Black hole X-ray binary jets

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Abstract. Relativistic jets powered by stellar mass black holes in X-ray binaries appear to come in two types: steady outflows associated with hard X-ray states and large scale discrete ejections associated with transient outbursts. We show that the broadband radio spectrum of a ‘quiescent’ stellar mass black hole closely resembles that of canonical hard state sources emitting at four orders of magnitude higher X-ray levels, suggesting that a relativistic outflow is being formed down to at least a few $10^{-6}$ times the Eddington X-ray luminosity. We further report on the discovery of a low surface brightness radio nebula around the stellar black hole in Cyg X-1, and discuss how it can be used as an effective calorimeter for the jet kinetic power

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ASTROPHYSICAL RELEVANCE

The production of jets, collimated bipolar outflows with relativistic velocities, appears to be a common consequence of accretion of material onto black holes on all mass scales. However, despite decades of study, we still lack a comprehensive theory that might account for the mechanism(s) of jet production, acceleration and collimation, and address the issue of the coupling between the outflow of matter and the accretion flow (e.g. [1]). The advantage of studying relativistic jets powered by stellar mass objects is simply given by their rapid variability: as the physical timescales associated with the jet formation are thought to be set by the accretor’s size, and hence mass, then by observing stellar mass black holes in Galactic X-ray binary systems (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 (AGN). Even though such jets are expected to be highly radiatively inefficient – being adiabatic expansion the dominant cooling process – in the recent years it has become apparent that they may carry away a significant (if not the dominant) fraction of the liberated accretion power in low luminosity systems, possibly acting as a major source of energy and entropy for the interstellar medium.

RADIO STATES OF BLACK HOLE X-RAY BINARIES

Historically, the key observational aspect of X-ray binary jets lies in their radio emission ([20], [33]): in BHXBs, different radio properties are associated with different X-ray spectral states (see [10], [30] and Remillard, in these Proceedings, for recent reviews).
FIGURE 1. Spectral energy distribution of the prototypical 10 $M_{\odot}$ BH in the high mass X-ray binary Cygnus X-1. When the X-ray spectrum (above $\sim 10^{18}$ Hz) is dominated by a hard power-law component (triangle-points), the system is persistently detected in the radio band. The radio-mm spectrum is flat, due to an inhomogeneous, partially self-absorbed steady jet resolved on milliarcsec-scales [41]. Above a critical X-ray luminosity, the disc contribution becomes dominant (in units of $\nu F_\nu$), while the hard X-ray power law softens (star-points). In this ‘thermal dominant’ state the radio emission is quenched by a factor up to about 50 with respect to the hard state. Adapted from [43].

This is illustrated schematically in Figure 1, which shows the spectral energy distribution, from radio to $\gamma$-ray wavelengths, of the (prototypical) stellar mass black hole in Cygnus X-1 over different accretion regimes.

While accreting gas at relatively low rates (below a critical X-ray luminosity of a few per cent of the Eddington X-ray luminosity, $L_{\text{Edd}}$), BHXB systems emit the bulk of their radiation in form of a hard X-ray power law component that cuts off at a few hundreds of keV, traditionally interpreted as due to Comptonization of disc photons in a rarefied electron/positron plasma ([42], [44]). In terms of radio properties this hard X-ray state is radio active, associated with persistent emission and a flat or slightly inverted spectrum which extends up to near-IR (possibly optical) frequencies, thought to be synchrotron in origin ([12] and ref. therein). The outflow nature of the synchrotron-emitting (and thus relativistic) plasma is inferred by brightness temperature arguments, leading to minimum linear sizes for the emitting region that often exceed the typical orbital separations, and thus making it unconfinable by any known component of the binary. This, together with the fact that BHXBs in the hard state display persistent radio emission despite being inevitably subject to expansion losses, imply the presence of a continuously replenished relativistic plasma that is flowing out of the system. The flat radio spectrum would arise in a steady partially self-absorbed conical jet, becoming progressively more transparent at lower frequencies as the matter travels away from the launching site ([2], [21]). The collimated nature of these outflows is less certain, as it requires direct imaging to be proven. Milliarcsec-resolution observations of Cyg X-1 in the hard X-ray state have
confirmed the jet interpretation of the flat radio-mm spectrum in this system, imaging an extended structure extending to about 15 milliarcsec (∼30 A.U. at 2 kpc), and with an opening angle of less then 2° ([14]).

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 polarization maps of GX 339−4 over a two year period ([7]). 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 ([17]), clearly indicates a favoured ejection axis in the system. Finally, the milliarcsec scale jet of the (somewhat peculiar) BH candidate GRS 1915+105 ([9]; [15]) in the hard state supports the association of hard X-ray states of BHXBs with steady, partially self-absorbed jets.

It is worth mentioning that some authors propose a jet interpretation (rather than a Comptonizing ‘corona’) for the X-ray power law which dominates the spectrum of BHXBs in the hard/quiescent (see next Section) state ([28], [27]). 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.

Above a few per cent of \( L_{\text{Edd}} \), BHXBs enter the so called thermal dominant X-ray state (starred points in Figure 1), during which the power output is dominated by a thermal component with typical temperatures of about 1 keV, interpreted as the clear signature of a geometrically thin optically thick accretion disc ([39]) extending very close to the central hole. No core radio emission is detected while in the thermal dominant state: the radio fluxes are quenched by a factor up to about 50 with respect to the hard X-ray state ([14], [3]), probably corresponding to the physical disappearance of the steady jet. This has been taken as a strong arguments in favour of magneto-hydrodynamic jet formation in geometrically thick accretion flows ([31]).

Additionally, we observe a second variety of radio jets powered by BHXBs: hard-to-thermal 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 ([33], [10] and ref. therein). Unlike milliarcsec scale steady jets, such discrete ejection events display optically thin synchrotron spectra and rapidly decaying fluxes. We shall refer to them as transient jets.

**RELATIVISTIC OUTFLOWS IN ‘QUIESCENCE’**

What are the required conditions for a steady jet to exist? We wonder especially whether the steady jet survives in the very low luminosity, quiescent X-ray state (with \( L_X \lesssim 10^{33.5} \text{ erg sec}^{-1} \), i.e. below a few \( 10^{-5}L_{\text{Edd}} \)). In such a regime, very few systems have been detected in the radio band, mainly because of sensitivity limitations on the existing telescopes. Among them, the faintest is V404 Cygni, hosting a 12 M⊙ black hole ([38]) and emitting in the X-rays at a few \( 10^{-6}L_{\text{Edd}} \) ([28]). Given the quite large
degree of uncertainty about the overall structure of the accretion flow in quiescence (see [30] and ref. therein), it has even been speculated that the total power output of a quiescent BH could be dominated by a radiatively inefficient outflow ([18], [13]) rather than by the local dissipation of gravitational energy in the accretion flow. It is therefore of primary importance to establish the nature of radio emission from quiescent BHXBs.

Radio observations (using the Westerbork Synthesis Radio Telescope, WSRT) of this system, performed on 2002 December 29 (MJD 52637.3) at four frequencies, over the interval 1.4–8.4 GHz, have provided us with the first broadband radio spectrum of a quiescent stellar mass black hole. We measured a mean flux density of 0.4 mJy, consistent with that reported by [22], and a flat/inverted spectral index $\alpha = 0.09 \pm 0.19$ (such that $S_\nu \propto \nu^\alpha$). WSRT observations performed one year earlier, at 4.9 and 8.4 GHz, resulted in a mean flux density of 0.5 mJy, confirming the relatively stable level of radio emission from V404 Cyg on a year time-scale; even though the spectral index was not well constrained at that time, the measured value was consistent with the later one.

Synchrotron emission from a partially self-absorbed relativistic outflow of plasma seems to be the most likely explanation for the flat radio spectrum. Optically thin free-free emission as an alternative is ruled out, on the basis that far too high mass loss rates would be required in order to sustain the observed radio flux: even taking into account geometrical effects, such as outflow collimation and/or clumpiness, the mass loss rates can not be lower than $10^{-3}$ times the Eddington rate (assuming a 10 per cent efficiency in converting mass into light), i.e. still far too high for a sub-$10^{-5}$ Eddington BH to produce any observable radio emission (see [16] for details).

The collimated nature of this outflow remains to be proven; based on brightness temperature arguments and the 5.5-hour time-scale variability detected at 4.9 GHz, we conclude that the angular extent of the radio source is constrained between 0.01 at 1.4 GHz and 10 mas at 4.9 GHz (at a distance of 4 kpc; [23]). These arguments led us to suggest that a relativistic jet is being formed in the quiescent state of V404 Cyg, and probably in BHXBs between a few $10^{-6}$ and a few per cent of $L_{Edd}$ (were the collimated jet is actually resolved), strengthening the notion of ‘quiescence’ as a low luminosity version of the canonical hard X-ray state ([16]).

A UNIFIED PICTURE

The question remains whether the steady and transient jets of BHXBs have a different origin or are somewhat different manifestations of the same phenomenon. [11] have addressed this issue, showing that: i) the power content of the steady and transient jets are consistent with a monotonically increasing function of $L_X$; ii) the measured bulk Lorentz factors of the transient jets are systematically higher than those inferred for the steady jets. Based upon these arguments, a unified model for the jet/accretion coupling in BHXBs has been put forward. The key idea is that, as the disc inner boundary moves closer to the hole (hard-to-thermal state transition), the escape velocity from the inner regions increases. As a consequence, the steady jet bulk Lorentz factor rises sharply, causing the propagation of an internal shock through the slower-moving outflow in front of it. Eventually, the result of this shock is what we observe as a post-outburst, optically thin radio plasmon. For a thorough description of the model, we refer the reader to
FIGURE 2. Westerbork Synthesis Radio Telescope 1.4 GHz of the field of view of the BHXB and Galactic jet source Cyg X-1: the arcmin scale, semi-ring-like structure northeast of the binary core (marked by a cross) seems to draw an edge between the bright HII region west of Cyg X-1 and the direction of the Cyg X-1 milliarcsec scale jet, shown in the inset (VLBA map from [41]); the average monochromatic flux of the ring is of about 0.08 mJy/beam. We interpret this structure as the result of a strong shock that develops at the location where the collimated jet impacts on the ambient ISM (Gallo, Fender, Kaiser & Russell, in preparation).

Belloni, in these Proceedings.

**DISCOVERY OF A JET-POWERED RADIO NEBULA IN CYG X-1**

The importance of BHXB jets for the overall energetics and dynamics of the accretion process, and furthermore as a potentially major source of energy input into the galactic interstellar medium (ISM), has yet to be well quantified. For both the steady and transient jets we are forced to make assumptions about the spectral extent (as the jet high frequency emission is generally blocked by the accretion disc or the companion star) and radiative efficiency, basing our estimates on, for example, assumptions of equipartition for which there is little a priori justification. Alternatively, we can constrain the jets’ power content by looking at their (gradual or abrupt) interaction with the surrounding medium. As in AGN, the total energy associated with radio lobes and termination shocks was, and to a certain extent remains, the safest way to estimate the jet power×lifetime product ([3]). In the case of Galactic stellar mass BHs, arcmin-scale radio lobes are associated with two hard state sources in the galactic centre, 1E 1740.9-2942 and GRS 1758-258 ([34], [37]). [4] identified two IRAS sources with flat spectrum symmetric about GRS1915+105 (see also [36]) but argued that a possible association with the arc-
sec scale jets in these system seemed inconclusive. \cite{25} suggest instead that the two IRAS regions would be the actual jets’ impact sites; applying a fluid dynamical model developed for AGN jets (\cite{24}) to this stellar mass system, they conclude that the time-averaged energy transport rate in the jet may be as low as $10^{36}$ erg s$^{-1}$ (i.e. at least one order of magnitude than what inferred for the discrete ejecta; \cite{14}). If correct, this association would place GRS 1915+105 at the same distance of the two IRAS sources, i.e. at 6.5 kpc (rather than the 12 kpc estimated by \cite{19}), casting doubts even on its ‘superluminal’ nature. Finally, we have recently witnessed the dynamic formation of arcmin-scale decelerating radio and X-ray lobes, following an outburst of the transient BHXB XTE J1550-564 (\cite{5}). These results suggest that radio lobe formation is a common occurrence which might be associated with many more sources and has not been found to date due to low signal-to-noise.

Such considerations led us to look for extended radio nebulae around the more promising (i.e. radio-loud) binary systems powering jets with the WSRT. Observations performed in May 2003 at 1.4 GHz resulted in the discovery of an arcmin scale semi-ring-like radio nebula around the Galactic jet source Cyg X-1, presented in Figure 2 (Gallo, Fender, Kaiser & Russell, in preparation). The structure appears to be perfectly aligned with the collimated jet resolved on milliarcsec scale. We note that previous attempts to look for lobes around Cyg X-1 (\cite{29}) resulted in several ‘interesting structures’ at 1.4 GHz, whose association with Cyg X-1 could not be proven yet. Interestingly, Martí and collaborators (1996) already talked of a ‘suggestive shell appearance of the structures’ around Cyg X-1, which led them to investigate the possibility of a weak supernova remnant interpretation, eventually excluded due to too low surface brightness.

**Modelling the ring of Cyg X-1: jet power and lifetime**

Following the self-similar model developed by \cite{24} for extragalactic jet-cocoon systems, we have interpreted the semi-ring radio structure of Cyg X-1 as the result of a strong shock that develops at the location where the collimated jet (resolved on milliarcsec scales) impacts on the ambient ISM. The jet particles inflate a radio lobe which is over-pressured with respect to the surrounding medium, thus the lobe expands sideways forming the observed bow shock that emits bremsstrahlung radiation – hypothesis which needs to be confirmed through approved optical and deep 90 cm observations of this field. The very pressure in the cocoon is responsible for keeping the jet confined. Following their formalism, we assume:

1. that the jet and the shocked ISM are in pressure balance;
2. that the rate of energy input is constant and given by the average jet power, $Q_0$;
3. that the rate of mass transport along the jet is constant and supplied by the bulk kinetic energy of the jet;
4. that the shock expands into an atmosphere of constant mass density $\rho_0$.

This model implicitly requires the bow shock to be self-similar and a roughly constant jet direction (which seems to be the case here, as the measured proper motion of Cyg X-1 rules out large velocity kicks; \cite{32}).
Knowing the ring monochromatic luminosity, we are able to derive the density of the ionized particles in the ring from the expression of the bremsstrahlung emissivity $\varepsilon_{\nu}$ for a pure hydrogen gas emitting at a typical temperature of $T \simeq 10^4$ K (below which the ionization fraction becomes negligible, and above which the cooling time becomes too short). The measured luminosity density, $L_{1.4\,\text{GHz}} \simeq 4.8 \times 10^{17}$ erg s$^{-1}$ Hz (estimated assuming a distance of 2 kpc to Cyg X-1), equals the product $\varepsilon_{\nu} \times V$, where the source volume $V$ is given by the beam area times the measured ring thickness: $V \simeq 2.0 \times 10^{53}$ cm$^3$. For $T \simeq 10^4$ K and a Gaunt factor $g \simeq 6$, we derive a particle density $n_e$ of the ionized particles of $\sim 24$ cm$^{-3}$. The total particle density in the bow shock region will be a factor $1/x$ higher though, where $x$ is the ionization fraction. At $\sim 10^4$ K, $x = 0.019$ (40), resulting in a particle density $n_t$ of 1260 cm$^{-3}$.

For a strong shock in a mono-atomic gas, the velocity of the bow shock, $v_{\text{bow}}$, depends on the temperature $T$ of the shocked gas as: $v_{\text{bow}} = \sqrt{(16k_B/3m_p)T}$. For $10^4$ K, $v_{\text{bow}} \simeq 2.1 \times 10^6$ cm sec$^{-1}$, justifying the strong shock assumption. In (24) the length $L$ of the jet within the cocoon grows with the time in such a way that: $t = (L/c_1)^{(5/3)} \times (\rho_0/Q_0)^{(1/3)}$ (where the factor $c_1$ depends on the thermodynamical properties of the jet material and on the aspect ratio; here $c_1 \simeq 1.5$). By writing the time derivative of the above equation, we obtain $t = \frac{3}{5}(L/v_{\text{bow}})$, resulting in a jet lifetime of $\sim 0.2 \times (\sin \theta)^{-1}$ Myr, where $\theta$ is the jet angle to the line of sight. This value has to be compared with the estimated age of the progenitor of the black hole in Cyg X-1, of a few Myr (42). For $t \simeq 0.3$ Myr (obtained with $\theta = 35^\circ$; 43), and adopting a mass density $\rho_0$ of the un-shocked material that is $\sim 4$ times lower than that of the shocked material, we obtain an average jet power $Q_0$ of a few $10^{35}$ erg s$^{-1}$, which would be a significant fraction of the measured 0.1-200 keV X-ray power of Cyg X-1 at the peak of the hard X-ray state (8). The results presented here clearly illustrate that finding and measuring jet-powered nebulae in stellar mass black holes offers an alternative and valuable method to address the debated issue of the jet power content in these systems.

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$1 \varepsilon_{\nu} = 6.8 \times 10^{-38} g(\nu,T) T^{(-1/2)} n_e^2 \exp(h\nu/k_B T)$ erg cm$^{-3}$ sec$^{-1}$ Hz$^{-1}$
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