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Accretion modes and jet production in black hole X-ray binaries

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Abstract. We review our current understanding of the radio properties of black hole X-ray binaries in connection with the X-ray spectral states, and discuss them in the framework of the recently proposed unified model for the jet-accretion coupling in these systems.

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

1. X-ray states of black hole binaries

The spectral-energy distribution (SED) of the gravitational power released as radiation when gas accretes on to a black hole is far from unique. Different accretion modes are possible, and the same initial conditions at the outer boundaries may admit more than one solution for the accretion flow at the inner boundary, with often different radiative properties. The main goal of accretion flows theory is to understand and distinguish all the possible different modes of accretion, and classify the observed sources in terms of such modes. The energy spectra of black hole X-ray binaries (BHXBs) at energies greater than 10 keV are roughly described by a power law, which may or may not have a detectable high energy cutoff. The slope of this power-law is characterized by the photon index, Γ, where the photon number flux per unit energy (photons cm^{-2} s^{-1} keV^{-1}) is $F_{\rm N}(E) \propto E^{-\Gamma}$, where E is the photon energy. Broadly speaking, the 'classical' five X-ray states of BHXBs are distinguished by the bolometric X-ray luminosity, and by the relative contribution to the X-ray luminosity of the hard power-law component with respect to a 'soft', quasi-thermal component, which peaks around 1 keV. At luminosities close to the Eddington one, BHXBs are often in the 'very high state' (VHS), where both of the two components contribute substantially to the SED. At slightly-lower luminosities, the quasi-thermal one dominates and the power-law is usually steeper ($\Gamma > 2$) and extended to the γ-ray band. This state is traditionally termed 'high/soft' (HS). At even lower luminosities, typically below a few per cent of Eddington, the spectra are completely dominated by a hard power-law component (having $\Gamma \simeq 1.7$), with the quasi-thermal one extremely weak or even absent: these are the so-called 'low/hard' states (LS). Sometimes, at luminosities intermediate between those of the soft and the hard states, an intermediate state (IS) is observed, with properties similar to those of the very high state. It is often the

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case that the same source, either persistent or transient, undergoes a transition between spectral states, and therefore between accretion modes. Below a few 10^{-5} Eddington, a 'quiescent state' is identified, with properties similar to the low/hard state.

It is generally believed that the main parameter driving the transition between states is the instantaneous accretion rate $\dot{m}$, even though a 'two-dimensional behaviour' has recently emerged, suggesting that a second parameter may play a role (Homan *et al.* 2001).

There are a number of extensive reviews describing in detail the properties of X-ray states of BHXBs; we refer to the reader to: Esin (1997); Done (2001); Homan *et al.* 2001; McClintock & Remillard (2005); Homan & Belloni (2005). In particular, McClintock & Remillard (2005) have introduced a new classification that is partly based on the 'old' scheme described above, but no longer uses luminosity as a selection criterion. They still recognize a quiescent state, hard state, soft state (renamed 'thermal dominant') and a very high state (renamed 'steep power law' state) but drop the intermediate one as a *bona fide* state.

2. Accretion modes

The majority of spectral studies of BHXBs in the X-ray band suggest that the power-law continua of these sources are produced by thermal Comptonization (Shapiro *et al.* 1976; Sunyaev & Titarchuk 1980) in a hot, rarefied 'corona' of electron and positrons, which probably resides where most of the accretion energy is released, namely in the inner part of the flow. Furthermore, there is evidence that this hot, Comptonizing medium strongly interacts with the colder thermal component: such an interaction is not only required to explain the ubiquitous reflection features in the X-ray spectra (Lightman & White 1988; Matt, Perola & Piro 1991; Fabian *et al.* 2000), but could also provide the feedback mechanism that forces the observed values of coronal temperature and optical depth to lie in very narrow range for all the different observed sources (Haardt & Maraschi 1991).

From the theoretical point of view, the soft quasi-thermal component is thought to be the clear signature of a geometrically thin, optically thick accretion disc (Shakura & Sunyaev 1973; Pringle 1981). Thus, the observed hard-X-ray power laws represent a universal signature of a *physical process* more than of specific accretion dynamics. This is why, if there is little doubt that the standard thin accretion disc model accounts for the basic physical properties of black holes in their soft states, the accretion mode responsible for the low–luminosity hard/quiescent states is still a matter of debate. Radiatively inefficient accretion can take place at low accretion rates if the density of the accreting gas is low enough to inhibit the energy coupling between protons and electrons. Under such conditions the flow remains hot, assumes a puffed-up geometry and radiates very inefficiently.

Since their rediscovery in recent years (Narayan & Yi 1994, 1995; Narayan, Mahadevan & Quartaet 1998), radiatively inefficient, advection-dominated accretion flows (Ichimaru 1977; Rees *et al.* 1982) have been regarded as natural solutions. The key feature of an 'ADAF' is that the radiative efficiency of the accreting gas is low, so that the bulk of the viscously dissipated energy is stored in the gas as thermal energy (or entropy). ADAF solutions only exist below a critical accretion rate, $\dot{m} < 10^{-2} - 10^{-1}\dot{m}_{\rm Edd}$. The optically thin gas in an ADAF radiates with a spectrum that is very different from the blackbody-like spectrum of a thin disc; more importantly, the luminosity of an ADAF has a steep dependence on the accretion rate. The efficiency with which thermal energy is transferred from ions to electrons (to be subsequently radiated) is proportional to $\dot{m}$, hence $L \propto \dot{m}^2$. The quadratic scaling arises because the gas is in the form of a two-temperature plasma, with the ions being much hotter than the electrons. In contrast, the luminosity of a Shakura-Sunyaev disc varies as $L \propto \dot{m}$. The key difference is that whereas in a thin disc a large fraction of the released energy is radiated, in an ADAF nearly all the energy remains locked up in the gas as thermal energy and may be advected into the central object.

When tested against the best data for hard state BHXBs, though, as in the case of XTE J1118+480 (Esin et al. 2001) or Cygnus X-1 (Esin et al. 1998), ADAF models alone cannot work. A transition between an inner ADAF and an outer Shakura-Sunyaev disc is needed, as can also be inferred from studies of X-ray reflection components (Esin, McClintock & Narayan 1997; Done 2001).

There are also concerns with this solution, the main one being that the accreting gas is generically unbound and can escape freely to infinity. The reason is that the gas is likely to be supplied with sufficient angular momentum to orbit the hole and its inflow is controlled by the rate at which angular momentum is transported outward. This angular momentum transport is necessarily associated with a transport of energy. If one attempts to conserve mass, angular momentum and energy in the flow, it is found that the Bernoulli function – the energy that the gas would have if it were allowed to expand adiabatically to infinity – is twice the local kinetic energy.

Blandford & Begelman (1999) have proposed an alternative solution called adiabatic inflow outflow solution (ADIOS). Here the key notion is that the excess energy and angular momentum is lost to a wind at all radii. This mass loss makes the accretion rate on to the black hole much smaller than the rate at which mass is supplied at the outer radius. In this model the radial energy transport drives an outflow that carries away mass, angular momentum and energy, allowing the disc to remain bound to the hole. The final accretion rate into the hole may be only a tiny fraction (in extreme cases 10^{-5}) of the mass supply at large radius. This leads to a much smaller luminosity than would be observed from a 'conservative' flow. This is important from an observational perspective, because different assumptions concerning the extent and nature of the outflow affect the derived densities and temperatures of the emitting regions, and can lead to very different conclusions based on phenomenological fits to multi-wavelength data.

Another possible scenario for low-luminosity black holes is that proposed by Merloni & Fabian (2002), where strong, unbound, magnetic coronae are powered by thin discs at low accretion rates. These coronal-outflow-dominated solutions are both thermally and viscously stable, as in general are all standard Shakura-Sunyaev accretion disc solution in the gas pressure dominated regime. However, rapid and dramatic variability in the observed high-energy flux is expected, as X-rays are produced by coronal structures that are the eventual outcome of the turbulent magnetic field generation inside the disc. The geometry of these structures (open *vs* closed field lines, for example) plays a very important role and may be such that, at times, parts of the corona become temporarily radiatively efficient.

It remains to be seen which, if any, of these models comes closest to reproducing the observational characteristics of accretion on to black holes at different accretion rates. Nevertheless numerical simulations of radiatively inefficient accretion flows also seem to form outflows, either collimated or not (Hawley & Balbus 2002).

3. The fifth element

There also exists a fifth element: the region extending from around the black hole and the inner edge of the accretion disc and extending out along the symmetry axis to form a *jet*: a narrow stream of energy and particle flowing out of the system with relativistic velocities. Although there is a general consensus that the formation and initial collimation of jets requires magnetic fields, we still lack a comprehensive theory that might account for the process of jet formation, acceleration and collimation. We do not understand why certain sub-classes of object produce powerful jets whilst others do not; the composition of jets is also a matter of debate: relativistic electrons and magnetic field must be present, but it is unclear whether the positively-charged particles are protons or positrons (see e.g. Hughes (1991) for a thorough review of astrophysical jets).

The advantage of studying relativistic jets powered by stellar mass objects is simply given by their rapid variability: as the phys-

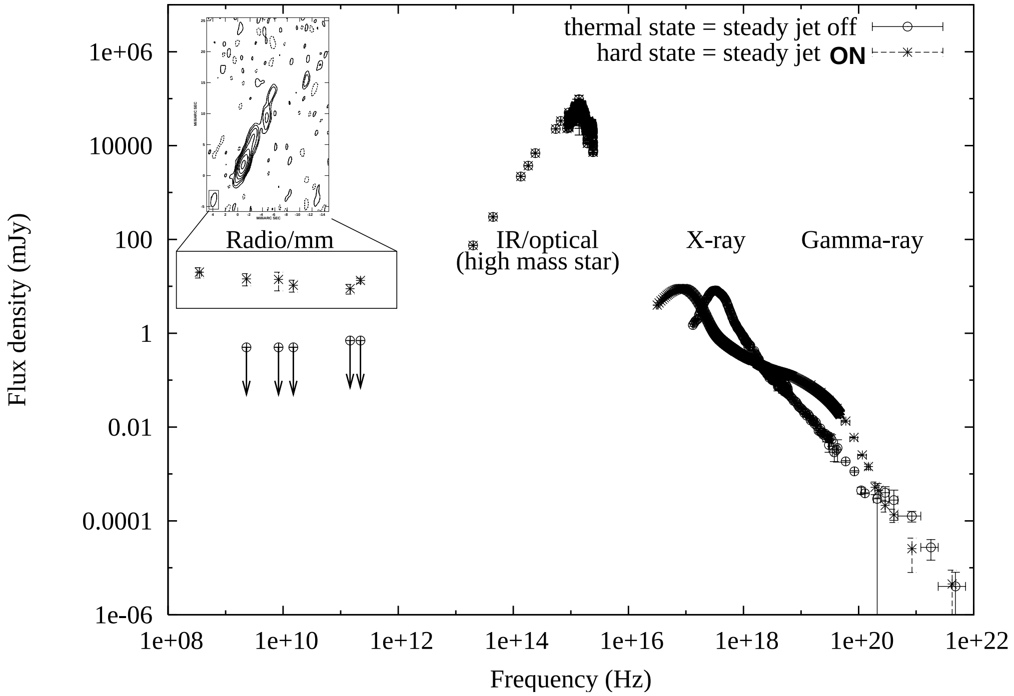

Fig. 1. Spectral energy distribution of the prototypical 10 $M_\odot$ BH in the high mass X-ray binary Cygnus X-1, over different accretion regimes. When the hard (above 10^{18} Hz) X-ray spectrum is dominated by a hard power-law component, the system is persistently detected in the radio band. The radio-mm spectrum is flat, due to a partially self-absorbed steady jet resolved on milliarcsec-scales (inset VLBA map from Stirling *et al.* 2001). Above a critical X-ray luminosity of a few per cent Eddington, the disc contribution becomes dominant (in units of νF_ν), while the hard X-ray power law softens. In this 'high/soft', or 'thermal dominant' state the radio emission is quenched by a factor of at least 30 with respect to the hard state.

ical timescales associated with the jet formation are thought to be set by the accretor's size, and hence mass, then by observing BHXBs on timescales of days to decades we are probing the time-variable jet:accretion coupling on timescales of tens of thousands to millions of years or more for supermassive black holes at the centres of active galactic nuclei.

4. Radio emission from black hole X-ray binaries

Historically, the key observational aspect of X-ray binary jets lies in their synchrotron radio emission (Hjellming & Han 1995; Mirabel & Rodríguez 1999; Fender 2005). The *synchrotron* nature of the radio emission from X-ray binaries in general is inferred by the high brightness temperatures, high degree of polarization and non-thermal spectra. The *outflow* nature of this relativistic (as it emits synchrotron radiation) plasma is inferred by brightness temperature arguments, leading to minimum linear sizes for the emitting region that often exceed the typical orbital separations, making it unconfinable by any known component of the binary.

Different jet properties are associated with different X-ray spectral states of BHXBs. This is illustrated schematically in Figure 1, which shows the spectral energy distribution, from radio to γ-ray wavelengths, of the (prototypical) stellar mass black hole in Cygnus X-1 over different accretion regimes.

4.1. Steady jets

BHXBs in hard states display persistent radio emission with flat radio-mm spectrum. Since we are in presence of a relativistic outflow, which is inevitably subject to expansion losses, the persistence of the emission implies the presence of a continuously replenished relativistic plasma. The flat spectral indexes can only be produced by inhomogeneous sources, with a range of optical depths and apparent surface brightness, and therefore are generally interpreted in terms of synchrotron emission from a partially self-absorbed, steady jet which becomes progressively more transparent al lower frequencies as the particles travel away from the launching site (Blandford & Königl 1979; Hjellming & Johnston 1988; Falcke & Biermann 1996). We shall refer to them as *steady jets*. Confirmations of the *collimated* nature of these hard state outflows come from Very Long Based Array (VLBA) observations of Cyg X-1 (Stirling *et al.* 2001) and GRS 1915+105 (Dhawan *et al.* 2000; Fuchs *et al.* 2003), showing milliarcsec-scale (tens of A.U.) collimated jets. The presence of a steady jet can also be inferred by its long-term action on the local interstellar medium, as in the case of the hard state BHXBs 1E1740.7−2942 and GRS 1758−258, both associated with arcmin-scale radio lobes (Mirabel *et al.* 1992; Martí *et al.* 2002). Further indications for the existence of collimated outflows in the hard state of BHXBs come from the stability in the orientation of the electric vector in the radio polarisation maps of GX 339−4 over a two year period (Corbel *et al.* 2000). This constant position angle, being the same as the sky position angle of the large-scale, optically thin radio jet powered by GX 339−4 after its 2002 outburst (Gallo *et al.* 2004), clearly indicates a favoured ejection axis in the system.

Some authors propose a jet interpretation (rather than the standard Comptonizing corona) for the X-ray power-law which dominates the spectrum of BHXBs in the hard/quiescent state (Markoff, Falcke & Fender 2001; Markoff *et al.* 2003). In this model, depending on the location of the frequency above which the jet synchrotron emission becomes optically thin to self-absorption and the distribution of the emitting particles, a significant fraction – if not the whole – of the hard X-ray photons would be produced in the inner regions of the steady jet, by means of optically thin synchrotron and synchrotron self-Compton emission.

No core radio emission is detected while in soft (thermal dominant) state: the radio fluxes are *quenched* by a factor up to about 50 with respect to the hard X-ray state (Fender *et al.* 1999; Corbel *et al.* 2001), probably corresponding to the physical disappearance of the steady jet.

4.2. Transient jets

VLA observations of apparent superluminal motions from GRS 1915+105, back in 1994, demonstrated unequivocally that BHXBs could produce highly relativistic jets (Mirabel & Rodríguez 1994). These kind of events have proved to be rather common among BHXBs. X-ray state transitions appear to be associated with arcsec-scale (thousands of A.U.) synchrotron-emitting plasmons moving away from the binary core with highly relativistic velocities (Mirabel & Rodríguez 1994, 1999; Fender *et al.* 1999). Unlike milliarcsec-scale steady jets, such discrete ejection events display optically thin synchrotron spectra above some frequency, from which the underlying electron population can be derived. The monotonic flux decay observed after a few days in these transient radio ejections seems to be primarily due to adiabatic expansion losses, as the decay rate is the same at all frequencies. Significant loss of energy through the synchrotron emission process itself, or via inverse Compton scattering, would result in a more rapid decay at higher frequencies. The fact that adiabatic losses dominate indicates that the synchrotron radiation observed from such events is only a small fraction of the total energy originally input. We shall refer to them as *transient jets*.

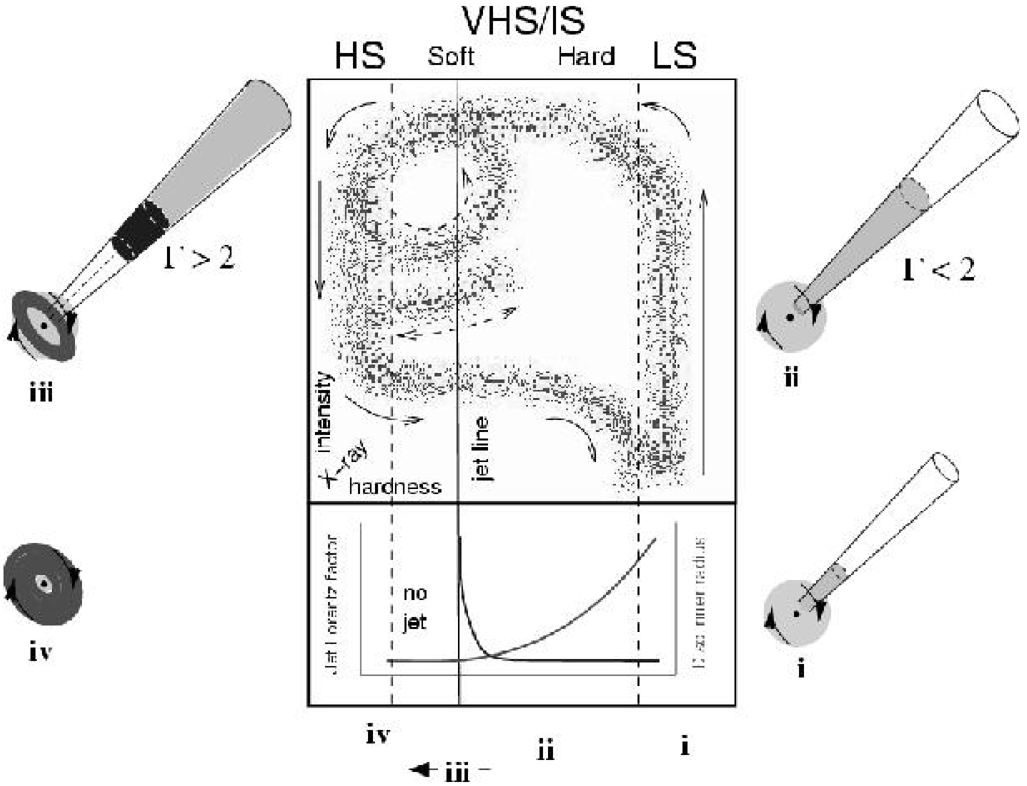

Fig. 2. A schematic of our simplified model for the jet-disc coupling in black hole binaries. The central box panel represents an X-ray hardness-intensity diagram (HID); 'HS' indicates the 'high/soft state', 'VHS/IS' indicates the 'very high/intermediate state' and 'LS' the 'low/hard state'. In this 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 (**iii**) followed in general by cessation of jet production in a disc-dominated HS (**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.

5. Towards a unified model for BHXB jets

Based upon a collection of quasi-simultaneous radio/X-ray observations of BHXBs undergoing X-ray state transitions, Fender, Belloni & Gallo (2004) have attempted to construct a unified, semi-quantitative, model for the disc-jet coupling in BHXBs. The model is summarized in Figure 2, 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 four sketches around the outside of the schematics indicate our suggestions as to the state of the source at the various phases **i–iv**. The path of a typical

X-ray transient is as indicated by the solid arrows.

- Phase **i**: Sources are in the low-luminosity low/hard X-ray state (LS), producing a steady jet. This phase probably extends down to the quiescent state.
- Phase **ii**: The motion in the HID, for a typical outburst, has been nearly vertical. There is a peak in the hard state after which the motion in the HID becomes more horizontal (to the left) and the source moves into the 'hard' (portion of the) very-high/intermediate state (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 hard state.
- Phase **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.
- Phase **iv**: The source is in the 'soft' (portion of the) VHS/IS or the canonical high/soft state (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 Figure 2, back across the jet line, However, with the exception of GRS 1915+105, the number of such excursions is generally a few. When crossing the jet line from right to left, the jet is re-activated 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 inner disc may subsequently recede, in which case a steady jet is reformed, 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 (via e.g. build up of magnetic field near the innermost stable orbit) which results in the hardening of the X-ray spectrum, perhaps via pressure it exerts on the disc to push it back, or simply via Comptonization of the inner disc as it spreads.

In the context of the nature and classification of black hole states, these states, whether 'classical' or as redefined by McClintock & Remillard (2005) 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 innermost stable orbit. The dividing 'jet line' may also correspond, at least approximately, to a singular switch in X-ray timing properties (Belloni 2004; Homan & Belloni 2005; Remillard 2005) 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 the above model.

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