multiplied by $\Gamma$. So, compensating for both Doppler shifts and kinetic energy, the relativistic ‘correction factor’ $F(\Gamma, i) = \Gamma \delta^{-3}$. This function is plotted for a range of velocities, at all inclinations, in Fig 6. Note most importantly that as the effect becomes more significant, ie. for the highest velocities, the chances of overestimating the jet power from observations (ie. when $F(\Gamma, i) < 1$) decrease rapidly; for a random sample of inclination angles the total jet power is more likely to be underestimated if relativistic bulk motion is neglected. This is because to first order the radiation will be beamed within an angle $\sim 1/\Gamma$ of the forward direction of motion of the ejecta. In the case of Cyg X-1, best estimates of $i$ (presumed to be equal to the orbital inclination) are around 30°; inspection of Fig 6 shows that at this inclination the above method will not overestimate the total jet power by more than a factor of 3, and for high velocities (e.g. $\nu = 0.98c$, $\Gamma = 5$) we may be underestimating the jet power by up to a factor of 5. For example, for Cyg X-1, assuming $\nu_{\text{HIGH}} = 10^{14}$ Hz, $\eta = 0.05$, $\Gamma = 5$ and $i = 30^\circ$, $L_{\text{jet}}/L_X \gtrsim 0.2$.

Furthermore, Brocksopp et al. (1999) and Corbel et al. (2000) report approximately linear relations between the X-ray and radio fluxes of Cyg X-1 and GX 339-4 when these sources are in the Low/Hard X-ray state, a trend also observed in GS 2023+338 (Han & Hjellming 1992). If this relation holds for all sources in the Low/Hard X-ray state then we can estimate the radio flux density based on X-ray observations, and vice-versa. Empirically, the relation is

$$S_{\nu_{\text{CRAB}}} \sim 75 \left( \frac{S_X}{\text{Crab}} \right) \text{ mJy}$$

Note that since there is evidence for inversion of the spectrum as the source weakens, this correlation will be strongest for higher radio frequencies. Note also that this relation is approximately equivalent to 1 mJy of radio flux density for 1 RXTE ASM ct/sec; the quantitative nature of this relation will be explored elsewhere. This approximately linear relation indicates that whatever the previous accretion and ejection history, when in the Low/Hard X-ray state, black hole X-ray binaries produce a jet whose power is an approximately fixed, and probably large, fraction of the accretion luminosity. Furthermore, the comparable radio luminosity of the four persistent Low/Hard state sources (Fig 5; see also Fender & Hendry 2000) agrees with this interpretation as long as the X-ray luminosities of the four sources are within an order of magnitude of each other, which seems to be the case.

8 \ LOW/HARD STATES IN GRS 1915+105

GRS 1915+105 is a very luminous X-ray binary black hole candidate and the first Galactic source of superluminal radio
jets (Mirabel & Rodríguez 1994; Fender et al. 1999a; Belloni et al. 2000). Its relevance to this discussion is twofold:

(i) It was the first X-ray binary source for which there was firm evidence for an extension of a flat-spectrum synchrotron component extending through the millimetre (Ogley et al. 2000, Fender & Pooley 2000) to the near-infrared (Fender et al. 1997b; Mirabel et al. 1998; Fender & Pooley 1998, 2000) bands. Most of this evidence is in the form of oscillation events, associated with repeated accretion cycles, which are identical at radio, mm and near-infrared wavelengths.

(ii) The source occasionally displays ‘plateau’ X-ray states, which are reminiscent of the canonical Low/Hard state, but more luminous (Belloni et al. 2000). Associated with these states is a steady, flat-spectrum synchrotron component in the radio band (Fender et al. 1999a).

The plateau states (class χ, state C of Belloni et al. 2000) are dominated by a power-law component, with little or no disc contribution in the X-ray band (Belloni et al. 2000). In this sense they are similar to the Low/Hard X-ray state. Fig 7 illustrates the radio – infrared spectrum of the source during one such state, in 1996 August. Other examples of the plateau also show a flat spectrum in the range 1–15 GHz (Hannikainen et al. 1998a; Fender et al. 1999a), but the 1996 August event appears to be the only plateau with simultaneous infrared observations (Bandyopadhyay et al. 1998). So again, in circumstances which are rather different (a more luminous, exotic source) from the ‘quiet’ Low/Hard state of e.g. Cyg X-1, we again find a flat-spectrum, with evidence for absorption at low radio frequencies and a high-frequency extension to the near-infrared. The reader is reminded that the synchrotron oscillation events in GRS 1915+105 are also associated with brief excursions (or ‘dips’) to the same state which characterises the ‘plateaux’ and, in these cases there is little doubt that the synchrotron spectrum does extend to the near-infrared (Fender et al. 1997c; Pooley & Fender 1997; Eikenberry et al. 1998, 2000; Mirabel et al. 1998; Fender & Pooley 1998). Very recently Dhawan, Mirabel & Rodríguez (2000) have confirmed that the plateau state in GRS 1915+105 is associated with a compact jet.

9 CONCLUSIONS

There are four persistently accreting black hole candidates in our Galaxy which spend most of their time in the power-law-dominated Low/Hard X-ray state. These are Cyg X-1, GX 339-4, 1E1740.7-2942 and GRS 1758-258. It is shown that all four sources have comparable radio spectra, namely weak emission with a flat/inverted (0 ≤ α ≤ 0.5) spectrum. Furthermore in two, probably three, of the four systems, jets have been directly imaged at radio wavelengths.

It is unusual for transient black hole X-ray sources to spend an extended period in the Low/Hard X-ray state, but this was the case for at least three systems, GS 2023+338, GRO J0422+32 and GS 1354-64, during periods of extensive radio coverage. All three systems were found to have radio spectra which, after initial optically thin events associated with the state transition, were very similar to those of the persistent sources in the Low/Hard state, and very different from the bright, optically thin outbursts seen from most other transients (Fig 4). As previously suspected (Fender 2000), all black hole X-ray binaries, whether persistent or transient, display a flat radio spectrum when in the Low/Hard X-ray state. For further comparison of the observational properties of Low/Hard state transients, see Brocksopp et al. (2001).

The flat radio spectra observed from these sources do not show high-frequency cut-offs, but on the contrary show evidence for extension into the millimetre, infrared and maybe even optical bands. All three transient sources show some correlated radio : optical behaviour, and have approximately flat spectra from the radio through to the optical bands. All three systems also show evidence for absorption at lower frequencies as the flux levels decline, possibly (although certainly not conclusively) evidence for increasing free-free absorption as the jet shrinks back towards the core of the system. A similar radio-millimetre-infrared spectrum is observed from the jet source GRS 1915+105 when in a spectrally similar (ie, dominated by a power-law), but more luminous hard X-ray state (Fig 7).

In the case that the flat spectral component does extend to the optical or near-infrared bands, and the jet has a low (< 5%) radiative efficiency, then the luminosity of the jet is likely to exceed 5% of the observed X-ray luminosity, and is furthermore likely to scale linearly with the X-ray flux. All this evidence supports a jet–disc ‘symbiosis’ model (Falcke & Biermann 1996, 1999) in which the jet luminosity is some fixed, and probably large, fraction of the accretion luminosity. The observed comparable correlation between the radio and hard X-ray (Comptonised) emission in different systems implies that these two components do not have very different beaming; this in turn implies that unless the hard X-ray emission is strongly beamed (possibly via synchrotron self-Compton in the jet) then the jet in the Low/Hard state is unlikely to have a very large Lorentz factor (Γ < 5 or so).

Further observations to determine the high-frequency extent of the flat spectral component are of great importance. Confirmation of a high fraction of the accretion luminosity being diverted into the jet during hard, power-law-dominated X-ray spectral states will have great significance.

Figure 7. The radio–infrared spectrum of GRS 1915+105 during the ‘plateau’ state in August 1996 (∼ MJD 50300). Data are from Pooley & Fender (1997), Hannikainen et al. (1998a), Bandyopadhyay et al. (1998).
for our understanding of the accretion flow near a black hole, not least for models of advection-dominated accretion.

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unabsorbed spectral index and \( \tau \) fit by the following simple model

This longer radio wavelengths, the four spectra in Fig 5 have been single power-law which is absorbed by free-free emission at

In order to see if the radio–optical spectra can be fit by a absorption of a compact jet.

APPENDIX A: FOREGROUND FREE-FREE ABSORPTION OF A COMPACT JET

In order to see if the radio–optical spectra can be fit by a single power-law which is absorbed by free-free emission at longer radio wavelengths, the four spectra in Fig 5 have been fit by the following simple model

\[
S_\nu = S_0 \nu^\alpha e^{-\tau_1 \nu^{-2.1}}
\]

where \( S_0 \) is the amplitude of the power law, \( \alpha \) is the unabsorbed spectral index and \( \tau_1 \) is the optical depth at 1 GHz (free-free optical depth \( \propto \nu^{-2.1} \) at radio wavelengths, e.g. Gordon 1988). The fits are illustrated in Fig 5 and tabulated in Table A1. It is interesting that the fits give an unabsorbed spectral index which is approximately constant at a slightly inverted value. The amplitude decreases and the optical depth to free-free absorption increases for the first three epochs, then decreases again for the final epoch. If this is a correct modelling of the data, then two possibilities suggest themselves - either a cloud of ejecta from the outburst slowly moved outward and enveloped the jet and then eventually dispersed, or as the jet weakened its characteristic size scale decreased and it withdrew back within a shroud of material still enveloping the system post-outburst. Note that in the very inner regions of the SS 433 jet the radio spectrum becomes inverted, probably due to free-free absorption (Paragi et al. 1999).

Could the low-frequency inversion be due instead to synchrotron self-absorption? This seems hard to reconcile with the observations since, if the emission does arise in a conical jet, then the lowest frequencies, which we observe to be increasingly suppressed, should arise on the largest scales. Thus in order for synchrotron self-absorption to affect lowest frequencies, it would appear that we would require some enhancement of magnetic field and/or particle number density to occur towards the end of the jet. Perhaps as the stratified jet recedes towards its base this could happen; without entering into modelling of the jet itself this is unclear. Further detailed low-frequency observations of the jet spectrum are desirable to investigate this.

| MJD  | \( S_0 \)   | \( \alpha \) | \( \tau_1 \) |
|------|------------|-------------|-------------|
| 47685 | 55.1 ± 1.8 | 0.04 ± 0.00 | 0.00 ± 0.13 |
| 47755 | 12.5 ± 1.1 | 0.04 ± 0.01 | 1.91 ± 0.71 |
| 47830 | 6.0 ± 0.4  | 0.03 ± 0.01 | 9.29 ± 2.51 |
| 47940 | 1.1 ± 0.1  | 0.06 ± 0.01 | 1.56 ± 0.47 |

Table A1. Fits to the radio–optical spectra presented in Fig 7 to the function \( S_0 \nu^\alpha e^{-\tau_1 \nu^{-2.1}} \).