Microquasars: hard X-ray/$\gamma$-ray emission

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Abstract.

I review some of the basic observational details of jets from X-ray binaries, or ‘microquasars’. It is shown that in both (Z and Atoll) NS and BHC systems radio emission, and therefore jet formation, is correlated with the presence of hard (30–500 keV) X-ray emission. At $\gamma$-ray (> 500 keV) energies, the relation is not so clear. Possible physical connections between the presence of a jet, with a population of relativistic electrons, and the emission of hard X-rays, are briefly discussed.

INTRODUCTION – JETS FROM X-RAY BINARIES

The study of ‘microquasars’, or the phenomenon of relativistic jets from X-ray binary systems, is one of the most vigorously pursued fields in observational high-energy astrophysics in recent years. Once Mirabel & Rodriguez (1994) had shown that X-ray binary systems were capable of producing relativistic (bulk Lorentz factor $\Gamma \geq 2$) outflows, whose primary signature was in the radio band, it was recognised that such ‘jets’ may constitute an important aspect of the ‘accretion’ process onto compact objects. In recent years observations have clearly demonstrated the presence of jets in most classes of X-ray binary, and furthermore have clearly indicated a strong coupling with the accretion ‘state’ of the source, whether neutron star (e.g. Penninx et al. 1988) or black hole accretor (e.g. Fender et al. 1999b). See e.g. Hjellming & Han (1995), Mirabel & Rodriguez (1999), and other papers by this author for reviews of radio emission and jets from X-ray binaries (although note that new observations are coming thick and fast all the time!). See e.g. Lewin, van Paradijs & van den Heuvel (1995) for an excellent volume containing reviews of the models for the different ‘states’ of accreting neutron stars and black holes (admittedly from the era before the ubiquity and significance of jets was widely recognised).

In Fig 1 and 2 I summarise the current understanding of the empirical relation of radio emission to X-ray ‘state’ of the neutron star (NS) and black hole candidate (BHC) systems respectively. In addition to the relations indicated in these figures, it seems that discrete, radio-emitting ejection events (in which the radio spectrum
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**FIGURE 1.** Top panel: a qualitative sketch of the relation of jets to accretion in the three `types’ of neutron star XRB. In the low-field ‘Atoll’ sources the accretion rate is believed to be < 10% Eddington, except possibly during rare transient outbursts (e.g. Aql X-1); the evidence is marginal so far but it appears such sources are ‘radio on’ when in the ‘Island State’ (IS) in the X-ray colour-colour diagram (CD). The Z sources are believed to be accreting at a much higher rate, near Eddington, and are ‘radio on’ when on the ‘Horizontal Branch’ and maybe also, at a lower level, the ‘Normal Branch’ in the CD. Note that for both Atoll and Z sources the estimates of surface magnetic field are very uncertain. Finally, in the high-field X-ray pulsars no radio synchrotron emission has ever been detected; possibly this is due to truncation of the accretion disc a long way from the neutron star. Lower panel: the jets of the Z source Sco X-1, directly resolved with the VLBA (Bradshaw, Fomalont & Geldzahler 1999).
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rapidly becomes optically thin) are associated with state transitions (including outbursts of transients – Fig 3).

While some areas of the coupling between accretion flow and jet are still empirically uncertain (the Atoll sources, the Intermediate/Very High state for BHCs), it seems that all XRBs except the high-field X-ray pulsars will, under the right conditions, produce a synchrotron-emitting jet. It is therefore an important question to address the significance of this jet, energetically and dynamically, for the process of accretion onto compact objects as a whole. One thing obvious from inspection of Figs 1(a),(b) is the apparent anti-correlation between the mass accretion rate, $\dot{m}$, traditionally estimated from X-ray studies alone, and the presence of a jet, in both NS and BHC systems (see also Belloni, Migliari & Fender 2000 and Homan et al. 2001 for further discussion). The energetics of jets from X-ray binaries in general, and BHCs in the Low/Hard state in particular, are discussed in detail in Fender (2001a,b), in which it is concluded that the jets probably contain at least 20% of the liberated accretion energy, maybe much more.

**HARD X-RAYS : $\sim 30–500$ KEV**

In this energy band (rather arbitrarily defined here) there are several detections of X-ray binary systems.

**Neutron stars**

Both of the two major groups of neutron star systems which probably produce jets, Z and Atoll sources, have been detected in some cases to energies $\geq 30$ keV. In the case of the Z sources, a picture now seems to be emerging whereby a hard tail, extending to $\geq 100$ keV, is present in varying degree, being strongest on the Horizontal Branch (HB) of the X-ray colour diagram (CD) and weakest (or non-existent) on the Flaring Branch (FB; see Fig 1 for a schematic of a ‘typical’ CD). Asai et al. (1994) first found evidence for a hard tail from GX 5-1 which decreased from the Normal Branch (NB) to the FB. More recently Di Salvo et al. (2001 a,b) have reported the detection of a hard X-ray tail from the Z sources GX 17+2 and GX 349+2; again the data seem to be consistent with the hard X-ray tail being strongest in the HB/NB and weakest on the FB. Iaria et al. (2001) also find evidence for a hard tail in the jet source Cir X-1, which may be an unusual Z source. Hard X-ray emission has also been reported from the archetypal Z source Sco X-1, although its correspondence with position on the Z is unclear (D’Amico et al. 2001). Strickman & Barret (2000) report that the hard X-ray emission in Sco X-1 may be correlated with periods of radio flaring. Comparison of this picture with Fig 1 shows that observationally, the presence of the hard tail seems to be correlated with the presence of radio emission (and therefore almost certainly jet production). Note that in the received wisdom $\dot{m}$ increases from HB$\rightarrow$NB$\rightarrow$FB, and so both jet and hard X-ray production are anticorrelated with $\dot{m}$. 

FIGURE 2. Top panel: the qualitative relation of radio emission to X-ray ‘state’ in BHC XRBs: the low/hard state is found to produce a steady, flat- (or inverted-)spectrum jet, the soft state produces no detectable radio emission. The relation of mass accretion rate, $\dot{m}$, to these states is not certain (e.g. Homan et al. 2001); nor are the radio characteristics of the relatively rare ‘Intermediate/Very High’ states well determined. The image in the lower panel is of the ‘steady’ jet from the BHC Cyg X-1, as resolved with the VLBA (Stirling et al. 2001).
FIGURE 3. Left panel: optically thin radio events associated with outbursts seem to arise in discrete ejections of material during the rapid state change. In the case of black hole systems if the source transits to the High/Soft X-ray state [stage 3(a)] the radio emission remains optically thin and fades away; if the system instead transits to the Low/Hard X-ray state [stage 3(b)] then a flat spectral component, probably the signature of a powerful partially self-absorbed jet, emerges (see Fig 2). Something like the sequence 1 → 2 → 3(a) may also occur in the NS (atoll-like) transients. Right panel: Resolved discrete relativistic ejections from the BHC GRS 1915+105 with MERLIN (Fender et al. 1999a).
A hard X-ray tail from the Z source GX 17+2 (di Salvo et al. 2000b); the left panel corresponds to the upper Horizontal Branch (HB), the right panel to the lower Normal Branch (NB; see Fig 1 for a sketch of the ‘Z’ indicating HB, NB and ‘Flaring Branch’ FB). It is clear that the hard (> 30 keV) X-ray excess is present only in the left spectrum; note further that the Horizontal Branch the state corresponding to most radio emission from Z sources (see Fig 1).

The Atoll sources, weaker as a population than the Z sources at radio wavelengths (Fender & Hendry 2000), also display hard X-ray states with emission detected up to and beyond 100 keV. For example, di Salvo et al. (2000) report the detection to such high energies of the atoll source 4U 1728-34, and Barret et al. (2000) report hard X-ray tails from four other Atoll-type X-ray binaries. It is clear that in ‘low’ states of the Atoll sources a hard X-ray power-law is present which seems to be the dominant component in the broadband spectral energy distribution. If, as we suspect, both by analogy with BHCs and recent observations, (work in preparation), that radio emission in Atoll sources is also associated with ‘low’ X-ray states, specifically the Island State (IS) in the Atoll CD, we again find, as with the Z sources, that radio and hard X-ray emission are correlated with each other and anti-correlated with apparent $\dot{m}$.

**Black Holes**

Many BHC systems have been detected at energies above 30 keV; in fact the X-ray power-law which dominates the high-energy radiation from BHCs in the Low/Hard spectral state generally extends to at least 100 keV. Furthermore, although the High/Soft state is dominated energetically by a ‘soft’ disc component, there is increasing evidence that a steep power-law extends beyond this thermal
component to at least several hundred keV (Grove et al. 1997, 1998; Poutanen 1998). Fig 2 illustrates the X-ray spectral and timing properties of the main ‘states’ schematically, and Fig 5 shows some examples of ‘real’ X-ray spectra. Hard X-ray emission seems to be a general, although not exclusive, property of BHCs.

The BATSE and OSSE instruments onboard the (late) CGRO mission contributed an exceptional amount to our understanding of the relation of the hard X-ray emission from BHCs (e.g. Grove et al. 1997, 1998). Brocksopp et al. (1999) and Corbel et al. (2000) showed that there is a strong correlation between hard X-rays (as measured with BATSE) and radio emission in the persistent BHCs Cyg X-1 and GX 339-4 (Fig 6). McCollough et al. (1999) showed that the jet source Cyg X-3 (which may be a BHC) shows both correlated and anti-correlated radio – hard X-ray behaviour (Fig 7); this may correspond to different X-ray ‘states’ and/or rapid state transitions in this source (whose accretion properties remain shrouded by a dense wind). The BHC GRS 1915+105 (see right panel of Fig 2) is probably the best-known ‘microquasar’ and is a strong source of hard X-rays, being well-detected by BATSE over a six-year period. Foster et al. (1996) reported hard X-ray states, or ‘plateaux’ in this source. These plateaux seem to be periods of steady jet production, like luminous variants on the ‘canonical’ Low/Hard X-ray state, and are generally followed by discrete, relativistic ejection events (Fender et al. 1999a; Dhawan et al. 2000). The GRANAT mission has also contributed immensely to our understanding of patterns of hard X-ray emission from X-ray
binaries (e.g. Ballet et al. 1994; Churazov et al. 1994). Many other examples of hard X-ray detections of BHCs exist in the literature, but it seems that the majority of detections are associated with the Low/Hard X-ray state and/or transient outbursts, both of which are associated with jet production (Figs 2 & 3).

Grove et al. (1998) clearly establish that while the hard (photon index \( \sim 1.5 \)) X-ray power laws observed in the Low/Hard state tend to break at about 100 keV, when the spectrum is dominated by a soft (presumably disc) component the steep (photon index \( \sim 2.5 \)) power-law tail observed does not show a break to at least several hundred keV. This weak, high energy tail in the soft state (when the jet is apparently off - Fig 2) probably requires a nonthermal population of Comptonising electrons (Poutanen 1998).

\[ \gamma\text{-RAYS : } > 500 \text{ KEV} \]

Above \( \sim 500\text{keV} \) the number of detections of X-ray binaries drops significantly. Cyg X-1, the classic BHC, was repeatedly detected at \( \geq 1 \text{MeV} \) with COMPTEL on CGRO, and may even be stronger above 1 MeV in the ‘High/Soft’ state (Fig 8; McConnell et al. 2001 a,b). The relativistic jet source GRO J1655-40 and the Low/Hard state source GRO J0422+32 are also both detected up to \( \sim 1 \text{ MeV} \) (Grove et al. 1998). More dramatically, Goldwurm et al. (1992) reported the detection of a positron annihilation line from GRO J0422+32, although this may in fact be associated with Lithium (e.g. Martin et al. 1994).

At even higher energies, Paredes et al. (2000 and references therein; Fig 9) re-
FIGURE 7. Bimodal hard X-ray [crosses] – radio [dotted line] (anti-)correlation in the jet source Cyg X-3. During ‘quiescent’ periods (e.g. JD 2448500-8550) hard X-rays and radio are anti-correlated. During ‘active’ periods, which constitute both flares and pre-flare quenching, radio and hard X-ray fluxes are well correlated (e.g. JD 2448420-8450). From McCollough et al. (1999).

port the discovery of radio jets from the X-ray binary LS 5039, which is coincident with one of the unidentified EGRET sources. They suggest that the $\gamma$-rays are produced by inverse Compton upscattering of lower-energy photons by the nonthermal relativistic electron population producing the resolved radio emission. It is worth noting that LSI+61° 303 is also an X-ray-faint, radio-bright system which may be associated with an EGRET source (Harrison et al. 2000 and references therein).

**DISCUSSION**

There seems to be a qualitative empirical relation between the presence of hard (rather arbitrarily defined as 30–500 keV) X-ray emission and radio emission in both NS and BHC X-ray binaries. Since the evidence strongly points to the radio emission arising in a synchrotron-emitting jet, this implies an association between the presence of a hard X-ray emission and the production of an outflowing, nonthermal, population of relativistic electrons. Are these two things related causally, or are they simply both more or less independent manifestations of a particular accretion/outflow ‘state’?

Since (a) the hard X-ray emission is generally taken to arise in (inverse) Comptonisation of soft photons by energetic electrons (Sunyaev & Titarchuk 1980; Poutanen 1998 and references therein), (b) the synchrotron emission from the jet directly in-
dicates a population of energetic electrons, it might seem reasonable to guess that the Comptonising electrons are part of the jet flow. In Fender et al. (1999b) it was suggested that the ‘base’ of the jet is responsible for the Comptonisation in the canonical Low/Hard X-ray state. However, the favoured models for the Low/Hard state invoke thermal Comptonisation (Poutanen 1998 and references therein).

Are the jets significant enough energetically to contribute in hard X-rays, or is the power-law distribution responsible for the synchrotron emission simply a small high-energy tail of a much more energetically significant thermal distribution? Without accurately normalised estimates of both populations for one source, it is hard to make a comparison. However, Fender (2000a,b) argues that the jets from BHCs in the Low/Hard state are likely to be a significant power output channel for the accretion energy. If the synchrotron spectrum extends merely to the near-infrared band (≈ 2µm) and the jet has a radiative efficiency of ≤ 0.05 then the jet is likely to contribute ≥ 20% of the bolometric luminosity of the system in this state. It seems therefore that in the Low/Hard state at least there is enough power in the jet to justify consideration of its contribution to the hard X-ray/γ-ray emission a source.

Aharonian & Atoyan (1998) and Atoyan & Aharonian (1999) discuss the possibility of γ-rays from the jets of GRO J1655-40, GRS 1915+105 and SS 433. In particular, Atoyan & Aharonian (1999) predict that inverse Compton emission (or maybe even direct synchrotron emission) directly from the jets in GRS 1915+105 could dominate the high-energy emission above an MeV or so. More radically, Markoff, Falcke & Fender (2000) suggest that in the Low/Hard X-ray state the broadband radio through X-ray spectrum is dominated by the jet (with some con-

**FIGURE 8.** MeV spectrum of Cyg X-1 in the low/hard and high/soft X-ray states. From McConnell et al. (2000a).
FIGURE 9. LS 5039: a γ-ray binary? The left panel shows the sky distribution of unidentified EGRET γ-ray sources. The weak X-ray binary LS 5039 is coincident with one of these (3EG J1824-1514). At radio wavelengths LS 5039 is clearly resolved into an asymmetric (and therefore probably relativistic) jet with the VLBA (right panel). From Paredes et al. (2000).

To conclude, it seems that, while some famous and poorly-explained exceptions exist in the literature (e.g. GRO J1655-40; Tavani et al. 1996), in general the presence of ‘hard’ X-ray emission (30–500 keV) is correlated with the presence of radio emission in both NS and BHC X-ray binaries (with the exception of high-field X-ray pulsars which do not seem to produce jets – Fender & Hendry 2000). In some cases (e.g. GX 339-4; Fig 6) this correlation is very tight. Adopting the classical picture of hard X-ray production via Comptonisation, this broad correlation implies the simultaneous presence of a Comptonising corona and synchrotron-emitting (and therefore relativistic) jet in ‘hard’ accretion ‘states’. This may suggest that the ‘base’ of the jet, within a few hundred Schwarzschild radii of the compact object, is providing the hot electrons for the Comptonisation process (Fender et al. 1999b), although models for Comptonisation in the Low/Hard state of BHCs favour a thermal population of electrons in the corona (Poutanen 1998 and references therein). More radically, the signature of the jet may extend to much higher energies than the radio regime, and may even challenge the Comptonisation model of hard X-ray...
production (Markoff et al. 2000).

The relation of jets to the presence of $\gamma$-ray ($> 500$ keV) emission is less clear, and further systematic studies (with e.g. INTEGRAL) are required. However, given that radio jets, with their population of very high energy electrons, are natural sites for the production of high energy photons via both inverse Compton scattering (Atoyan & Aharonian 1999; Paredes et al. 2000) and maybe even direct synchrotron emission (Markoff et al. 2000) such connections should be investigated in detail in the future.

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