

Jets from the faintest black holes

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Abstract. The question whether quiescent black hole X-ray binaries are capable of powering relativistic outflows is addressed by means of simultaneous radio/X-ray observations of a nearby system steadily emitting X-rays below 10^{-8} times the Eddington luminosity. The robust detection of a radio counterpart suggests that a synchrotron emitting outflow is being powered by this system, even though its degree of collimation remains unknown, and hard to investigate. With the inclusion of the A0620–00 data, the non linear radio/X-ray correlation for hard state black hole X-ray binaries appears to hold down to very low quiescent luminosities. However, an increasing number of outliers is being found at higher luminosities, questioning the universality of such correlation, or at least its normalization.

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QUIESCENT ACCRETION

Among the various issues that remain open in the field of accretion onto black hole binaries (BHBs) as well as super-massive black holes is the way the gas accretes at very low Eddington ratios, in the so called *quiescent* regime (where, for the binaries, the boundary between quiescence and a more active regime can be set around $10^{33.5}$ erg s⁻¹, corresponding to a few $10^{-6}L_{Edd}$ for a $10 M_{\odot}$ BH; the reader is referred to McClintock & Remillard [26] for a review of X-ray states). While there is little doubt that the thin disc model [35] captures the basic physical properties of BHBs in the thermal dominant state, the accretion mode responsible for powering quiescent BHs is still a matter of debate. Observations of highly sub-Eddington systems, most notably the Galactic Center super-massive BH, paved the way to radiatively inefficient accretion flow models (RIAFs). 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 [33][32]); in this low-density, two temperature inflow, a significant fraction of the viscously dissipated energy remains locked up in the ions as heat, and is advected inward. The ADAF model can successfully account for the overall shape of the UV-optical-X-ray spectra of quiescent BHBs (see McClintock et al. 2003 [27] for an application to the high quality data of XTE J1118+480). Nevertheless, alternative suggestions are worth being considered. For instance, convection, rather than advection, could be responsible for keeping the plasma circulating in eddies along the flow by transporting angular momentum inward, yielding zero net accretion rate (CDAF; [31]). A different solution is that elaborated by Blandford & Begelman [2], where the excess energy and angular momentum is lost 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 (ADIOS: ‘adiabatic inflow-outflow solution’).

Radiatively inefficient outflows may also be responsible for dissipating the bulk of the liberated accretion power (e.g. [23],[22],[38]). Roughly speaking, the question remains open whether quiescent BHBs are dim because of a highly reduced radiative efficiency, or a highly reduced inner accretion rate.

Recent Chandra observations of nearby elliptical galaxies [1] led to the discovery of a tight correlation between the Bondi accretion rate, \dot{m}_{Bondi} (as inferred from the measured temperature, BH mass and density profile) and the power emerging from these systems in the form of relativistic jets (estimated by the work they exert on the observed X-ray cavities). The jets' power is found to be comparable to $0.1\dot{m}_{Bondi}c^2$, implying that a significant fraction of the matter entering the accretion radius flows down to regions close to the black holes, where the jets are thought to be formed.

QUIESCENT JETS?

In the context of X-ray binaries, as well as super-massive black holes, the term 'jet' is typically used as a synonym for a relativistic outflow of plasma and implies a high degree of collimation (see Fender 2006 [11] for a comprehensive review on X-ray binary jets). As a matter of fact, high spatial resolution radio observations of BHBs in the hard state [26] have imaged highly collimated structures in two systems only: Cyg X-1 [36] 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 on much larger scales than the orbital separation. Both systems display relatively high X-ray (and radio) luminosities, with GRS 1915+105 being persistently close to the Eddington limit (e.g. [13]), and Cyg X-1 having a bolometric X-ray luminosity around 2 per cent of L_{Edd} [9]. This, however, should not be taken as evidence against collimated jets at lower luminosities: because of sensitivity limitations on current high resolution radio arrays, resolving a radio jet at microJy level (if any) simply constitutes an observational challenge. In addition, at such low levels, the radio flux could be easily contaminated by synchrotron emission from the donor star.

The presence of a collimated outflow can also be inferred by its long-term action on the local interstellar medium, as in the case of the hard state BHBs 1E1740.7–2942 and GRS 1758–258, both associated with arcmin-scale radio lobes [30], [24]. Further indications 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 [8]. 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 [16], clearly indicates a favoured ejection axis in the system.

On the other hand, failure to image a collimated structure in the hard state of XTE J1118+480 down to a synthesized beam of $0.6 \times 1.0 \text{ mas}^2$ at 8.4 GHz [29] can challenge the collimated jet interpretation, even though XTE J1118+408 was observed at roughly one order of magnitude lower luminosity with respect to e.g. Cyg X-1. If the jet size scaled as the radiated power, one could expect the jet of XTE J1118+408 to be roughly ten times smaller than that of Cyg X-1 (which is $2 \times 6 \text{ mas}^2$ at 9 GHz, at about the same distance), *i.e.* still point-like in the VLBA maps presented by Mirabel et al. 2001 [29].

Garcia et al. 2003 [19] have pointed out that long period ($\gtrsim 1$ day) BHBs undergoing

outbursts tend to be associated with spatially resolved optically thin radio ejections, while short period systems would be associated with unresolved, and hence physically smaller, radio ejections. If a common production mechanism is at work in optically thick and optically thin BHB jets [12], then the above arguments should apply to steady optically thick jets as well, providing an alternative explanation to the unresolved radio emission of XTE J1118+480, with its 4 hour orbital period, the shortest known for a BHB. It is worth mentioning that, by analogy, a long period system, like for instance V404 Cyg, might be expected to have a more extended optically thick jet (approved high spatial resolution observations of this system, with the High Sensitivity Array, will hopefully answer this question).

RADIO/X-RAY CORRELATION IN HARD STATE (2003)

In an attempt to assess the relation between accretion and jet production in hard state BHBs, Corbel et al. 2003, and Gallo, Fender & Pooley 2003 ([7],[17]) have established the existence of a tight correlation between the X-ray and the radio luminosity (L_X and L_R), of the form $L_R \propto L_X^{0.7 \pm 0.1}$. In those works, 10 hard state systems with nearly simultaneous radio/X-ray observations were considered; the correlation was found to hold over more than 3 orders of magnitude in L_X , up to a few per cent of L_{Edd} , above which the sources enter the thermal dominant state, and the core radio emission drops below detectable levels. Probably the most notable implication of the non-linear scaling was the predicted existence of a critical X-ray luminosity below which a significant fraction of the liberated accretion power is channelled into a radiatively inefficient outflow, rather than being dissipated locally by the inflow of gas and emitted in the form of X-rays (this does not necessarily imply the X-ray spectrum is dominated by non-thermal emission from the jet, as most of the jet power may be stored as kinetic energy [14]).

RADIO AND X-RAY EMISSION IN QUIESCENCE: THE CASE OF A0620–00

Due to its low X-ray luminosity ($L_X/L_{Edd} \sim 10^{-8.5}$ [21]) and relative proximity, the BHB in A0620–00 represented the most suitable known system to probe the radio/X-ray correlation beyond the hard state. Indeed, deep VLA observations, 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 $L_R = 7.5 \times 10^{26}$ erg sec⁻¹. By analogy with higher luminosity systems, partially self-absorbed synchrotron emission from a relativistic outflow appears as 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.

A0620–00 was observed simultaneously in the X-ray band with Chandra, its 0.3–8 keV spectrum well fitted by an absorbed power law with photon index $\Gamma = 2.08_{-0.35}^{+0.49}$ and hydrogen equivalent column density consistent with the optical value. The corresponding 2–10 keV luminosity was about 7×10^{30} erg sec⁻¹, a factor of two higher than in a previous Chandra observation, in February 2000.

The simultaneous Chandra observations of A0620–00 allowed us to test and extend the radio/X-ray correlation for BHBs by 3 orders of magnitude in L_X . The measured radio/X-ray fluxes seem to confirm the existence of a non-linear scaling between the radio and X-ray luminosity in these systems; with the addition of the A0620–00 point $L_R \propto L_X^{0.58 \pm 0.16}$ provides a good fit to the data for L_X spanning between $10^{-8.5}$ and $10^{-2} L_{\text{Edd}}$ (see Figure 1). 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 GX339–4, for which the correlation extends over 3 orders of magnitude in L_X and holds over different epochs.

IS THE CORRELATION TRULY UNIVERSAL?

Even though the A0620–00 data appear to follow the hard state radio/X-ray correlation, since 2003, when the compilation of quasi-simultaneous radio/X-ray observations of hard state BHBs was presented [17], many outliers have been found. To mention a few (those that came or were brought to the attention of this author at least): XTE J1720–318 [5],[3], SWIFT J1753.5–0127 [4], IGR J17497–2821 [34] and XTE J1650–500 [6], while in the hard state, all appear to lie significantly below the best-fitting correlation (Figure 1).

While a number of plausible ad-hoc ‘reasons’ can be adduced on a source-by-source basis, it simply seems more reasonable to conclude that the radio/X-ray correlation may not be universal, or, at least, that there is no universal normalization. This casts doubts on the possibility of relying on the best-fitting relation for estimating other quantities, such as distance or BH mass. A global re-assessment of the radio/X-ray correlation will be presented in a forthcoming paper.

INFLOW VS OUTFLOW: ENERGY BUDGET

While ADAF models predict the existence of bipolar outflows emanating from the surface layers of the equatorial inflow [32], generally they do not address the importance of such outflows with respect to the overall accretion process in terms of energetics. Ideally, one would like to be able to compare the total power carried away in the form of outflows/jets, with the total accretion power budget available to the black hole. As mentioned in the first Section, this has been done for a handful of nearby elliptical galaxies [1]; there, the mechanical jets power is found to be comparable to $0.1 \dot{m}_{\text{Bondi}} c^2$. This has been interpreted as evidence that a substantial fraction of the captured mass does reach the innermost regions of the flow before being ejected in the form of an outflow.

A similar conclusion has been reached in the case of the stellar mass BH in A0620–00 [15]. Based on models for the optical/UV emission of the outer accretion disc in dwarf novae [37], corrected downward to account for the mass difference, McClintock et al. 1995 [28] estimate $\dot{M}_{\text{out}} = y10^{-10}M_{\odot} \text{ yr}^{-1}$ for A0620–00, where y is a factor of the order unity, that can be up to a few. This value is also comparable to the $3 \times 10^{-11} M_{\odot}\text{yr}^{-1}$ inferred from the measure of the total energy released during the 1975 outburst of A0620–00 adopting 58 year recurrence time based on plate archives which showed an outburst in 1917. This time-averaged value had been calculated based on a distance of 1 kpc for A0620–00 (vs. a refined value of 1.2 kpc) and could still be underestimated by a factor 2 or so, to allow for the possibility that an intermediate outburst was missed. The putative luminosity associated with \dot{M}_{out} , if it was to reach the black hole with standard radiative efficiency, would be $L_{\text{tot}} \equiv \eta\dot{M}_{\text{out}}c^2 \simeq 6 \times 10^{35}y (\eta/0.1) \text{ erg sec}^{-1}$, five orders of magnitude than the observed X-ray (or bolometric) luminosity. In the above expression η is the accretion efficiency, which depends only on the BH spin. The various RIAFs provide different explanations for the much lower luminosities that are observed in terms of different ‘sinks’ for the energy.

In the ADAF scenario, it is assumed that all the \dot{M}_{out} is accreted onto the black hole ($\dot{M}_{\text{in}} = \dot{M}_{\text{out}}$) while the radiated luminosity $L_{\text{bol}} = \epsilon_{\text{rad}}\dot{M}_{\text{in}}c^2$ is much smaller as a result of a reduced radiative efficiency

$$\epsilon_{\text{rad}} \equiv \eta f(\alpha) = \eta \times \begin{cases} 1, & \dot{M}_{\text{out}} \geq \dot{M}_{\text{cr}} \\ (\dot{M}_{\text{out}}/\dot{M}_{\text{cr}})^{\alpha}, & \dot{M}_{\text{out}} < \dot{M}_{\text{cr}} \end{cases} \quad (1)$$

where \dot{M}_{cr} is the critical rate above which the disc becomes radiatively efficient. The index α is typically close to unity, but its exact value may depend on the micro-physics of ADAF and on how the bolometric luminosity is calculated. Writing the bolometric luminosity of A0620–00 as $L_{\text{bol}} = w 10^{32} \text{ erg sec}^{-1}$, being w a multiplicative factor, then $f(\alpha) = \left(\frac{\dot{M}_{\text{out}}}{\dot{M}_{\text{cr}}}\right)^{\alpha} \simeq 1.7 \times 10^{-4} (w/y) (0.1/\eta)$. For $\alpha = 1.3$, $\dot{M}_{\text{cr}} \simeq 8 \times 10^{-8} y^{(1+1/1.3)} w^{(-1/1.3)} (\eta/0.1)^{(1/1.3)} M_{\odot} \text{ yr}^{-1}$, which corresponds to an Eddington-scaled critical accretion rate $\dot{m}_{\text{cr}} \simeq 0.36 y^{(1+1/1.3)} w^{(-1/1.3)} (\eta/0.1)^{(1+1/1.3)}$. With $w \sim 5 - 10$, as implied by the ADAF spectral modelling, a self-consistent ADAF solution is obtained for \dot{m}_{cr} of a few times 10^{-2} , as expected on theoretical grounds.

Contrary to the ADIOS case, for the ADAF scenario to be self-consistent, the total kinetic power of the jet/outflow, L_{kin} , should be a negligible fraction of L_{tot} . In order to verify this, L_{kin} can be estimated making use of the normalization for the jet kinetic power vs. radio luminosity derived by [20]. Obviously, if this number is high enough, the jet contribution to the flow energetics (and dynamics) can be negligible with respect to advective cooling. In [20] the radio core emission of three well studied radio galaxies (M87, Per A and Cyg A) was directly compared to the radio lobe emission, used a jet calorimeter. They proposed that the jet kinetic power can be estimated from the core radio luminosity in the following way: $L_{\text{kin}} = 6.2 \times 10^{37} \left(\frac{L_{\text{R}}}{10^{30}\text{erg s}^{-1}}\right)^{\frac{1}{1.4-\alpha_r/3}} \mathscr{W}_{37.8} \text{ erg sec}^{-1}$ where α_r is the radio spectral index, and the parameter $\mathscr{W}_{37.8}$ carries the (quite large) uncertainty on the radio galaxy calibration. For A0620–00, assuming a flat radio spectral index $\alpha_r = 0$, and for $L_{\text{R}} = 7.5 \pm 3.7 \times 10^{26} \text{ erg sec}^{-1}$, there follows:

$L_{\text{kin}} \simeq 3.6 \times 10^{35} \mathcal{W}_{37.8} \text{ erg sec}^{-1}$, or $\frac{L_{\text{kin}}}{L_{\text{tot}}} \simeq 0.6 \times \mathcal{W}_{37.8} y^{-1} (\eta/0.1)^{-1}$. This would mean that the jet/outflow carries a significant amount of the accretion energy budget away from the system. I so, then any realistic accretion flow model for quiescence shall necessarily incorporate the effects of an outflow both in terms of energetics and dynamics, effectively ruling out a pure ADAF solution.

Using the estimate for the kinetic power of the jet in quiescence, we can calculate the total energy carried out by it in between outbursts, assuming again that the 58 years recurrence time is not overestimated. We obtain $E_{\text{jet}} \simeq 6.6 \times 10^{44} \mathcal{W}_{37.8} \text{ erg}$, of the same order of the energy released during an outburst. Interestingly, [25] calculated the outburst evolution for A0620–00 with a model accounting for evaporation of the cold outer disc (but neglecting outflows), and concluded that only about one third of the mass accreted during quiescence needs to be stored in the disc for the subsequent outbursting episode. Under the ADIOS working-hypothesis, the mass flowing from the outer disc does not reach the inner region, but is lost in a outflow. The accretion rate is now a function of radius:

$$\dot{M}(R) = \begin{cases} \dot{M}_{\text{out}}, & R_{\text{out}} > R > R_{\text{tr}} \\ \dot{M}_{\text{out}}(R/R_{\text{tr}})^{\alpha}, & R_{\text{tr}} > R > R_{\text{in}} \end{cases} \quad (2)$$

where we have assumed that mass loss sets in within the truncation radius R_{tr} . Proceeding as before, we can then estimate the truncation radius for $\dot{M}_{\text{in}} = \dot{M}(R_{\text{in}}=3R_{\text{S}})$, being R_{S} the Schwarzschild radius for a $10 M_{\odot}$ BH. For $\alpha = 1$ we obtain $R_{\text{tr}} \simeq 1.8 \times 10^4 (y/w) (\eta/0.1) R_{\text{S}}$ or $\simeq 5.4 \times 10^{10} (y/w) (\eta/0.1) \text{ cm}$, to be compared with the orbital separation of about $3 \times 10^{11} \text{ cm}$ [18].

Assuming that the the jet/outflow is powered by the mass lost from the accretion flow, then its total kinetic power L_{kin} is given by $L_{\text{kin}} = L_{\text{tot}} \left(1 - \frac{R_{\text{in}}}{R_{\text{tr}}}\right) \simeq L_{\text{tot}}$, i.e. in the ADIOS framework, a dominant fraction of the total accretion power is channelled into the jet/outflow.

In conclusion, by making use of the estimate of the outer accretion rate of A0620–00 in quiescence and of the jet radiative efficiency by [20], it has been argued that 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 [15]. On the other hand, as noted in the case of elliptical galaxies studied with Chandra [1], the large jets' mechanical power (compared to the available fuel supply) suggests that, before being expelled and carrying away a substantial fraction of the dissipated accretion power, the accreted mass must flow deep into the hole's potential well, where high efficiencies can be reached.

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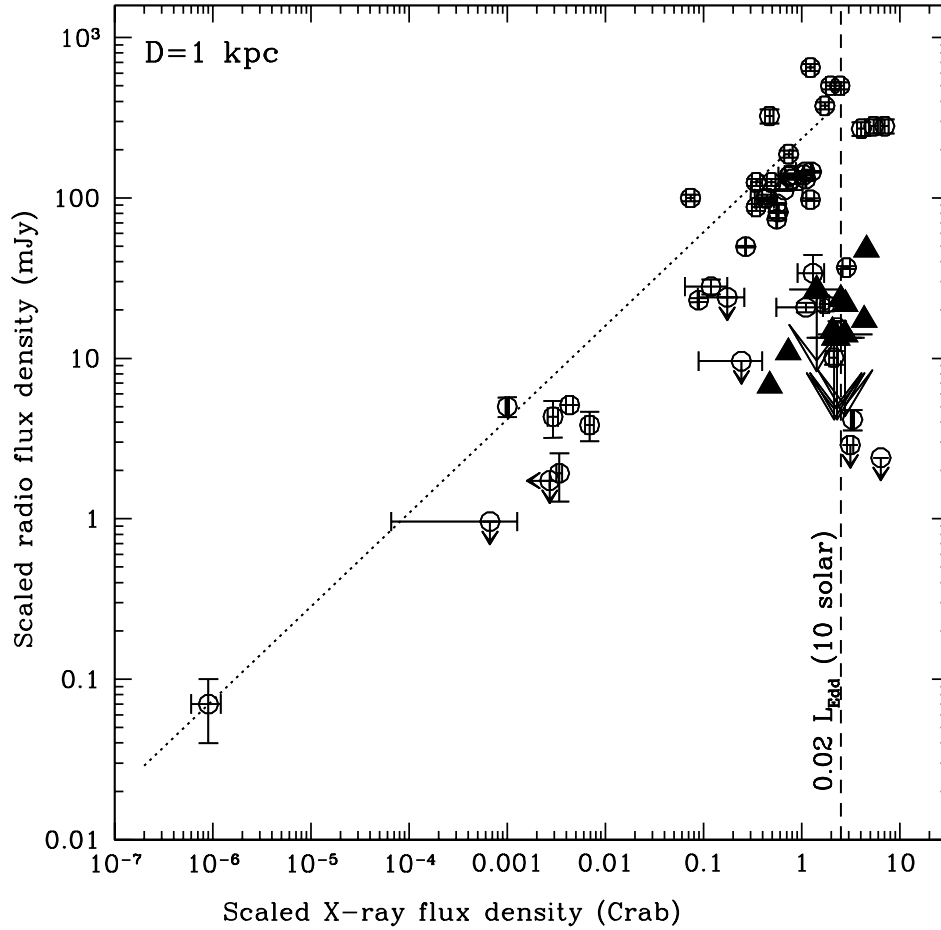


FIGURE 1. The radio/X-ray correlation in hard state BHBs [17], with the addition of the $10^{-8.5}L_{Edd}$ A0620-00 [15] (open circles). While this low Eddington ratio system appears to confirm the validity of a non-linear radio/X-ray correlation over more than 6 orders of magnitude in L_X , an increasing numbers of hard state outliers is being found at higher luminosities (filled triangles), whose radio flux is typically lower with respect to the best-fitting power-law (e.g. XTE J1720-318 [5],[3] and SWIFT J1753.5-0127 [4], IGR J17497-2821 [34], XTE J1650-500 [6]). This challenges the validity of such relation, or at least the universality of its normalization.

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