Accretion/ejection coupling in X-ray binaries
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Citation for published version (APA):

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On the nature of the “radio quiet” black hole binaries

Paolo Soleri & Rob Fender


Abstract

The coupling between accretion processes and ejection mechanisms in accreting black holes in binary systems can be investigated by empirical relations between the X-ray/radio and X-ray/optical-infrared luminosities. These correlations are valid over several orders of magnitude and were supposed to be universal. However, 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, suggesting that some other parameters or factors might be tuning the accretion/ejection coupling. 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. No obvious dependence is found. We also define a jet-toy model in which the bulk Lorentz factor becomes larger than $\sim 1$ above $\sim 0.1\%$ of the Eddington luminosity. With this model we are able to describe qualitatively the scatter of the X-ray/radio correlation and the “radio quiet” population.
7. On the nature of the “radio quiet” black hole binaries

7.1 Introduction

Relativistic ejections (jets) are a common consequence of accretion processes onto black holes in active galactic nuclei (AGN) as well as onto stellar mass black holes in X-ray binaries (XRBs, see Fender 2006 for a review). In the hard state (HS) and probably in the quiescent state of black hole candidates (BHCs) a compact-steady jet is on (Fender 2001; Gallo et al. 2006). The characteristic signature of compact-steady jets (Blandford & Königl 1979) is a flat/slightly inverted spectrum \( \alpha \gtrsim 0, F_\nu \propto \nu^\alpha \) observed in the radio band and sometimes extending to infrared (IR) and possibly optical frequencies (e.g. Hynes et al. 2000; Brocksopp et al. 2001). The jet power dominates over the accretion-powered luminosity in the HS at \( L_X \lesssim 1\% L_{Edd} \) (\( L_X \) and \( L_{Edd} \) are the X-ray and the Eddington luminosities, respectively; Fender, Gallo & Jonker 2003, Migliari & Fender 2006). There is strong evidence that the jet is highly quenched in the soft state (SS) of BHCs (Tananbaum et al. 1972; Fender et al. 1999).

Körding, Jester & Fender (2006) showed that a generalization of the accretion states used to describe BHCs could also be applied to AGN. This suggests that despite the different masses involved, systems that contain a black hole display similar accretion states and jet properties.

Hannikainen et al. (1998) and Corbel et al. (2003) found that the radio flux of the BHC GX 339-4 in the HS correlates over several orders of magnitude with the X-ray flux. Gallo, Fender & Pooley (2003) included other sources in the sample and proposed that a correlation of the form \( L_X \propto L_R^b \) (where \( L_X \) and \( L_R \) are the X-ray and radio luminosities, respectively) with \( b = 0.58 \pm 0.16 \) (Gallo et al. 2006) could be universal and also valid for sources in quiescence. This might indicate that the mechanisms responsible for the ejection of the outflows are coupled to the properties of the accretion flow. Russell et al. (2006) verified that an empirical correlation between the X-ray luminosity and the optical/IR luminosities also holds \( (L_X \propto L_{OIR}^{0.6}) \), where \( L_{OIR} \) is the optical/IR luminosity) for BHCs in the HS and in quiescence. There is evidence that the optical emission is not dominated by the jet but by the reprocessing of the X-rays in the outer regions of the accretion disc (Russell et al. 2006).

Merloni, Heinz & Di Matteo (2003) and Falcke, Körding & Markoff (2004) have independently shown that the same X-ray/radio scaling found for BHCs also holds for supermassive black holes in AGN, if the mass of the compact object is taken into account. This suggests that similar mechanisms rule accretion and ejection processes to/from black holes hold over \( \sim 9 \) orders of magnitude in mass.
The existence of the radio/X-ray correlation has broad implications. For example, the small scatter around it has been used as an argument by Heinz & Merloni (2004) to infer that jets from BHCs and AGN (once a mass-correction factor is introduced) are characterized by similar bulk velocities, unless they are all non-relativistic.

However, in the past few years, the supposed universality of the radio/X-ray correlation has been doubted (Xue & Cui 2007) and several “radio quiet” outliers have been found (Gallo 2007). These sources seem to feature similar X-ray luminosities to other BHCs but are characterized by a radio emission that, at a given X-ray luminosity, is fainter than expected from the radio/X-ray correlation. It is possible that a correlation with similar slope but lower normalisation than the other BHCs could describe this discrepancy, at least in a few sources (e.g. Corbel et al. 2004; Gallo 2007; Soleri et al. 2009b, §6). 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.

Garcia et al. (2003) investigated the dependence of the jet power on the orbital period of the binary. They noted that, among 14 dynamically confirmed BHCs, we can spatially resolve a powerful jet in 4 systems characterized by long orbital periods. This suggests that this binary parameter might play a role in powering jets from BHCs.

Pe’er & Casella (2009) presented a model for the emission from jets in XRBs in which the electrons are accelerated only once at the base of the jet (in variance with other models, in which multiple accelerations occur; see e.g. Maitra et al. 2009, Jamil, Fender & Kaiser 2009). In the model, the jet magnetic field is the parameter that can cause a quenching of the jet (when above a critical value $B_{cr} \approx 10^5$ G), without influencing the accretion conditions and the X-ray luminosity (Casella & Pe’er 2009).

The dependence of the jet power on the spin of the black hole has recently been investigated by Fender, Gallo & Russell (2009b). They inferred the jet power from the normalisations of the radio/X-ray and near-IR/X-ray correlations found by Gallo et al. (2006) and Russell et al. (2006). They concluded 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 AGN, the most powerful jets have been associated with high-spin black holes (Sikora, Stawarz & Lasota 2007). Considering the similarities between accretion states and jet properties in BHCs and AGN (Merloni et al. 2003, Falcke et al. 2004, Körding et al. 2006), this is an issue that broad-band jet models should take into account.
On the nature of the “radio quiet” black hole binaries

Table 7.1: Radio and IR normalisations for a sample of 17 BHCs. Unless it has been differently specified, the data used to calculate the radio normalisations are from Gallo et al. (2003, 2006) and Gallo (2007); the IR normalisations are from the BHCs sample of Russell et al. (2006, 2007). We also report the orbital period ($P_{\text{orb}}$), the mass of the accretor ($M_X$), the $q$ ratio ($q = M_X / M_2$, $M_2$ is the mass of the companion star), the size of the Roche lobe of the compact object ($R_L$), the orbital inclination ($i$) and the distance to the source ($D$). Unless more recent estimates are available, the inclinations are from Charles & Coe (2006) and all the other parameters from Russell et al. (2006).

<table>
<thead>
<tr>
<th>Source</th>
<th>Normalisations</th>
<th>$P_{\text{orb}}$ (hr)</th>
<th>$M_X$ ($M_\odot$)</th>
<th>$q$</th>
<th>$R_L$ ($R_\odot$)</th>
<th>$i$ ($^\circ$)</th>
<th>$D$ (kpc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H 1743-322</td>
<td>28.16 (1,2)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>7.5 (1)</td>
<td>GX 339-4</td>
</tr>
<tr>
<td>28.81</td>
<td>33.86</td>
<td>42.1</td>
<td>∼ 5.8</td>
<td>∼ 12.5</td>
<td>6.69</td>
<td>15−60 (3)</td>
<td>8 +7−1</td>
</tr>
<tr>
<td>BHC sample</td>
<td>Normalisations</td>
<td>28.51</td>
<td>33.20</td>
<td>4.1</td>
<td>6.8</td>
<td>1.61</td>
<td>81 ± 2</td>
</tr>
<tr>
<td>XTE J1118+480</td>
<td>28.51</td>
<td>33.20</td>
<td>4.1</td>
<td>6.8</td>
<td>1.61</td>
<td>81 ± 2</td>
<td>1.71 ± 0.05</td>
</tr>
<tr>
<td>GRS 1915+105</td>
<td>29.26</td>
<td>33.28</td>
<td>846</td>
<td>14.0</td>
<td>± 4.4</td>
<td>17.28</td>
<td>64.25</td>
</tr>
<tr>
<td>V404 Cyg</td>
<td>28.80</td>
<td>-</td>
<td>155.3</td>
<td>10.0</td>
<td>± 2.0</td>
<td>15.38</td>
<td>19.55</td>
</tr>
<tr>
<td>A0620-00</td>
<td>29.00</td>
<td>-</td>
<td>7.75</td>
<td>11.0</td>
<td>± 1.9</td>
<td>14.86</td>
<td>2.73</td>
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<tr>
<td>GRO J0422+32</td>
<td>27.63</td>
<td>-</td>
<td>5.09</td>
<td>3.97</td>
<td>± 0.95</td>
<td>8.63</td>
<td>1.39</td>
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<tr>
<td>GS 1354-64</td>
<td>28.86</td>
<td>-</td>
<td>61.1 (5)</td>
<td>7.83</td>
<td>± 0.50 (5)</td>
<td>7.68 (5)</td>
<td>8.99 &lt; 79</td>
</tr>
<tr>
<td>4U 1543-47</td>
<td>29.18</td>
<td>34.03 (6)</td>
<td>26.8</td>
<td>9.4</td>
<td>± 1.0</td>
<td>3.84</td>
<td>5.13</td>
</tr>
<tr>
<td>XTE J1550-564</td>
<td>27.92</td>
<td>33.50 (6)</td>
<td>36.96</td>
<td>10.6</td>
<td>± 1.0</td>
<td>7.41</td>
<td>7.16</td>
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<tr>
<td>GRO J1655-40</td>
<td>27.86 (8)</td>
<td>33.77</td>
<td>62.9</td>
<td>7.02</td>
<td>± 0.22</td>
<td>2.99</td>
<td>7.98</td>
</tr>
<tr>
<td>XTE J1650-500</td>
<td>27.60</td>
<td>-</td>
<td>7.63 &lt; 7.3 (10)</td>
<td>10 (10)</td>
<td>2.26</td>
<td>50 ± 3 (10)</td>
<td>2.6 ± 0.7 (11)</td>
</tr>
<tr>
<td>Swift J1753.5-0127</td>
<td>27.90 (12)</td>
<td>32.59 (12)</td>
<td>3.2 (13)</td>
<td>3.0 (13)</td>
<td>&lt; 10 (13)</td>
<td>0.91 &gt; 85 (14)</td>
<td>∼ 8 (13,15)</td>
</tr>
<tr>
<td>Cyg X-1</td>
<td>28.22</td>
<td>-</td>
<td>134.4 (16)</td>
<td>10.1 (16)</td>
<td>0.57 (16)</td>
<td>13.26</td>
<td>35 ± 5 (3)</td>
</tr>
<tr>
<td>XTE J1720-318</td>
<td>27.56</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>6.5 ± 3.5 (17)</td>
<td></td>
</tr>
<tr>
<td>1E1740.7-2942</td>
<td>27.99</td>
<td>-</td>
<td>305.52 (18)</td>
<td>-</td>
<td>-</td>
<td>∼ 8.5 (3)</td>
<td></td>
</tr>
<tr>
<td>GRS 1758-258</td>
<td>27.34</td>
<td>-</td>
<td>442.8 (18)</td>
<td>-</td>
<td>-</td>
<td>∼ 8.5 (3)</td>
<td></td>
</tr>
</tbody>
</table>

(1) Jonker et al. (2009); (2) McClintock et al. (2009); (3) Gallo et al. (2003); (4) Miller-Jones et al. (2009); (5) Casares et al. (2009); (6) Russell et al. (2007); (7) Hannikainen et al. (2009); (8) Migliari et al. (2007a); (9) Foellmi et al. (2006); (10) Orosz et al. (2004); (11) Homan et al. (2006); (12) Soleri et al. (2009b); (13) Zurita et al. (2008); (14) Hiemstra et al. (2009), S; (15) Cadolle Bel et al. (2007); (16) Herrero et al. (1995); (17) Chaty & Bessolaz (2006); (18) Smith et al. (2002).
In this paper we investigate whether there is any connection between the values of some binary parameters and properties of the outburst of BHCs and the compact steady-jet power. We also discuss how Doppler de-boosting effects could qualitatively explain the scatter around the radio/X-ray correlation, when a particular dependence of the bulk Lorentz factor of the jet on the accretion-powered luminosity is taken into account.

### 7.2 The hard state jet power

In this paper we will follow the approach presented in Fender et al. (2009b) to use the normalisations of the radio/X-ray and OIR/X-ray correlations as a proxy for the jet power. We will consider the slopes of the correlations as \( \sim 0.6 \). Although some sources have been found to follow a correlation with a different slope (e.g. H 1743-322, \( b \sim 0.18 \), Jonker et al. 2009) and this parameter is often badly constrained by fitting the data points (e.g. Swift J1753.5-0127, Soleri et al. 2009b), we can consider it universal, in order to have a rough estimate of the jet power. For more details on this method we address the reader to Fender et al. (2009b).

Table 7.1 lists the BHCs considered in this paper. Unless differently specified, the normalisations have been calculated using the data from Gallo et al. (2003, 2006), Gallo (2007) and Russell et al. (2006, 2007). Since the optical emission is not dominated by the jet, we considered only the near-IR data from Russell et al. (2006, 2007; J, K and H bands). For each source we fitted the X-ray and radio data using a relation of the form \( \log_{10}(L_R) = c_R + 0.6(\log_{10}(L_X) - 34) \), considering the normalisations \( c_R \) as free parameters. We applied the same method to obtain the normalisations \( c_{IR} \) from the X-ray and near-IR data. Since Gallo et al. (2003) and Russell et al. (2006) in some cases adopted different distances to the same source, in this paper we use the most recent estimates. For the BHC Cyg X-1 we do not include the data points that show evidence for suppression of the radio emission as the source enters softer X-ray states (see Figure 3 of Gallo et al. 2003 for the details). Although we are only considering BHCs in HS, we include in our sample GRS 1915+105 (which spends all its time in the intermediate states), using data from the radio-bright plateau state, which is approximately an analogous to the HS (see Fender & Belloni 2004 for a review on the source). The properties of the BHCs are reported in Table 7.1, as well as the normalisations \( (c_R \text{ and } c_{IR}) \) used as a proxy for the jet power. The properties of their outbursts are listed in Table 7.2.
Figure 7.1: Radio and near-IR normalisations as a function of the orbital period and the size of the Roche lobe of the black hole. See Table 7.1 for a list of the used values. A key of the symbols used in this plot and in the following ones is in the inset.
7.3 BHC properties and jet power

We will now examine whether three characteristic parameters of the binary system (the orbital period, the size of the accretion disc and the orbital inclination) and the properties of the outburst affect the energy output in the jet.

7.3.1 Binary parameters

Since the accretion disc occupies \( \sim 70\% \) of the Roche lobe of the black hole (Frank, King & Raine 2002), we calculated the size of the Roche lobe of the accretor as a measure of the disc size. Following Frank, King & Raine (2002), the orbital separation \( a \) is given by:

\[
a = 3.5 \times 10^{10} M_X^{1/3} \left(1 + \frac{1}{q}\right)^{1/3} P_{\text{orb}}^{2/3} \text{ cm}
\]

where \( M_X \) is the mass of the accretor (in \( M_\odot \) units), \( q \) is the mass ratio \( (q = M_X/M_2) \), \( M_2 \) is the mass of the donor and \( P_{\text{orb}} \) the orbital period (in hours). The size of the Roche lobe of the compact object \( R_l \) can be calculated

Figure 7.2: Radio and near-IR normalisations as a function of the inclination angles \( i \) of the BHCs. See Table 7.1 for a list of the used values. The dashed lines indicate an upper limit (GS 1354-64, filled circle) and a lower limit (Swift J1753.5-0127, downward open triangle). See Figure 7.1 for a key to the symbols.

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Table 7.2: Properties of the outbursts of 10 BHCs in our sample. The sources that showed only “normal” outbursts are not listed here. See Brocksopp et al. (2004) for the details. HIMS and SIMS mean hard-intermediate state and soft-intermediate state, respectively (see Belloni 2009 for a definition of the states).

<table>
<thead>
<tr>
<th>Source</th>
<th>Outbursts occurred</th>
<th>Additional remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>H 1743-322</td>
<td>several, normal or HS-HIMS only(1)</td>
<td>We use data from a normal one</td>
</tr>
<tr>
<td>GRS 1915+105</td>
<td>quasi persistent, in the HIMS-SIMS(2)</td>
<td>We use data from the radio-bright plateau state</td>
</tr>
<tr>
<td>V404 Cyg</td>
<td>one, HS only</td>
<td>possible transition to the SS(3)</td>
</tr>
<tr>
<td>XTE J1118+480</td>
<td>one, HS only</td>
<td>-</td>
</tr>
<tr>
<td>GRO J0422+32</td>
<td>one, HS only</td>
<td>-</td>
</tr>
<tr>
<td>GS 1354-64</td>
<td>four, normal and HS only</td>
<td>We use data from a HS-only one</td>
</tr>
<tr>
<td>4U 1543-47</td>
<td>four, normal and HS only</td>
<td>We use data from a normal one</td>
</tr>
<tr>
<td>XTE J1550-564</td>
<td>four, normal and HS only</td>
<td>We use data from a normal one</td>
</tr>
<tr>
<td>Swift J1753.5-0127</td>
<td>one, HS only(4)</td>
<td>see (5) for details on the data selection</td>
</tr>
<tr>
<td>Cyg X-1</td>
<td>persistent</td>
<td>-</td>
</tr>
</tbody>
</table>

(1) Capitanio et al. (2009); (2) Fender & Belloni (2004); (3) Zycki et al. (1999); (4) Cadolle Bel et al. (2007), its outburst is still ongoing at the moment of writing this paper, see Negoro et al. (2009); (5) Gallo et al. (2003)

as follows:

\[ R_l = a \frac{0.49 q^{2/3}}{0.6 q^{2/3} + \ln(1 + q^{1/3})} \text{ cm} \]

Figure 7.1 shows the radio and near-IR normalisations as a function of the size of the Roche lobe of the black hole and the orbital period of the binary. The lower panels of Figure 7.1 might suggest that the near-IR normalisation increases with the size of the Roche lobe of the accretor and with the orbital period, although the sample contains only 7 BHCs. Two of them do not follow this possible trend: XTE J1550-564 and GRS 1915+105.

We also investigate the dependence of the radio and near-IR normalisations on the orbital inclinations of the BHCs. Although there is evidence that
7.3 BHC properties and jet power

in some sources the binary inclination does not coincide with the inclination between the jet axis and the line of sight (e.g. the misalignment has been estimated to be $\sim 15^\circ$ in GRO J1655-40, see Maccarone 2002 and references therein), in this paper we will consider the orbital inclination as a proxy for the jet axis inclination to the line of sight. We will refer to this angle $i$ as either inclination or viewing angle. Compact-steady jets in the HS are thought to be mildly relativistic (with bulk Lorentz factor $\Gamma < 2$; Gallo et al. 2003, Fender, Belloni & Gallo 2004). That suggests that de-boosting effects should not be relevant and the jets, except for high inclination angles, should not be de-boosted. However, new results cast doubts on this fundamental assumption. Casella et al (2009) recently observed the BHC GX 339-4 in the HS at low X-ray luminosity ($L_X \sim 0.14\% L_{Edd}$, considering a distance to the source and a mass $M_X$ as in Table 7.1), with coordinated X-ray and IR observations at high-time resolution. From the analysis of the cross-correlation function, they inferred a lower limit on the bulk Lorentz factor of the jet $\Gamma > 2$ (at $3.8\sigma$ confidence level). This result suggests that de-boosting effects can become important, not only at high viewing angles. Assuming that the X-ray emission is un-beamed (but see Markoff, Nowak & Wilms 2005 for a model in which the X-rays are coming from the base of the jet in the HS), jets with $\Gamma \gtrsim 2$
and not pointed towards us, should result less luminous than expected from the empirical radio/X-ray and OIR/X-ray correlations. Figure 7.2 shows the radio and near-IR normalisations as a function of the inclination angles \(i\). From the upper panel, no obvious dependence can be found. In the lower panel, the distribution of the data points suggests that BHCs characterised by a high inclination could have a low near-IR normalisation. To test if a correlation exists, we calculated the Spearman coefficient \(\rho\) for the data points. We obtained \(\rho \sim -0.9\), with a probability for the null hypothesis (the probability the data are not correlated) of \(\sim 2\%\). This suggests that the anticorrelation between the inclination angle and the near-IR normalisation is strong. However, the lack of data points (compared to the upper panel of Figure 7.2) might have biased this result.

### 7.3.2 Properties of the outburst

During an outburst, BHCs usually show a transition to the SS (see Belloni 2009 and references therein). However, some sources spend the whole outburst in the HS, without transiting to the soft states (Brocksopp, Bandyopadhyay & Fender 2004). It is not clear why some BHCs do not soften. Considering that the transition from the hard to the soft states is possibly associated with the emission of highly relativistic jets (with \(\Gamma > 2\); Fender et al. 2004a), it is important to ascertain whether HS-only outbursts feature different jet properties. Furthermore, there is evidence that some sources (e.g. XTE J1550-564) feature different near-IR and radio normalisations (Russell et al. 2007 and Corbel et al. in preparation, respectively) when in the HS, depending on whether they are observed during the outburst rise or during the decay, before/after the transition to/from the SS. This suggests that the transition to the SS might affect the jet properties even when the source is not in the HS.

Table 7.2 presents the properties of the outbursts for 10 BHCs in our sample. Sources that occurred only “normal” outbursts (with “normal” we refer to BHCs that showed a transition to the soft states) have not been listed.

To see whether the type of outburst (HS only or with a transition to the soft states) affects the jet power, in Figure 7.3 we reported the radio and near-IR normalisations of our sample of BHCs, dividing it according to the properties of the outburst. No obvious dependence of the jet power on the type of the outburst can be found.
7.3 BHC properties and jet power

Figure 7.4: Left-hand panel: Lorentz factor of the jet (solid line) as a function of $L_X$ (in Eddington units, for a $\sim 10\, M_\odot$ black hole) as used in our toy model. $\Gamma$ becomes larger than $\sim 1.3$ above $0.1\%$ of $L_{Edd}$. Right-hand panel: Doppler boosting factor $\delta$ as a function of $L_X$, for 10 possible viewing angles (in the range $i \sim 18 - 87^\circ$, this corresponds to $\cos i \sim 0.05 - 0.95$).
7.4 The scatter of the radio/X-ray correlation: 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 $\Gamma$ on the accretion powered X-ray luminosity might qualitatively describe the scatter around the radio/X-ray correlation and the “radio quiet” BHCs population. As in §7.3.1, we are assuming that the X-ray emission is un-beamed (but see Markoff et al. 2005).

We will consider a $\Gamma$ Lorentz factor that becomes larger than $\sim 1.3$ above $\sim 0.1\%$ of the Eddington luminosity $L_{\text{Edd}}$ (see Figure 7.4, left panel). This assumption is based on the fact that compact steady jets are though to be mildly relativistic ($\Gamma \leq 2$; Fender et al. 2004a, but see Casella et al. 2009) in the HS below about 1% of $L_{\text{Edd}}$ (e.g. Fender et al. 2003, Migliari & Fender 2006) while major relativistic ejections ($\Gamma \geq 2$) are in some cases associated with the transition from the hard to the soft states. These transitions occur at a variable $L_X$ but usually above a few per cent of $L_{\text{Edd}}$ (Fender et al. 2004a). We calculated the Doppler boosting factor $\delta$ ($\delta = (\Gamma - 1) \times (1 - \beta \cos i)^{-1}$; $\beta = v/c$ is the bulk velocity of the emitting material; $\Gamma = (1 - \beta^2)^{-1/2}$) for 10 possible inclinations $i$. Since the orientation of the approaching jet is random on a hemisphere of $2\pi$ sr, $\cos i$ is uniformly distributed between 0 and 1. This does not imply that $i$ is uniformly distributed in the range $0^\circ - 90^\circ$. We considered a uniform distribution of 10 values of $\cos i$ between 0 and 1. Figure 7.4 (right panel) shows the evolution of $\delta^2$ as a function of $L_X$. At $L_X \gtrsim 10\% L_{\text{Edd}}$, only for one inclination angle (of the ten considered) the jet will be boosted ($\delta^2 > 1$) and not de-boosted. If the jet power is well traced by the radio luminosity $L_R$ and $L_R \propto L_X \delta^2$, for each inclination $i$ we can determine how the Doppler de-boosting will affect the radio-jet luminosity $L_R$. Figure 7.5 illustrates the results from our toy model. The data points represents the BHCs sample used to infer the radio normalisations reported in Table 7.1. The scatter around the best-fit correlation of Gallo et al. (2006, dashed line) can be partially reproduced.

7.5 Discussion

In this paper we tested whether there is a connection between the values of some characteristic binary parameters of BHCs, as well as the properties of their outbursts, and the energy output in the form of a jet. Our discussion is based on the assumption that the jet power can be traced by the radio and near-IR normalisations of the radio/X-ray and OIR/X-ray correlations (see Fender et al. 2009b).
Figure 7.5: Values of $L_R$ expected from our toy model for 10 viewing angles (in the range $0.05 \leq \cos i \leq 0.95$). The data points used to infer the radio normalisations $c_R$ are also plotted. For clarity, we did not include the Cyg X-1 data points. A key to the different symbols is in Figure 7.1. The dashed line represents the best fit correlation obtained in Gallo et al. (2006).
The upper panels of Figure 7.1 show that there is no connection between two (non independent) parameters of the binary system (the size of the Roche lobe of the black hole and the orbital period) and the radio normalisations. Garcia et al. (2003) suggested that long period BHCs could feature spatially-resolved powerful jets. However, our result is not unexpected: theoretical works predict that a powerful jet should be formed when a thick accretion flow is present (as it is thought the case in the HS; Livio et al. 1999; Meier 2001). Considering that the thick accretion flow does not extend to the outer regions of the accretion disc (although the details of its geometry are unknown, see Gilfanov 2009 and references therein), it seems unlikely that the jet power is affected by the size of the Roche lobe and the orbital period. In fact variations of these two parameters would leave the conditions in the vicinities of the black hole unchanged.

The distribution of the data points in the lower panels of Figure 7.1 suggests an increase of the near-IR normalisations with the size of the Roche lobe and the orbital period, although 2 out of 7 sources (GRS 1915+105 and XTE J1550-564) behave differently. It is possible that this trend is due to the lack of data points (compared to the upper panels of Figure 7.1). Furthermore, in some cases, the near-IR emission is not dominated by the jet but by thermal emission from the accretion disc (e.g. Swift J1753.5-0127, Soleri et al. 2009b), so the possible increasing trend is probably due to the high contribution from a large disc rather than from the jet.

In §7.3.2 we examined the spectral properties of the outbursts occurred by the BHCs in our sample. The transition to the soft states is characterized by sudden changes in the jet properties (Tananbaum et al. 1972; Fender et al. 1999; Fender et al. 2004a). Furthermore, Russell et al. (2007) and Corbel et al. (in preparation) found a dependence of the near-IR and radio normalisations on the phase of the outburst in which the BHC is observed. More specifically, the normalisations measured at the outburst rise (in the HS) are different from the normalisations measured at the outburst decay, after the source has transited back from the SS to the HS. For this reason, we can think that even in the HS, the jet properties (e.g. its bulk velocity and power) are influenced by the transition to the soft states. This could affect the jet properties of those sources that remain in the HS for the whole outburst (Brocksopp et al. 2004). Figure 7.3 shows that the type of outburst does not seem to influence both the radio and the near-IR normalisations. This suggests that the energy output in the jet in the HS is not regulated by the fact that the BHC transits or not to the soft states.

It is worth to note that the three known BHCs with the shortest orbital periods (Swift J1753.5-0127, XTE J1118+480 and GRO J0422+32) only had
hard outbursts (but see Negoro et al. 2009 for a possible softening of Swift J1753.5-0127). From binary evolution calculations, BHCs can in principle have orbital periods as short as \( \sim 2 \) hours and evolutionary models actually predict that short-period systems might form the majority of them, similarly to what is observed in cataclysmic variables (Yungelson et al. 2006). The fact that 16 BHCs in Table 7.1 have an orbital period \( P_{\text{orb}} \geq 4.1 \) hr is quite puzzling. A possible explanation is that in short-period systems, the mass transfer from the companion star might be interrupted by resonances within the primary’s Roche lobe, if the mass ratio is \( q \sim 50 \) (Yungelson et al. 2006). Zurita et al. (2008) suggested that the mass ratio in Swift J1753.5-0127 is \( q \gtrsim 10 \) and could be as high as approximately 40, thus making Swift J1753.5-0.127 the first BHC detected in this regime. However, even if the mass transfer in Swift J1753.5-0127 is partially interrupted (because of the high mass ratio), this does not explain why the source is less luminous than expected in the radio band (in other words why its radio and near-IR normalisations are low compared to the majority of the BHCs in our sample), although its X-ray luminosity is comparable to other BHCs (Soleri et al. 2009b). The behaviour of XTE J1118+480 is different: although it is the known BHC with the second shortest orbital period \( (P_{\text{orb}} = 4.1 \) hr) and its mass ratio is rather high compared the other sources in the sample \( (q \sim 27) \), its radio normalisation is higher than the one estimated for 7 other BHCs with longer orbital periods. This suggests that it features jet properties that are not different from the majority of the BHCs.

In \S\ 7.3.1 we investigated the connection between the inclination angles of the BHCs and the radio and near-IR normalisations. Casella et al. (2009) showed that compact steady jets can have bulk Lorentz factor \( \Gamma > 2 \), even in the HS at low X-ray luminosities \( (L_X = 0.14\% L_{\text{Edd}}) \), excluding the possibility that the observations were performed in proximity of the transition to the soft states. This new result suggests that Doppler de-boosting effects could be important for HS jets that are not pointed towards us. The upper panel of Figure 7.3 does not show any correlation between the radio normalisation and the inclination angles. The near-IR normalisation instead has a high probability to be anticorrelated to the inclination angle: we calculated a Spearman rank coefficient \( \rho \sim -0.9 \), with a probability for the null hypothesis of \( \sim 2\% \). More coordinated X-ray/near-IR observations are needed to enlarge the sample, since our results might be influenced by the small number of data points.

To further test if Doppler de-boosting effects play a role in populating the sample of BHCs characterised by a faint jet (Corbel et al. 2004, Gallo 2007, Soleri et al. 2009b), in \S\ 7.4 we defined a jet-toy model in which the bulk Lorentz
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factor $\Gamma$ becomes larger than $\sim 1$ above $L_X \sim 0.1\% L_{Edd}$. This model can qualitatively describe the scatter around the radio/X-ray correlation, considering a range of viewing angles (Figure 7.5). The line for $i \sim 18^\circ$ ($\cos i = 0.95$) increases its slope at $L_X \gtrsim 10^{-4} L_{Edd}$ (Figure 7.5). This is expected, since for $i \sim 18^\circ$ the jet is boosted, as already noted in §7.4 (Figure 7.4, right panel). The model predicts that the radio/X-ray correlation, because of de-boosting effect, should become flatter at high $L_X$. This might be the case for the BHC H1743-322 (for which $L_R \approx L_X^{0.18}$, Jonker et al. 2009), although other sources, e.g. XTE J1650-500 and Swift J1753.5-0127 (Corbel et al. 2004; Soleri et al. 2009b), feature a steeper slope than the one obtained by Gallo et al. (2006; $b \sim 0.6$). We also note that the BHC V404 Cyg lies approximately on the line for $i \sim 18^\circ$. This does not match the measured value of $55 \pm 4^\circ$ (Table 7.1). Most of the BHCs are actually scattered over several lines: this suggests that, although the model can qualitatively describe the scatter in the $(L_X, L_R)$ plane, it should be only seen as a viable possibility to describe the “radio quiet” population. In fact, at the moment we do not know whether the “radio quietness” is an intrinsic property or it might change with time.

7.6 Conclusions

We examined three characteristic parameters of BHCs and the properties of their outbursts to test whether they regulate the energy output in the form of a jet. This has been motivated by the fact that a growing population of sources seems to feature similar accretion flows to the majority of the BHCs (e.g. similar radiative efficiency) but fainter jets than expected. Garcia et al. (2003) suggested that spatially-resolved powerful jets might be associated with long period systems. 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-jet power. The jet power inferred from near-IR observations possibly shows a positive correlation with those two parameters. However, this result might be due to the lack of data points and to the fact the IR emission is not dominated by the jet in some sources.

We retrieved the properties of the outbursts occurred by the BHCs in our sample to see if HS-only outbursts feature different jet properties. We did not find any association between the jet power and the fact that a BHC transits to the soft states during an outburst.

We also considered the inclination angles for our sample of BHCs. A recent result shows that compact-steady jets in the HS can have bulk Lorentz factor $\Gamma > 2$. This suggests that not only jets with a high inclination can suffer de-boosting effects. However, 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 might be biassed by the small number of BHCs for which we have IR data. We defined a jet-toy model in which the bulk Lorentz factor $\Gamma$ becomes larger than $\sim 1$ above $0.1\% L_{\text{Edd}}$. Considering an uniform distribution of viewing angles in the $\cos i$ space, the model can qualitatively reproduce the scatter around the radio/X-ray correlation. Although this result is quite promising, we stress that the toy-model has several limitations, for instance it can not reproduce the measured inclination angles of the BHCs in our sample. Nevertheless we think that it suggests a valid possibility that theoretical models should explore in more detail.

**Acknowledgments**

The authors thank Elena Gallo and David Russell for providing the original data used to calculate the radio and near-IR normalisations. PS would like to thank Monica Colpi, Piergiorgio Casella and Alessandro Patruno for useful discussion.