Jets at all scales
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On the nature of the "radio quiet" black hole binaries

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Abstract. The accretion/ejection coupling in accreting black hole binaries has been described by empirical relations between the X-ray/radio and X-ray/optical-infrared luminosities. These correlations were initially supposed to be universal. However, recently many sources have been found to produce jets that, given certain accretion-powered luminosities, are fainter than expected from the correlations. This shows that black holes with similar accretion flows can produce a broad range of outflows in power Here we discuss whether typical parameters of the binary system, as well as the properties of the outburst, produce any effect on the energy output in the jet. We also define a jet-toy model in which the bulk Lorentz factor becomes larger than ~ 1 above $\sim 0.1\%$ of the Eddington luminosity. We finally compare the "radio quiet" black holes with the neutron stars.

Keywords. X-rays: binaries, ISM: jets and outflows, accretion, accretion disks

1. Introduction

Relativistic ejections (jets) are a common consequence of accretion processes onto stellar-mass black holes. In the low/hard state (LHS) and in the quiescent state of black hole candidates (BHCs) a compact, steady jet is on. The jet is highly quenched in the high/soft state (HSS) of BHCs (see Fender 2010 for a review).

Corbel *et al.* (2003) and Gallo *et al.* (2003) found that the radio luminosity of many BHCs in the LHS correlates over several orders of magnitude with the X-ray luminosity. They proposed that a correlation of the form $L_X \propto L_R^{0.58\pm0.16}$ (where L_X and L_R are the X-ray and radio luminosities) could be universal and also valid for sources in quiescence (Gallo *et al.* 2006). This relation describes a coupling between the accretion processes and the ejection mechanisms. A similar correlation also hold between the the X-ray and the optical/infrared (IR) luminosities (Russell *et al.* 2006).

However, in the past few years, several "radio quiet" outliers have been found (Xue & Cui 2007; Gallo 2007). These sources seem to feature similar X-ray luminosities to other BHCs but are characterized by a radio emission that, given a certain X-ray luminosity, is fainter than expected from the radio/X-ray correlation. It is possible that a correlation with similar slope but lower normalization than the other BHCs could describe this discrepancy, at least in a few sources (e.g. Soleri *et al.* 2010). If confirmed, this would suggest that some other parameters might be tuning the accretion-ejection coupling, allowing accretion flows with similar radiative efficiency to produce a broad range of outflows.

Casella & Pe'er (2009) suggested that different values of the jet magnetic field can cause a quenching of the radio emission, without influencing the energy output in the X

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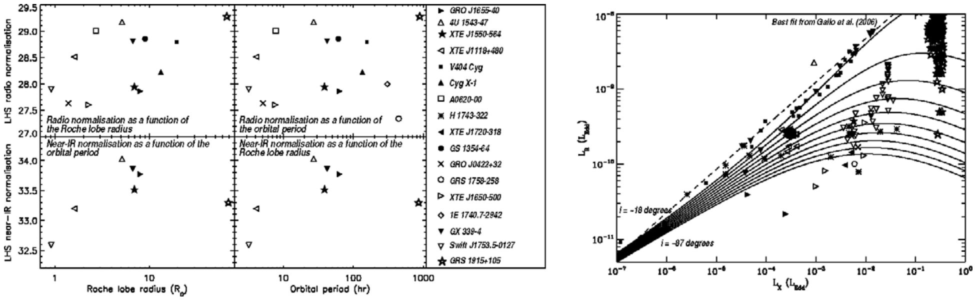

Figure 1. *Left-hand panel:* Radio and near-IR normalizations as a function of the orbital period and the size of the Roche lobe of the BHCs. Our BHC sample is listed in the inset. The inset also shows a key to the symbols. *Right-hand panel:* Values of the radio luminosity expected from our toy model for 10 viewing angles, in Eddington units. See the left-hand panel for a key to the symbols.

rays. Fender *et al.* (2010) showed that, if our measures of the spin and the estimates of the jet power are correct, the spin does not play any role in powering jets from BHCs.

In this conference Proceedings we investigate whether there is a connection between the values of some binary parameters and properties of the outburst of 17 BHCs (listed in Figure 1, left-hand panel) and the compact steady-jet power. We will follow the approach presented in Fender *et al.* (2010) to use the normalizations of the radio/X-ray and IR/X-ray correlations as a proxy for the jet power. The data used to calculate the normalizations are from Gallo *et al.* (2003), Gallo *et al.* (2006), Gallo (2007), Russell *et al.* (2006), Russell *et al.* (2007) and Soleri *et al.* (2010). We develop a jet-toy model to study whether de-boosting effects can explain the scatter around the radio/X-ray correlation. We also compare the "radio quiet" BHCs to the accreting neutron star (NS) X-ray binaries.

2. BHC properties and jet power

Since the accretion disc occupies $\sim$ 70% of the Roche lobe of the black hole, we calculated the size of the Roche lobe of the accretor as a measure of the disc size. Figure 1 (left-hand panel) shows the radio and near-IR normalizations as a function of the size of the Roche lobe of the black hole and the orbital period of the binary. To test whether there is any correlation between the jet power and these two orbital parameters, we calculated the Spearman rank correlation coefficients. The values of the correlation coefficients ρ, as well as the null hypothesis probabilities (the probability that the data are not correlated), are reported in Table 1. Clearly no correlation is present.

We also investigate the dependence of the radio and near-IR normalizations on the inclination between the jet axis and the line of sight. We will refer to this angle i as either inclination or viewing angle. Casella*et al.*(2010) recently showed that compact-steady jets from BHCs can have rather high bulk Lorentz factor $\Gamma > 2$. This result suggests that de-boosting effects can become important, not only at high viewing angles. In our analysis we are assuming that the X-ray emission is un-beamed (but see Fender 2010 and references therein). To test if a correlation exists, we calculated the Spearman coefficients ρ. We show them in Table 1. In the case of the near-IR normalizations, we obtained $\rho \sim -0.9$, with a probability for the null hypothesis of $\sim$ 2%. This suggests that there is an anticorrelation between the inclination angle and the near-IR normalization. However, the lack of data points (only 7) might have biased this result.

During an outburst, BHCs usually show a transition to the HSS. However, some sources spend the whole outburst in the LHS (or in the LHS and in the intermediate states),

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Table 1. Spearman rank correlation test for our data points. The number of data points, as well as the probabilities for the null hypothesis are reported.

Normalization	Number of points	Spearman coefficient ρ	Probability for the null hypothesis (%)
		Size of the Roche lobe	
radio	13	0.5	11.0
near IR	7	0.3	43.0
		Orbital period	
radio	15	0.2	54.2
near IR	7	0.4	33.2
		Inclination angle	
radio	13	-0.2	44.7
near IR	7	-0.9	2.4

without transiting to the soft states (see Belloni 2009 and references therein). We investigated whether the type of outburst (LHS only or with a transition to the soft states) affects the jet power, but we could not find any obvious dependence.

3. A jet-toy model

Here we define a jet-toy model. The aim is to test whether a dependence of the bulk Lorentz factor of the jet Γ on the accretion powered X-ray luminosity might qualitatively describe the scatter around the radio/X-ray correlation and the "radio quiet" BHCs population. We will consider a Γ Lorentz factor that becomes larger than ~ 1.4 above $\sim 0.1\%$ of the Eddington luminosity L_{Edd}. This assumption is based on the fact that compact steady jets are usually thought to be mildly relativistic ($\Gamma \leqslant 2$ but see Casella *et al.* 2010) in the LHS while major relativistic ejections ($\Gamma \geqslant 2$) are tentatively associated with the transition from the hard to the soft states. We considered a uniform distribution of 10 values of $\cos i$ between 0 and 1. Figure 1 (right-hand panel) illustrates the results from our toy model: it clearly results in a distribution in the (L_X, L_R) plane which broadens at higher luminosities. The toy model can qualitatively reproduce the scatter around the radio/X-ray correlation.

4. Comparison with neutron stars

NSs are known to be fainter in radio than BHCs, given a certain X-ray luminosity, by a factor $\gtrsim 30$ (see e.g. Migliari & Fender 2006). This difference in radio power can be reduced to a factor $\gtrsim 7$ if a mass correction from the fundamental plane of black hole activity (Merloni *et al.* 2003) is applied. We will now compare the "radio quiet" BHCs to the population of NSs that have been detected in radio. Our sample of NSs includes the same data points as in Migliari & Fender (2006) with the addition of points from recent observations of Aql X-1, 4U 0614-091 and IGR J00291+5934 (Tudose *et al.* 2009, Migliari *et al.* 2010 and Lewis *et al.* 2010, respectively). To test whether the "radio quiet" BHCs and the NSs are statistically distinguishable in the (L_X, L_R) plane, we performed a two-dimensional Kolmogorov-Smirnov (K-S) test. The K-S test shows that the probability that the "radio quiet" BHCs and the NSs are statistically indistinguishable (i.e. the probability of the null hypothesis) is different from 0, despite being small ($P \sim 0.13\%$), if a mass correction is applied. If we do not apply a mass correction, the probability of the null hypothesis is consistent with 0: the two groups constitute two different populations.

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5. Conclusions

We examined three characteristic parameters of BHCs and the properties of their outbursts to test whether they regulate the energy output in the jet. If our estimates of the jet power are correct, both the orbital period and the size of the accretion disc are not related to the radio and near-IR jet power. We could also not find any association between the jet power and the type of outburst (with or without a transition to the HSS). We did not find any association between the viewing angles and the jet power inferred from radio observations. The jet power obtained from near-IR measurements decreases when the inclination angle increases. This result could favour a scenario in which the jet decelerates moving from the IR-emitting to the radio-emitting part.

We defined a jet-toy model in which the jet Lorentz factor becomes larger than ~ 1 above $0.1\% \, L_{Edd}$. The model results in a distribution in the (L_X, L_R) plane which broadens at high luminosities. However, the model has several limitations, for instance it can not reproduce the measured inclination angles of the BHCs in our sample.

We finally compared the "radio quiet" BHCs to the NSs. A two-dimensional K-S test can not completely rule out the possibility that the two families are statistically indistinguishable in the (L_X, L_R) plane, if a mass correction is applied. This result suggests that some "radio quiet" BHCs could actually be NSs; alternatively it suggests that some BHCs feature a disc-jet coupling similar to NSs.

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Discussion

Sambruna: Do you have enough data to place these rq sources on the Fender hard/soft diagram?

Soleri: No, we did not do that. They are supposed to be in a hard state.

Yuan: This is a comment on X-ray/radio correlation. We predict Yuan & Cui (2005) that the correlation should steepen when $L_X < L_{\rm crit}$. This prediction was confirmed in Yuan, Yu, & Ho (2009).

Soleri: For what concerns black hole X-ray binaries there are also detections of systems in quiescence at very low X -ray luminosities ($10^{-8} L_{\rm Edd}$, Gallo *et al.* 2006). These systems follow the "normal" correlation with a slope of ~ 0.6.

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