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Radio emission and jets from Galactic microquasars

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Thanks to aggressive campaigns of multi-wavelength observations of X-ray binaries in outbursts over the last decade or so, we have now reached a reasonable understanding of their radio phenomenology in response to changes in the global X-ray properties. Here I shall subjectively review the latest progresses made in assessing the interplay between inflow and outflow from an observational point of view, as well as point out a number of open issues that still need to be addressed both theoretically and observationally.

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1. Warning

As most of our knowledge in this field is based on black hole X-ray binary (BHB) systems, this review will be inevitably biased towards BHBs' properties. Section 5 and part of Section 4.2 will focus on jets from neutron star X-ray binaries and the importance of comparing these two classes for a deeper understanding of the jet phenomenon as a whole.

2. Radio jets' morphology

A meaningful description of the different varieties of radio emitting outflows from BHBs demands a parallel description of the different 'X-ray states'[1] over which they are typically observed. The underlying assumption – motivated by the non-thermal spectra, polarization degree and brightness temperature arguments – is that of radio emission from X-ray binaries in general as due to synchrotron radiation from outflowing plasma (although, at very low radio fluxes, tens of μJy, gyrosynchrotron emission from the donor star could easily dominate). Radiatively inefficient hard X-ray states are associated with flat/slightly inverted radio-to-mm spectra and persistent radio flux levels [13]. In analogy with compact extragalactic radio sources [6], the flat spectra are thought to be due to the superimposition of a number of peaked synchrotron spectra generated along a conical outflow, or jet, with the emitting plasma becoming progressively thinner at lower frequencies as it travels away from the jet base. The jet interpretation has been confirmed by high resolution radio maps of two hard state BHBs: Cygnus X-1 [43] and GRS 1915+105 [10] are both resolved into elongated radio sources on milliarcsec scales – that is tens of A.U. – implying collimation angles smaller than a few degrees. Even though no collimated radio jet has been resolved in any BHB emitting X-rays below a few per cent of the Eddington limit, it is widely accepted, by analogy with the two above-mentioned systems, that the flat radio spectra associated with unresolved radio counterparts of X-ray binaries are originated in conical outflows. Yet, it remains to be proven whether such outflow would maintain highly collimated at very low luminosity levels, in the so called 'quiescent' regime. The answer clearly lies in the very jet production mechanism, and its relation with the inner accretion rate, and will be most likely addressed my means of magneto-hydrodynamic simulations.

Radiatively efficient, thermal dominant X-ray states, on the contrary, are associated with no detectable core radio emission [19]; as the radio fluxes drop by a factor up to 50 with respect to the hard state (e.g. [7], [8]), this is generally interpreted as the physical suppression of the jet taking place over this regime.

Transient ejections of optically thin radio plasmons moving away from the binary core in opposite directions are often observed as a result of bright radio flares associated with hard-to-thermal X-ray state transitions. This are surely the most spectacular kind of jets observed from X-ray binaries: those that have inspired the fortunate term 'microquasar' [39]. As proven by the case of GRS 1915+105, and more recently by Cygnus X-1 as well [14], the same source can produce either kind of jets, persistent/partially self-absorbed, and transient/optically thin, dependently on the accretion regime.

[1] Throughout this review, I shall make use of the X-ray state terminology recently introduced by McClintock & Remillard [30].

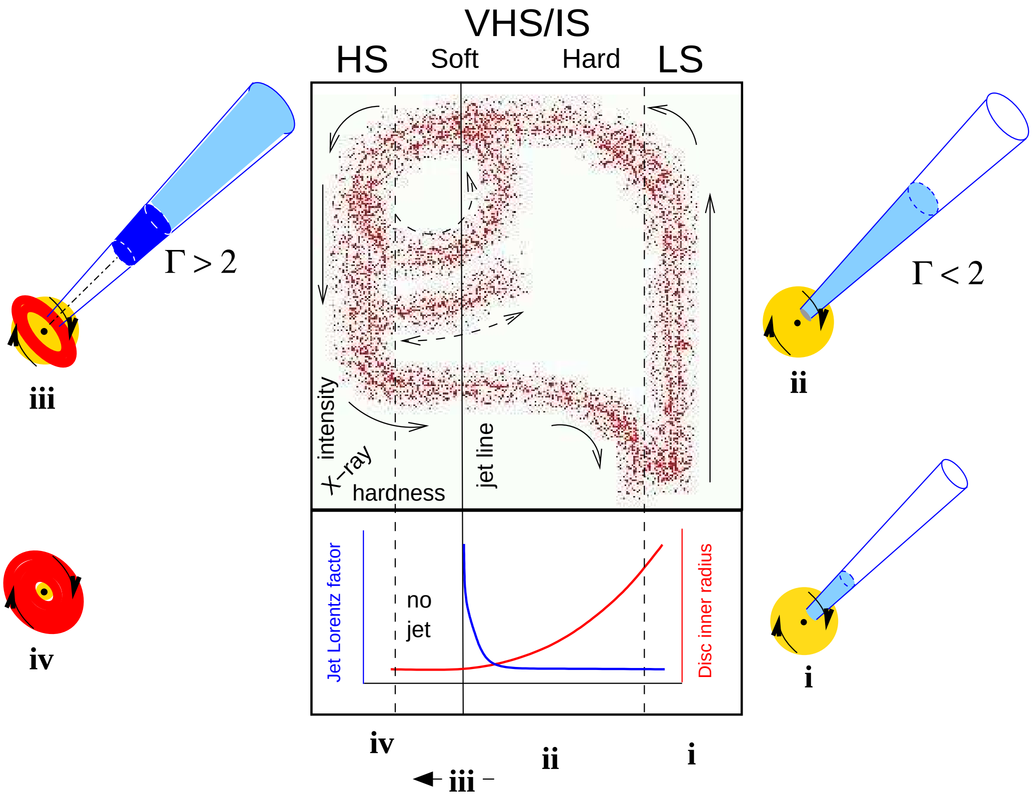

Figure 1: Schematic of the unified model for black hole X-ray binary jets. From [15].

The above description is meant to give a broad overview of the different variety of jets powered by BHBs (see [11] for a thorough review). Recently, a unified scheme for BHB jets has been put forward [15], whose aim is to provide a more dynamical description of a typical BHB cycle, both in terms of accretion and jet properties; this will be the subject of the next Section.

3. A unified scheme for black hole jets

Broadly speaking, this phenomenological model aims to put together the various pieces of a big puzzle that were provided to us by years of multi-wavelength monitoring of BHBs, and to do so under the guiding notion that the jet phenomenon has to be looked at as an intrinsic part of the accretion process. [15] collected as many information as possible about the very moment when major radio flares occur in BHBs, and proposed a way to 'read them' in connection with the X-ray state over which they took place as well as the observed jet properties prior and after the radio flare itself. The study makes use of simultaneous X-ray – typically RXTE – and radio – ATCA and/or VLA – observations of four outbursting systems: GRS 1915+105, XTE J1550–564, GX 339–4 and XTE J1859+229; X-ray Hardness-Intensity Diagrams (HID) have been constructed for the various outbursts and linked with the evolution of the jet morphology, radio luminosity, total power, Lorentz factor and so on.

Figure 1, apparently a.k.a. 'the turtle head diagram', illustrates a schematic of the model. The top panel represents a HID for a (rather well behaved) BHB outburst: the time arrow progresses counterclockwise. Starting from the bottom right corner, the system is a low-luminosity hard X-ray state, producing a (supposedly) mildly relativistic, persistent outflow, with flat radio spectrum. Its luminosity starts to increase at all wavelengths, while the X-ray spectrum remains hard; around a few per cent of the Eddington X-ray luminosity, a sudden transition is made (top horizontal branch) during which the global properties of the accretion flow change from radiatively inefficient to efficient (hard-to-thermal dominant state transition), while a bright radio flare is observed, likely due to a sudden ejection episode. This is interpreted as the result of the inner radius of a geometrically thin accretion disc moving inward, as illustrated in the bottom panel: the Lorentz factor of the ejected material, due to the deeper potential well, exceeds that of the hard state jet, causing an internal shock to propagate through it, and to possibly disrupt it. Once the transition to the thermal dominant state is made, no core radio emission is observed, while large scale rapidly fading radio plasmons are often seen moving in opposite direction with highly relativistic speed.

The bright radio flare associated with the transition could coincide with the very moment in which the hot corona of thermal electrons, responsible for the X-ray power law in the spectra of hard state BHBs, is accelerated and ultimately evacuated. This idea of a sudden evacuation of inner disc material is not entirely new, and in fact dates back to extensive RXTE/PCA observations of the rapidly varying GRS 1915+105: despite their complexity, the source spectral changes could be accounted for by the rapid removal of the inner region of an optically thick accretion disc, followed by a slower replenishment, with the time-scale for each event set by the extent of the missing part of the disc [2],[3]. Subsequently, multi-wavelength (radio, infrared and X-ray) monitoring of the same source suggested a connection between the rapid disappearance and follow up replenishment of the inner disc seen in the X-rays, with the infrared flare starting during the recovery from the X-ray dip, when an X-ray spike was observed.

Yet it remains unclear what drives the transition in the radio properties after the hard X-ray state peak is reached. Specifically, radio observations of GX 339–4 and XTE J1550-564 and GRS 1915+105 indicate that in this phase the jet spectral index seems to 'oscillate' in an odd fashion, from flat to inverted to optically thin, as if the jet was experiencing some kind of instability as the X-ray spectrum softens. Recent simultaneous RXTE and INTEGRAL observations of GX 339–4 [1] have shown that the high energy (few 100s of keV) cutoff typical of hard state X-ray spectra, either disappears or shifts towards much higher energies within timescales of hours ($<$8 hr) during the transition. Previous suggestions of such behaviour were based on X-ray monitoring campaigns with instruments such as OSSE, for which the long integration times required in order to accumulate significant statistics did not allow to constrain the timing and significance of rapid changes in the X-ray spectra. The suggestion that the so called 'jet line' (see Figure 1), where the radio flare is observed and the core radio emission is suddenly quenched might correspond to a peculiar region in the time domain – 'The Zone' (see Homan these Proceedings) – seems to be at odds with recent radio observations (Fender, again these Proceedings).

Finally, there are at least a couple of recent results that might challenge some of the premises the unified scheme is based on (according to this author at least). The first one is the notion that, for the internal shock scenario to be at work and give rise to the bright radio flare at the state transition, whatever is ejected must have a higher velocity with respect to the pre-existing hard state steady jet. From an observational point of view, this was supported, one one side, by the lower limits on the transient jets' Lorentz factors, typically higher than 2 [12], and, on the other hand, by the relative small scatter about the radio/X-ray correlation in hard state BHBs [23] (see Section 4.1). The latter has been challenged on theoretical grounds [26]; while a recent work [34] has demonstrated that, from an observational point of view, the average Lorentz factors do not differ substantially between hard and transient jets (albeit the estimated Lorentz factors rely on the assumption of no lateral confinement). While this is further explored in Section 7, here I wish to stress that, even if the hard and transient jets' velocities were indeed different, much work needs to be done in order to test the consistency of the internal shock scenario as a viable mechanism to account for the observed changes in the radio properties, given the observational and theoretical constraints for a given source (such as emissivities, radio/infrared delays, cooling times, mass outflow rates, etc.).

In addition, recent high statistics X-ray observations of a hard state BHB undergoing outburst [33] suggest that a cool, thin accretion disc extends already near to the innermost stable circular orbit (ISCO) already during the bright phases of the hard state, that is prior to the horizontal brunch in the top panel of Figure 1. This would challenge the hypothesis of a sudden deepening of the inner disc potential well as the cause of a high Lorentz factor ejection. Possibly, whether the inner disc radius moves close to hole prior or during the softening of the X-ray spectrum does not play such a crucial role in terms of jet properties; if so, then the attention should be diverted to a different component, such as the presence/absence, or the size [27], of a Comptonizing corona (which could in fact coincide with the very jet base [28]).

One of the most interesting aspects of this proposed scheme – assuming that is correct in its general principles – is obviously its possible application to super-massive BHs in Active Galactic Nuclei (AGN), and the possibility to mirror different X-ray binary states into different classes of AGN: radio loud vs. radio quiet, LLAGN, FRI, FRII etc.. The interested reader is referred to Jester and Fender, these Proceedings, for novel approaches towards a 'great unification scheme'.

4. Global correlations

4.1 Radio/X-ray

In a first attempt to quantify the relative importance of jet vs. disc emission in BHBs, [23] collected quasi-simultaneous radio and X-ray observations of ten hard state sources. This study established the presence of a tight correlation between the X-ray and the radio luminosity, of the form $L_R \propto L_X^{0.7\pm0.1}$, first quantified by [9] for GX 339–4. The correlation extends over more than 3 orders of magnitude in L_X and breaks down around 2 per cent of the Eddington X-ray luminosity, above which the sources enter the thermal dominant state, and the core radio emission drops below detectable levels. Given the non-linearity of the correlation, the ratio radio-to-X-ray luminosity increases towards quiescence; one wonders however whether the steady jet survives in this very low luminosity state (with $L_{\rm X} \lesssim 10^{33.5}$ erg sec^{-1}, i.e. below a few $10^{-5} L_{\rm Edd}$). In such a regime, very few systems have been detected in the radio band, mainly because of sensitivity limitations on the existing telescopes. Given the quite large degree of uncertainty about the overall structure of the accretion flow in quiescence, it has even been speculated that the total power output of quiescent BHBs could be dominated by a radiatively inefficient outflow [17], rather than by the local dissipation of gravitational energy in the accretion flow.

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Due to its extremely low X-ray luminosity ($L/L_{Edd} \sim 10^{-8.5}$) and relative proximity, the 10 solar mass BH in A0620–00 represents the most suitable known system to probe the radio/X-ray correlation beyond the hard state. Deep VLA observations of this system, performed in 2005 August, resulted in the first radio detection of a quiescent BHB emitting at such low X-ray luminosities. The level of radio emission – 51 μJy at 8.5 GHz – is the lowest ever measured in an X-ray binary. At a distance of 1.2 kpc, this corresponds to a radio luminosity $L_{\rm R} = 7.5 \times 10^{26}$ erg sec^{-1}. By analogy with higher luminosity systems, partially self-absorbed synchrotron emission from a relativistic outflow appears to be the most likely interpretation. Free-free wind emission is ruled out on the basis that far too high mass loss rates would be required, either from the companion star or the accretion disc, to produce observable emission at radio wavelengths, while gyrosynchrotron radiation from the corona of the companion star is likely to contribute to less than 5 per cent to the measured flux density.

The simultaneous *Chandra* observation allowed to test and extend the radio/X-ray correlation for BHBs by 3 orders of magnitude in $L_{\rm X}$. The measured radio/X-ray fluxes confirm the validity of a non-linear scaling between the radio and X-ray luminosity in hard and quiescent systems; with the addition of the A0620–00 point, $L_{\rm R} \propto L_{\rm X}^{0.58\pm0.16}$ provides a good fit to the data for $L_{\rm X}$ spanning between $10^{-8.5}$ and $10^{-2} L_{\rm Edd}$ (see Figure 2). The fitted slope, albeit consistent with the previously reported value of 0.7 ± 0.1, is admittedly affected by the uncertainties in the distance to GX 339–4, for which the correlation extends over 3 orders of magnitude in $L_{\rm X}$ and holds over different epochs. Pending a more accurate determination of the distance to this source, we can nevertheless exclude the relation breaking down and/or steepening in quiescence. That the non linear radio/X-ray correlation for hard state black hole X-ray binaries extends down to very low quiescent luminosities implies that the ratio of jet-to-accretion radiative power is a decreasing function of L_X over the luminosity range that is explorable with current instrumentation [20].

4.2 Optical-IR/X-ray

In order to quantify the relative importance of jet vs. disc emission as a function of the state and luminosity in a frequency window that is undoubtedly crucial and yet shaped by a number of competing mechanisms, [42] put together nearly-simultaneous optical-IR (termed OIR) and X-ray observations of X-ray binaries, BHs and neutron stars. A global correlation is found between OIR and X-ray luminosity for low-mass BHBs in the hard state, of the form $L_{OIR} \propto L_X^{0.6}$ (see Figure 3). This correlation holds over eight orders of magnitude in L_X and includes data from BHBs in quiescence. A similar correlation is found in low-mass neutron star X-ray binaries in the hard state. Similarly to what happens for the radio emission, for thermal dominant state BHBs all of the near-IR and some optical emissions are suppressed, indicating that the jet is quenched during the hard-to-thermal transition. By comparing these empirical correlations with existing models, [42] come to the conclusion that, for the BHs, X-ray reprocessing in the disc and emission from the jets both contribute to the optical-IR while in the hard state, with the jet accounting for up to 90 per cent of the near-IR emission. In addition, it is shown that the optically thick jet spectrum of BHBs is likely to extend to near the K band.

X-ray reprocessing dominates the in hard state neutron stars, with possible contributions from the jets and the viscously heated disc, only at high luminosities.

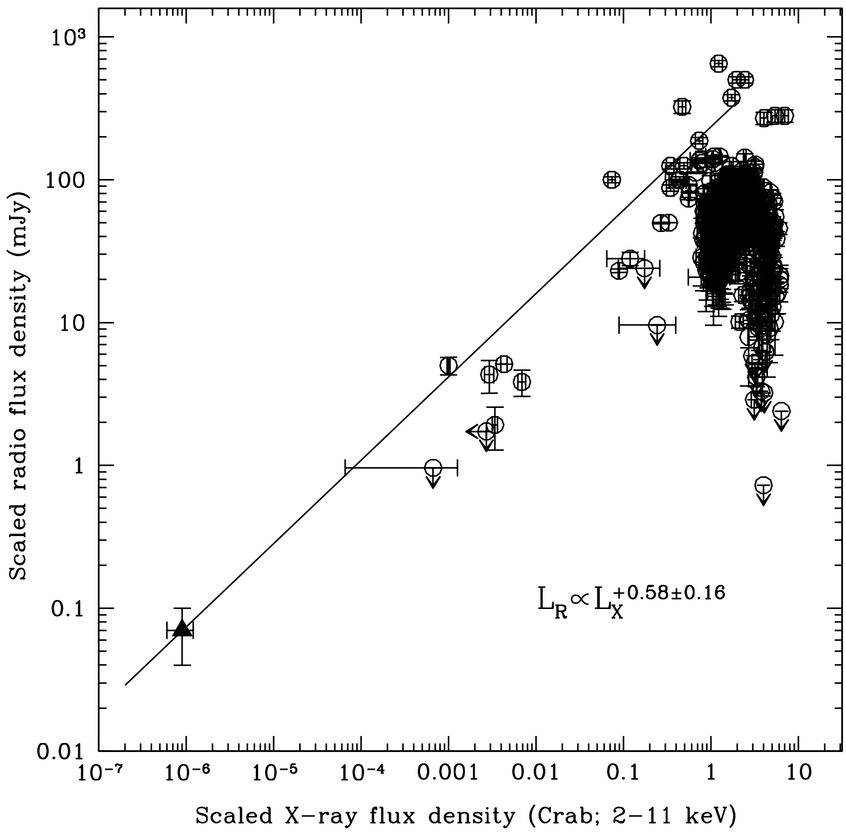

Figure 2: Radio/X-ray correlation for black hole X-ray binaries, with the addition of the $L_X/L_{Edd} \simeq 10^{-8.5}$ BH A0620–00. From [20].

5. Black holes vs. neutron stars

The mechanism(s) of jet production, from an *observational* point of view, remains essentially unconstrained. While in the case of super-massive BHs in AGN it is often implicitly assumed that the jets extract their energy from the rotation of the centrally spinning black hole via large scale magnetic field lines that thread the horizon, in the case of X-ray binaries, the relatively low (lower limit on the) jets' Lorentz factor do not appear to require especially efficient launching mechanisms. On the 'experimental' side, substantial improvements are being made with fully relativistic magneto-hydrodynamic simulations (see Krolik, these Proceedings); from the observer perspective it seems (to this author) that a fruitful – and yet relatively unexplored – path to pursue is that to compare in a systematic fashion the properties of jets in black hole systems to that of e.g. low magnetic field neutron stars. A comprehensive study comparing the radio properties of BHs and neutron stars [36] has highlighted a number of relevant difference/similarities (see Figure 4):

1. Below a few per cent of the Eddington luminosity (in the hard, radiatively inefficient states) both black holes and neutron stars produce steady compact jets, while transient jets are associated with variable sources/flaring activity at the highest luminosities.

2. For a given X-ray luminosity, the neutron stars are less radio loud, typically by a factor of 30.

3. Unlike black holes, neutron stars do not show a strong suppression of radio emission in the soft states.

4. Hard state neutron stars exhibit a much steeper correlation between radio and X-ray luminosities (see Körding, these Proceedings for a theoretical interpretation),

One other difference, even though it should be confirmed by observations of a larger sample of neutron stars, has to due with the location of the optically thick-to-thin jet break. While the study by Russell et al. [42] indicate that, for the BHBs, the break takes place in the mid-IR, this could happen at lower frequencies for the neutron stars (we know however from observations of GX 339–4, the only BHB where the optically thin jet spectrum has been perhaps observed [7], that the exact frequency of the break can vary with the overall luminosity, possibly reflecting changes in the magnetic field energy density, particle density and mass loading at the jet base). That the optically thin jet IR-emission in GX 339–4 connects smoothly with the hard X-ray power law has led to challenge the 'standard' Comptonization scenario for the hard X-ray state [29], whereas recent Spitzer observations of the ultra-compact neutron star X-ray binary 4U 0614+091, with the Infrared Array Camera, unambiguously showed that jet the break frequency must take place in the far-IR in this system, effectively ruling out a synchrotron origin for the X-ray power law [35]. The upper limit on the break frequency immediately allows to conclude that, at least in terms of radiative output, the jet power in this neutron star X-ray binary is lower than in a hard state BHB emitting X-rays at a comparable level, at least by a factor of ten.

Nevertheless, perhaps ironically, the most relativistic jet discovered in the Galaxy so far, is that the neutron star X-ray binary Circinus X-1 [16], for which the inferred Lorentz factor exceeds 15.

6. Jet power

Estimate of the radiative jet power in X-ray binaries are severely biased by the contamination of competing emission mechanisms in the IR-optical band, most notably the donor star and the outer accretion disc, where the break from partially self-absorbed to optically thin is thought to occur. Given that most of the jet radiation is emitted at higher frequencies, the jet 'radiative efficiency' depends ultimately on the location of the high-energy cutoff induced by the higher synchrotron cooling rate of the most energetic particles. Once again, this quantity has proved hard to measure.

A fruitful method, again borrowed from the AGN community, is that to constrain the jet power-times-lifetime product by looking at its interaction with the surrounding interstellar medium (see Heinz, these Proceeding for a comprehensive review). A well known case is that of the nebula around the first Galactic jet source discovered: SS 433. The 'ears' of W50 act as an effective calorimeter for the jets' mechanical power, which is estimated to be greater than 10^{39} erg sec^{-1} (e.g. [4]). More recently, a low surface brightness arc of radio emission has been discovered around Cygnus X-1 [21] (Figure 5) and interpreted in terms of a shocked compressed hollow sphere of free-free emitting gas driven by an under-luminous synchrotron lobe inflated by the jet of Cygnus X-1.

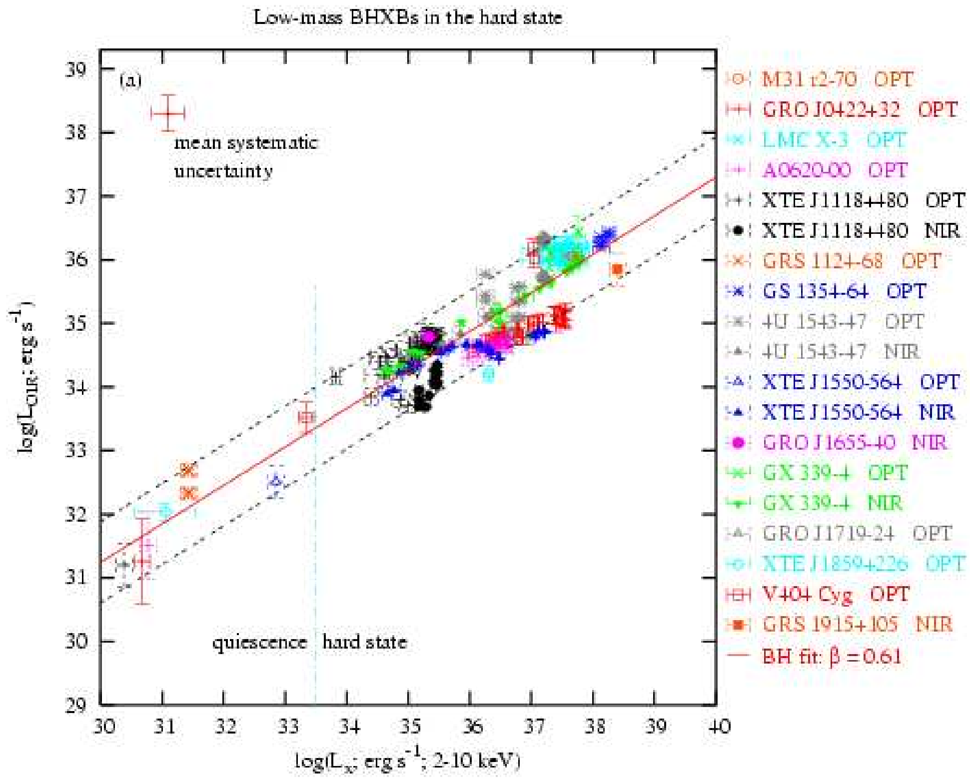

Figure 3: Optical-IR vs. X-ray correlation in hard state black holes. From [42]

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The lack of a visible counter arc is ascribed to the lower interstellar matter density in the opposite direction; in fact, it is likely that X-ray binary jets require a particularly dense environment in order to produce visible signs of interaction with the surroundings (Heinz, these Proceedings). The reader is referred to Russell, these Proceedings, for follow-up optical observations of the Cygnus X-1 nebula, as well as other X-ray binaries', and Tudose, these Proceedings, for a study of the jet-powered radio nebula around the neutron star X-ray binary Circinus X-1 [44].

Estimates of the total jet power are obviously to be compared with the total accretion energy budget; this is especially interesting in very low-luminosity systems, where the fate of the accreting gas remains a matter of debate. Observations of highly sub-Eddington BHs, most notably the Galactic Centre super-massive BH, paved the way to radiatively inefficient accretion flow models. By reviewing the vast literature on the subject, one immediately comes to the conclusion that the most widely accepted/adopted model for reproducing the spectral energy distribution of quiescent BHs is the 'advection-dominated accretion flow' solution (ADAF; e.g. [40]). Here, a significant fraction of the viscously dissipated energy remains locked up in the gas as heat, and is advected inward. The ADAF model successfully accounts for the overall shape of the UV-optical-X-ray spectra of quiescent BHBs (see e.g. [31] for an application to the high quality data of XTE J1118+480). Nevertheless, alternative suggestions are well worth being considered. [5] elaborated an 'adiabatic inflow-outflow solution', in which the excess energy and angular momentum is lost

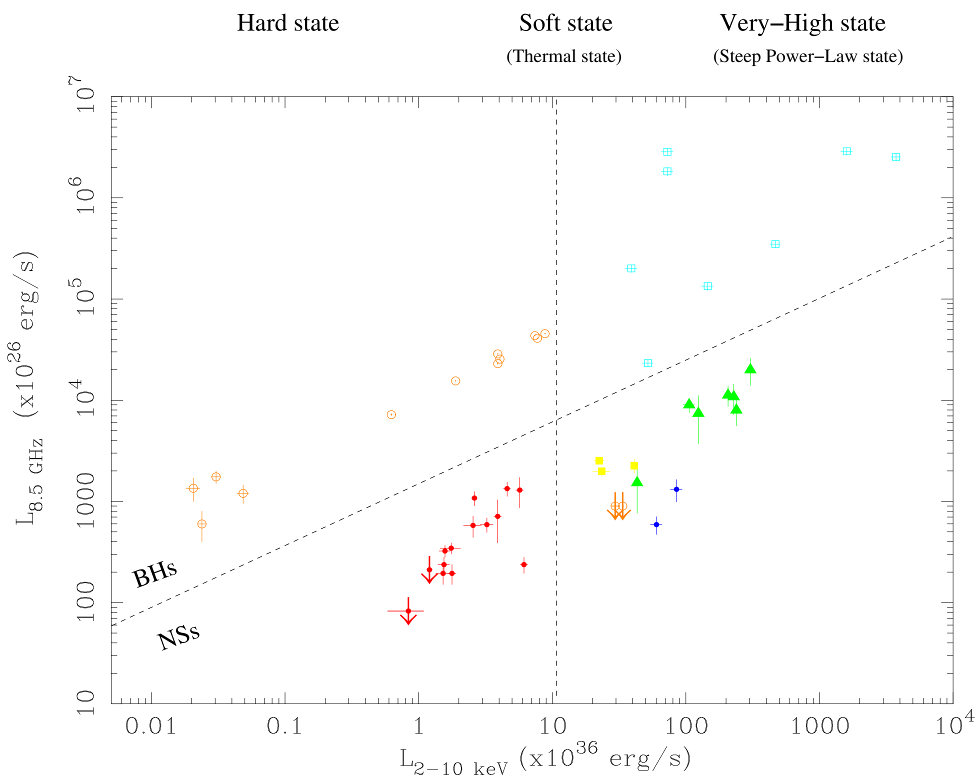

Figure 4: A comparison between radio/X-ray properties of neutron star and black hole X-ray binaries. From [36].

to an outflow at all radii; the final accretion rate into the hole may be only a tiny fraction of the mass supply at large radii.

A0620–00 provides an instructive (albeit not conclusive) test for those models. Interestingly enough, based on models for the optical/UV emission of the outer accretion disc in dwarf novae, corrected downward to account for the mass difference, [32] estimate $\dot{M}_{\rm out} = y10^{-10} M_{\odot}$ yr^{-1} for A0620–00, where y is a factor of the order unity, that can be up to a few. The putative luminosity associated with $\dot{M}_{\rm out}$, if it was to reach the hole with a standard radiative efficiency of 10 per cent, would be $L_{tot} \equiv \eta \dot{M}_{out} c^2 \simeq 6 \times 10^{35} y\ (\eta/0.1)$ erg sec^{-1}, about 5 orders of magnitude larger than the measured X-ray luminosity (where η is the accretion efficiency, which depends only on the BH spin). The various radiatively inefficient accretion flow models offer different explanations for the much lower luminosities that are observed in terms of different 'sinks' for the energy. Making use the expression for the jet radiative efficiency by Heinz & Grimm [25], it can be shown directly that, in the case of A0620–00, the outflow kinetic power accounts for a sizable fraction of the accretion energy budget, and thus must be important with respect to the overall accretion dynamics of the system. In spite of the many uncertainties in the above calculations, this would effectively rule out a *pure* ADAF solution for the dynamics of the accretion flow in quiescence. However, within these uncertainties there is still room for a hybrid solution to apply, one in which at each $\dot{M}$ about half of the energy is carried away by the outflow, while the rest is advected inward and finally added to the BH mass. It is worth mentioning that the possibility that an ADAF could naturally launch outflows was already explored back in 1995 [41], even though the outflow contribution to

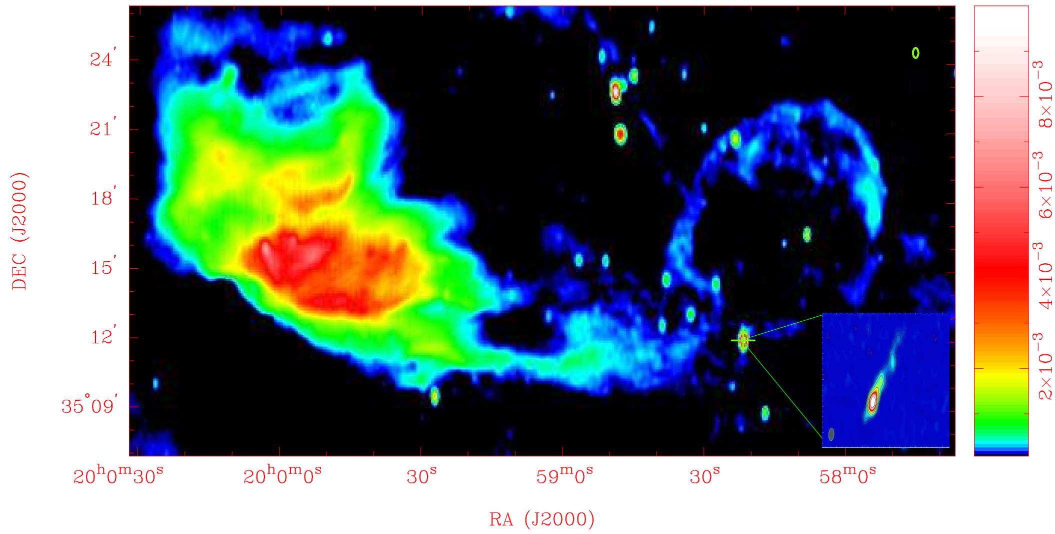

Figure 5: A jet-powered nebula around Cygnus X-1. From [21].

the radiation spectrum is typically neglected in the calculations.

7. Jet composition, speed and confinement

A less debated issue seems that of X-ray binary jets' speed. Perhaps erroneously so. It is often assumed that the velocity the the steady jet is only mildly relativistic, with $\Gamma \simeq 2$ [23]. This comes from the relative spread about the radio/X-ray correlation, interpreted as evidence for a low average Lorentz factor. However, as mentioned in Section 4.1, this argument has been confuted on theoretical grounds [26]. As far as the transient jets are concerned, there is a high degree of uncertainties in estimating their Lorentz factors, mainly because of distance uncertainties [12].

In a recent work [34] make a substantial step forward by means of the observational upper limits on the jets' opening angles. This method relies on the fact that, while the jets could undergo transverse expansion at a significant fraction of the speed of light, time dilation effects associated with the bulk motion will reduce their apparent opening angles. [34] have calculated the Lorentz factors required to reproduce the small opening angles that are observed in most X-ray binaries, with very few exceptions, under the crucial assumption of no confinement. The derived values, mostly lower limits, are larger than typically assumed, with a mean Γ>10 (see Figure 6). No systematic difference appears to emerge between hard state steady jets and transient plasmons. If

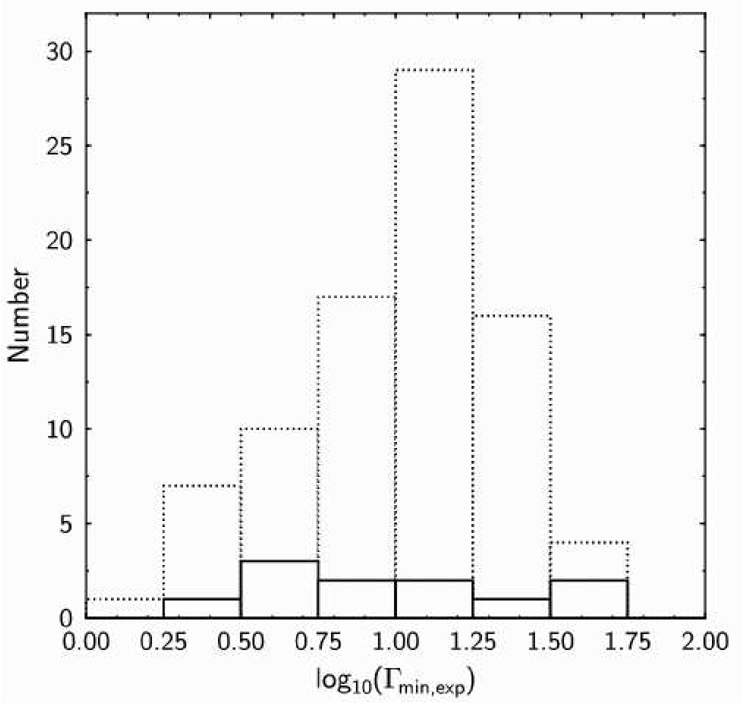

Figure 6: Mean Lorentz factors for X-ray binaries from opening angles' constraints (solid), compared to AGN from proper motions' (dashed). From [34].

indeed the transient jets were as relativistic as the steady jets, as already mentioned, this would challenge the hypothesis of internal shocks at work during hard-to-thermal state transitions in BHBs. In order for that scenario to be viable, the transient jets must have higher Lorentz factor; in other words, steady jets ought to be laterally confined.

The issue of the jets' matter content remains highly debated. Perhaps with the exception of SS 433 (e.g. [45], [37]), where atomic lines have been detected at optical at X-ray wavelengths along the jets, various studies come to different conclusions for different sources. For example, circular polarization, which in principle can provide an excellent tool for investigating the baryonic content of the jets, is only detected in a handful of sources (see [11] and references therein), where no strong conclusion could be placed yet. Entirely different studies (e.g. based on modelling large scale jet-ISM interaction structures by means of self-similar jet fluid models) also draw different conclusions: in the case of Cygnus X-1 for instance, some authors ([21] and [24]) argue for cold baryons in the flow, while an electron/positron jet seems to be favored in GRS 1915+105 based on energetics arguments [18].

8. Open issues

I shall conclude this review by simply listing a number of issues that remain open in this field, and that may stimulate further thoughts.

- Unified model refinement: while it seems to hold in its basic principles, the unified scheme for BHB jets needs to be carefully tested on theoretical grounds and hopefully answer the questions posed by recent observations, such as the possibility that a thin disc is already present down to the ISCO prior to the actual hard-to-thermal state transition. If so, what causes the bright radio flare? In addition: under the internal shock scenario working-hypothesis, would the observed radio plasmons be able to radiate synchrotron emission at thousands of A.U. from the actual location of the shock? If so, what are the required initial conditions at the jet base? If not, are perhaps multiple or external shocks required?

- Neutron star jets: how do they behave in detail? Are they truly less powerful with respect to BH jets? Are they collimated (no elongated radio structure has been resolved yet in a 'hard state' neutron star)? In order to complete the picture and possibly gain meaningful information on the very jet formation mechanism(s), aggressive multi-wavelength campaigns are needed for neutron stars as well (and are already in place).

- The big picture: the ultimate goal is of course that to bridge the gap between micro-and-macro: between stellar and super-massive BHs. It seems that we are now at the beginning of a new phase in our understanding of the behaviour of matter in the vicinity of black holes, one in which quantitative scalings have emerged on all mass scales, and we may be able to apply the results obtained from BHBs to the study of AGN, and vice versa (see Jester and Fender, these Proceedings). Eventually, our relatively deep knowledge about BHB radio/X-ray cycles could help us understanding AGN duty cycles and radio modes, which in turn appear to play a role of paramount importance in driving the very evolution of galaxies over cosmological times.

Acknowledgments

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