No evidence for black hole spin powering of jets in X-ray binaries

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Abstract

In this paper, we consider the reported measurements of black hole spin for black hole X-ray binaries and compare them against the measurements of jet power and speed across all accretion states in these systems. We find no evidence for any correlation between the properties of the jets and the reported spin measurements. These constraints are strongest in the hard X-ray state, which is associated with a continuous powerful jet. We are led to conclude that one or more of the following is correct: (i) the calculated jet power and speed measurements are wrong, (ii) the reported spin measurements are wrong and (iii) there is no strong dependence of the jet properties on the black hole spin. In addition to this lack of observational evidence for a relation between the black hole spin and jet properties in stellar mass black holes, we highlight the fact that there appear to be at least three different ways in which the jet power and/or radiative efficiency from a black hole X-ray binary may vary, two of which are certainly independent of spin because they occur in the same source on relatively short time-scales and the third which does not correlate with any reported measurements of black hole spin. We briefly discuss how these findings may impact upon interpretations of populations of active galactic nuclei in the context of black hole spin and merger history.

Key words: ISM: jets and outflows.

1 Introduction

Black holes (BH) remain one of the most bizarre and intriguing aspects of astrophysics. In general relativity, a BH is entirely described by only three parameters: mass, spin and charge. Mass is the easiest of these parameters to measure (most accurately by observing the orbits of other bodies around the BH, such as a binary companion, nearby stars, masers, etc.) and charge is generally supposed to be unimportant, with the astrophysical source electrically neutral on average on macroscopic scales. BH spin is not just a curiosity; a spinning BH has a smaller event horizon than a non-rotating hole and consequently a deeper gravitational well outside of the horizon, potentially increasing the efficiency of accretion. In addition, the rotational energy of spinning BHs may be enormous (~30 per cent \(Mc^2\) for a maximally spinning BH) and could potentially be tapped as an energy source (Penrose 1969; Christodoulou 1970). This concept was placed into the framework of accretion by Blandford & Znajek (1977), who investigated the extraction of BH spin by a magnetic field supported by an accretion disc and concluded that energy and angular momentum could be extracted from the BH in this way. This concept was extended by MacDonald & Thorne (1982) and more recently discussed by Livio, Ogilvie & Pringle (1999), who concluded that the likely extraction of rotational energy of the BH had been overestimated. McKinney (2005) however arrived at the opposite conclusion, deriving a very strong dependence of jet power on the BH spin [see also De Villiers et al. (2005) for parallel work on the influence of spin on jets from numerical simulations]. The most frequent discussion of BH spin is in the context of the apparent radio-loud:radio-quiet ‘dichotomy’ in active galactic nuclei (AGN; e.g. Sramek & Weedman 1980; Stocke et al. 1992; Miller, Rawlings & Saunders 1993; Xu, Livio & Baum 1999), which may have an origin in the powering of AGN jets by the BH spin (e.g. Rees et al. 1982; Wilson & Colbert 1995; Sikora, Stawarz & Lasota 2007) and may tell us about the merger history of galaxies (e.g. Volonteri, Sikora & Lasota 2007).

In recent years, it has become clear that many aspects of BH accretion and jet formation are directly comparable between AGN and lower mass (typically ~10M_\odot) BHs in X-ray binary (XRB) systems. This is to be expected, given the very simple scalings with mass for BHs in general relativity, although there is likely to be a larger diversity of environments in AGN. Scalings between mass, radio luminosity and X-ray luminosity are reported in Merloni, Heinz & di Matteo (2003) and Falcke, Körding & Markoff (2004; see also Körding, Falcke & Corbel 2006a); scaling of fast variability properties with mass and accretion rate are reported in McKinney, Jester & Markoff (2006) and Körding et al. (2007); more qualitative similarities between XRB and AGN accretion are noted in Körding, Jester...
& Fender (2006c) and also discussed in Marscher et al. (2002) and Chatterjee et al. (2009). The temporal evolution of XRB jets, relatively rapid compared to AGN, has allowed many estimates of the power (e.g. Fender 2001; Gallo et al. 2005; Körding, Fender & Migliari 2006b) and speed (e.g. Mirabel & Rodriguez 1994; Miller-Jones, Fender & Nakar 2006) of the jets and their connection to the accretion ‘state’ as characterized by the X-ray emission (e.g. Fender et al. 1999; Fender, Belloni & Gallo 2004, hereafter FBG04, Corbel et al. 2004). Importantly these studies have shown that the jet power of a BH XRB, as well as the radiative efficiency of the accretion flow, can change dramatically in the same source at the same overall radiative luminosity on time-scales far shorter than those associated with significantly changing mass or angular momentum.

In very brief summary, in BH XRBs the coupling of radio emission (and hence jets) to the X-ray state and luminosity is as follows: at Eddington ratios (in terms of X-ray luminosity) below about 0.01, sources seem to be exclusively in the ‘hard’ X-ray state in which the X-ray emission is dominated by a component extending to \( \sim 100 \text{ keV} \), widely (but not universally) accepted to arise via thermal Comptonization of seed photons by a hot flow/corona. In this state, there is strong aperiodic variability and a steady, powerful, flat-spectrum jet. The luminosities of the two components scale roughly as \( L_{\text{radio}} \propto L_X^{\sim 0.7} \). At higher Eddington ratios, reached generally by transient outbursting systems, sources can switch into ‘softer’ states in which the X-ray spectrum is dominated by a cooler (\( \sim 1 \text{ keV} \)) component with a near-blackbody spectrum, generally interpreted as the inner accretion disc. In this state the radio emission is either dramatically suppressed by a factor of \( \sim 50 \) or evolves to a fading, optically thin, state, both scenarios suggesting the ‘quenching’ of the core jet (possibly with some remnant extended emission). In transitions from hard to soft states major radio flares, often resolved as discrete, powerful, ejection events, are commonly observed. Sources generally fade in the soft state until they are once again at a few per cent Eddington (in \( L_X \)) and then make a transition back to the hard state in which mode they fade further. The initial hard \( \rightarrow \) soft state transition is usually at a higher luminosity than the soft \( \rightarrow \) hard return branch, i.e. hysteresis when spectral hardness is compared to luminosity. Note that the same source has been observed to make both hard \( \rightarrow \) soft and soft \( \rightarrow \) hard transitions at different luminosities in different outbursts; note further that some sources, e.g. Cyg X-1, never drop below the 1 per cent Eddington threshold and remain ‘persistent and variable’. For comprehensive reviews on these phenomena, see FBG04, Remillard & McClintock (2006), Done, Gierlinski & Kubota (2007), Fender, Homan & Belloni (2009) and Belloni (2010). The most comprehensive compilation of X-ray data on BH binaries is presented in Dunn et al. (2010). Note that the XRB systems with comparable properties but hosting a neutron star instead of a BH (candidate) also show jets, but with a lower ratio of \( L_{\text{radio}} \) to \( L_X \) (Fender & Kuulkers 2001; Migliari & Fender 2006).

In parallel with these advances in the study of BH jet power, speed and relation to the accretion state, there has been a rapid recent growth in the number of estimates of spin of BHs in XRB systems [the spin is generally discussed in terms of the dimensionless spin parameter \( a_*= cJ/|GM^2| \), which has a range from 0 (non-rotating, or ‘Schwarzschild’ BH) to 1 (maximally rotating, or ‘extreme Kerr’ BH)]. Two approaches have been taken based on detailed fitting of X-ray spectra. In the first approach, the accretion disc continuum is modelled; in the second approach the ‘reflection’ component, including the iron line around 6.4 keV, is also modelled. One of the earliest attempts to measure spin from accretion disc continua was made by Zhang, Cui & Chen (1997), who reported that the two superluminal jet sources, GRS 1915+105 and GRO J1655−40, had high \( (a_*>0.9) \) spin whereas three other X-ray transients had much lower \( |a_*|<0.05 \) and, possibly in some cases, retrograde (compared to the inner accretion disc) spins. More recent disc-modelling results have been presented by, amongst others, Shafee et al. (2006), McClintock et al. (2006), Davis, Done & Blaes (2006), Middleton et al. (2006), Nowak et al. (2008), Steiner et al. (2009) and Gou et al. (2010). Recent results from modelling of the reflection component are compiled in Miller et al. (2009). General points to consider from the presented results are reports of very high spins for some BHs (e.g. 0.98−1.00 for GRS 1915+105 from disc measurements in McClintock et al. 2006; 0.98 ± 0.01 for GRO J1655−40 from reflection components in Miller et al. 2009), some discrepancies (see discussion in Miller et al. 2009 and our Table 1) and low-spin measurements for both Cygnus X-1 (0.05±0.01; Miller et al. 2009) and A0620−00 (0.12−0.20; Gou et al. 2010). Several criticisms of the spin-fitting methods have appeared in the literature (e.g. Done & Diaz-Trigo 2010; Kolehmainen & Done 2010). In the context of disc-fitting, we further note that Fragile (2010) has reported that fits to a system where the BH spin and inner accretion disc axes are misaligned by only 15° are enough to render essentially useless inferred measurements of spin via this method.

In this paper we take these reported measurements of BH spin and compare them against different methods of estimating the power and, in some cases, speed of the jet observed in such systems. From these comparisons we will draw conclusions about evidence for the dependence of jet power, or speed, on spin, in accreting BHs. Note that in this paper we are not considering estimates of the BH spin based upon other methods, such as frequencies of quasi-periodic oscillations.

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Table 1 lists all the reported measurements of BH spin which we have been able to find for XRB systems, as well as the four reported spin measurements for AGN (not counting spins inferred for entire populations of AGN based on distributions of radio loudness and/or radiative efficiency). As noted above there are some intriguing claims, notably that the XRBs GRS 1915+105 and GRO J1655−40, as well as the AGN MCG 6-30-15 and 1H 0707−495, have very high spins, whereas the BH binaries Cyg X-1 and A0620−00 have very low spins. Fig. 1 summarizes using histograms the current distributions of reported spins; clearly there is a bias towards higher spin measurements, which is to be expected since these cases should correspond to the strongest observational effects. In the following, we shall compare these reported spin measurements with estimates of the jet power in the hard state and both jet speed and power in transient outbursts. Most of the sources with reported spin measurements have radio and/or near-infrared (near-IR) measurements which allow estimates of the jet power. Note that in these histograms and the subsequent analyses, we do not use the spin measurements reported by Zhang et al. (1997), although we do list them in Table 1. This is because they are likely to have been superseded by more recent refinements of the disc-fitting method, although in some cases their measurements are in agreement with more recent fits (see e.g. discussion in McClintock et al. 2006).

2.1 The hard state jet

In the hard state, we can only really compare jet power, and not speed, between sources to see if it correlates with estimates of the BH spin. We note that the analyses of Gallo, Fender & Pooley (2003) and Heinz & Merloni (2004) already indicate that the range
Table 1. A compilation of published spin (and mass) measurements for BHs in both XRB systems and AGN, based on disc and reflection line measurements. All of these measurements, except those of Zhang et al. (1997; see the text for discussion) and the two upper limits, are presented in Fig. 1.

| Source      | Mass (M$_\odot$) | Spin estimate | References |
|-------------|-----------------|---------------|------------|
| M33 X-7     | 15.6 ± 1.5      | 0.77 ± 0.05   | 1, 6, 7, 17|
| LMC X-1     | 10.9 ± 1.4      | 0.96$^{+0.04}_{-0.09}$ | 1, 7, 18 |
| LMC X-3     | 11.6 ± 2.1      | <0.8          | 4, 7, 19 |
| GS 2000+25  | 7.2 ± 1.7       | 0.03          | 13 |
| GS 1124-68  | 6.0 ± 1.5       | −0.04         | 13 |
| 4U 1543-47  | 9.4 ± 1.0       | 0.7±0.85      | 12, 3, 7, 8|
| GRO J1655-40| 6.30 ± 0.27     | 0.65–0.8      | 1, 2, 3, 7, 9|
| GRS 1915+105| 14 ± 4          | 0.93          | 13 |
| XTE J1550-564| 9.7–11.6        | <0.8          | 1, 7 |
| XTE J1650-500| 5 ± 2           | 0.79 ± 0.01   | 1, 7 |
| GX 339-4    | ≥6              | 0.94 ± 0.02   | 1, 7 |
| SAX J1711.6-3808         |                | 0.6, 0.2      | 7 |
| XTE J1908+094          |                | 0.75 ± 0.09   | 7 |
| Cygnus X-1          | 10 ± 5          | 0.05 ± 0.01   | 1, 7 |
| 4U 1957+11          | 3–16            | 0.8–1.0       | 1, 12 |
| A0620-00            | 6.6 ± 0.3       | 0.12–0.20     | 21 |
| MCG 6-30-15        | (4.5 ± 2) × 10$^6$ | 0.989$^{+0.009}_{-0.002}$ | 14 |
| SWIFT J2127.4+5654  | 10$^7$          | 0.6 ± 0.2     | 15 |
| Fairall 9          | (2.6 ± 0.6) × 10$^8$ | 0.60 ± 0.07   | 16 |
| IH 0707-495        | 10$^7$          | ≥0.98         | 20 |

Note. Ref 1 = Remillard & McClintock (2006) and McClintock & Remillard (2009), Ref 2 = McClintock, Narayan & Shafee (2007), Ref 3 = Shafee et al. (2006), Ref 4 = Davis et al. (2006), Ref 5 = McClintock et al. (2006), Ref 6 = Liu et al. (2008), Ref 7 = Miller et al. (2009), Ref 8 = Gallo et al. (2003), Ref 9 = Fender, Homan & Belloni (2009) and references therein, Ref 10 = Kato (2004), Ref 11 = Middleton et al. (2006), Ref 12 = Nowak et al. (2008), Ref 13 = Zhang et al. (1997), Ref 14 = Brenneman & Reynolds (2006), Ref 15 = Miniutti et al. (2009), Ref 16 = Schnoll et al. (2009), Ref 17 = Orosz et al. (2007), Ref 18 = Orosz et al. (2009), Ref 19 = Val-Baker, Norton & Negueruela (2007), Ref 20 = Fabian et al. (2009), Ref 21 = Gou et al. (2010), Ref 22 = Blum et al. (2009) and references therein.

of Lorentz factors of such hard state jets is likely to be small (although the absolute value is as yet undetermined). Therefore, we can immediately conclude that if the reported range of spins in the hard state, 0.05–0.99, is correct then the speed of jets in the hard state does not have a strong dependence on the BH spin (unless the jets are sub-relativistic, when a dependence on the spin would not be measurable in terms of Doppler boosting effects).

A variety of approaches may be taken to estimate the power of BH XRB jets in the hard X-ray state (e.g. Fender 2001; Fender, Gallo & Jonker 2003; Malzac, Merloni & Fabian 2004; Gallo et al. 2005; Körding et al. 2006b); nearly all result in high normalizations for the relation, such that in bright (typically in the range from 10$^{-3}$ to 10$^{-1}$ Eddington in X-ray luminosity) hard states the radiative (X-ray) and kinetic luminosities are comparable. At lower luminosities in the hard state, the jet probably comes to dominate over the X-ray emission (Fender, Gallo & Jonker; see also discussion in Cabanac et al. 2009). In particular, Körding et al. (2006b) present a summary of jet power as a function of the accretion rate for a small sample of both BH and neutron star binaries. There may be a slightly higher rate of jet power per unit accreted mass (a factor of order unity) for the BHs. Importantly, both Cyg X-1 and GRS 1915+105 are in the sample and there is no evidence that there is any difference in the normalization of the jet power as a function of the accretion rate between them, to a level of within a factor of 2.

However, we can test the relation between jet power and BH spin estimates for a sample of BH XRBs more explicitly. Under the assumption (reasonable, but not proven) that the radio through infrared spectral energy distributions of BH XRBs in the hard state are broadly the same from system to system (although a varying function of the accretion rate), we can use measurements of jet emission in different bands to compare the relative power of jets between sources. Note that the relation between the observed flat-spectrum synchrotron luminosity and total jet power is believed to be of the form $L_{\text{radio}} \propto L_{\text{jet}}^{1/2}$ (Blandford & Königl 1979; see e.g. Körding et al. 2006b for observational support for this scaling). Recent simulations of XRB jets with internal shocks appear to reproduce this scaling (Jamil, Fender & Kaiser 2010).

In Fig. 2, we present the most up-to-date compilation of quasi-simultaneous radio and X-ray observations of hard state BH XRBs; Table 2 lists the distances adopted for this plot – some are notably different from those used in Gallo et al. (2003). Note that (as with the near-IR, see below) the radio flux densities have been multiplied by the frequency of the radio observations (typically 5–8 GHz) to give an estimate of the radio power. It is clear that the ‘universal’ correlation reported in Gallo et al. (2003) is in fact something much broader, at least at high luminosities. In fact without Cyg X-1, the plot looks rather like there are two distinct tracks, reminiscent of the ‘radio-loud’:radio-quiet’ divide in AGN. In order to make
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Figure 1. A compilation of reported spin measurements for BHs. The first panel shows measurements for BH XRBs based on disc continuum fitting; the three purple measurements are the three different spins reported for the system GRS 1915+105. The second panel shows measurements for BH XRBs based on disc reflection (including iron-line) fitting. The third panel shows measurements for AGN, all of which are based upon reflection fits. The fourth panel shows the sum total of the three previous histograms.

a uniform estimate of the jet power for each of these sources, we fit a straight line to each system: the slope of the fit is fixed to +0.6 (i.e. $L_{\text{radio}} \propto L_X^{0.6}$) as found in Gallo et al. (2006) for the most recent ensemble analysis, so we are simply fitting normalizations to the relation as a proxy for relative jet power. Note that for 4U 1543-47, XTE J1550-564 and A0620-00 we only have a single datum, and so the ‘fit’ is a simple scaling. Note also that we do not consider upper limits, and that for Cygnus X-1 we do not include points which include any evidence for suppression of the radio emission as the source enters softer X-ray states (see fig. 3 of Gallo et al. 2003 for an illustration of this). The normalizations, $c$, are simply fitted as

$$\log_{10} L_{\text{radio}} = c + 0.6(\log_{10} L_X - 34).$$

This process can be repeated with near-IR data, which have been convincingly demonstrated to have a large contribution from the jet (e.g. Homan et al. 2005; Russell et al. 2006). In Fig. 3, we plot the equivalent ensemble of near-IR data and perform the same analysis of normalizations. For XTE J1550-564 we plot data in both the rise and decline phases of an outburst, which show different normalizations – see Russell et al. (2007a) and our discussion later. Note also that the correlation in Russell et al. (2006) extends to lower luminosities because it also utilizes optical data; however, these data are generally dominated by the irradiated accretion disc and are not suitable for estimating the jet power.

For both the radio and infrared data sets, we include a ‘representative’ measurement for the hard ‘plateau’ state of GRS 1915+105 (Fender & Belloni 2004). These measurements should be interpreted with caution as this system – persistently very luminous since entering outburst in 1992 – has not been observed to enter a true canonical hard state. Nevertheless, the properties of the source in this plateau state (which is probably a ‘hard intermediate’ state in the terminology of Belloni 2010), including a steady powerful radio jet, are rather similar to those of the canonical hard state.

We can now compare these measurements of the radio and near-IR normalizations, as proxies for jet power, with the reported measurements of BH spin from reflection and disc modelling. This is done in Fig. 4, where for each normalization measurement we estimate a systematic uncertainty of 0.3 dex. There is clearly no correlation in any of the four panels. Notably, for the reflection fits, Cyg X-1 appears to have more or less average radio power despite a low reported spin. Equally, A0620-00 has a strong radio normalization (admittedly based on a single measurement), compared to a low reported spin from disc fits. Note that we indicate (with solid red circles of Fig. 4) all three of the other reported spin measurements for GRS 1915+105. The lower panels also clearly illustrate the large difference in relative jet power fitted to the source XTE J1550-564 (indicated with dashed blue circles of Fig. 4) when fitting either the rise (lower measurement) or decay (upper measurement) phases of an outburst.

It is important to note that while there are considerable uncertainties in the absolute normalization and form of the relation between radio luminosity and total jet power, what we have measured here is a fairly well-defined ranking. In this context it is important to note that the source with the lowest reported spin, Cygnus X-1, is also one of the best constrained, being at a relatively small distance and with detailed studies of the jets (Gallo et al. 2005; Heinz 2006). Note also that XTE J1650-500 (see Corbel et al. 2004 for more details) clearly shows the pattern of the global correlation, but at a lower normalization than the rest (Fig. 2), despite having a relatively high reported spin (0.79 ± 0.01).
Black hole binary jets

Figure 2. The radio:X-ray plane for low/hard state BH XRBs. All currently available data are plotted, illustrating both the overall correlation over more than $10^8$ in X-ray luminosity and also the increasing number of ‘radio-quiet' sources being found at relatively high X-ray luminosities. The first nine sources in the key, indicated in bold, have reported spin measurements (see Table 1). For those sources, we have fitted a function with the same slope as the ensemble (+0.6) but with variable normalizations. In turn, we have used this normalization as a measure of the relative jet power of the source and compare it later to the reported spin measurements.

Table 2. Source distances adopted in this paper.

| Source         | Distance (kpc) | References |
|----------------|----------------|------------|
| GRS 1915+105   | 11.0           | 1          |
| GX 339-4       | 8.0            | 2          |
| 4U 1543-47     | 7.5            | 2          |
| XTE J1550-564  | 5.3            | 2          |
| XTE J1650-500  | 2.6            | 3          |
| GRO J1655-40   | 3.2            | 2          |
| Cygnus X-1     | 2.1            | 1          |
| Swift J1753.5-0127 | 8.0 | 4          |
| GRO J0422+32   | 2.5            | 2          |
| 1E 1740.7-2942 | 8.5            | 1          |
| A0620-00       | 1.2            | 2          |
| GRS 1758-258   | 8.5            | 1          |
| GS 1354-64     | 25.0           | 5          |
| XTE J1118+480  | 1.7            | 2          |
| XTE J1720-318  | 6.5            | 6          |
| V404 Cyg       | 2.4            | 7          |
| H1743-322      | 7.5            | 8          |

Note. Ref 1 = Gallo et al. (2003) and references therein; Ref 2 = Russell et al. (2006) and references therein; Ref 3 = Hannikainen et al. (2009); Ref 4 = Zurita et al. (2008); Ref 5 = Casares et al. (2009); Ref 6 = Chatty & Bessolaz (2006); Ref 7 = Miller-Jones et al. (2009), Ref 8 = Jonker et al. (2010).

2.2 Powerful, transient jets

For the powerful, transient, jets we may potentially explore both jet power and jet speed (since we have proper motions in several cases) as functions of the estimated BH spin (whereas for the hard state jets, there are no clear speed measurements), although as we will see below that we only really have lower limits to the jet speeds and cannot make much progress.

2.2.1 Transient jet power

It is not straightforward to measure the power associated with the transient ejection events. Typically, we calculate the minimum energy associated with some synchrotron event and divide by the rise time to get the average power going into the jet. This approach is useful to provide lower limits on, and order-of-magnitude estimates of, jet power but is very susceptible to errors resulting from poor sampling of events, uncertainties in Doppler boosting, assumptions about equipartition, etc. As a result, both the normalization and ranking of jet powers between different sources are less accurate than for the hard state. Nevertheless we can make a comparison, and for this purpose we will use the transient jet powers estimated in FBG04, compared with the spin measurements compiled in this paper.

In Fig. 5, we plot as a function of X-ray luminosity the estimated transient jet powers for five systems listed in FBG04 for which there are reported spin measurements. The fitted lines are of a fixed slope of +0.5 (as fitted to the ensemble of transient jet powers by FBG04), and so we may compare the fitted normalizations in a process analogous to that employed for the hard state radio and near-IR measurements earlier in the paper. The normalizations, $c$, in this case are

$$\log_{10} L_{\text{jet}} = c + 0.5(\log_{10} L_X - 34).$$

Overall, we conclude that while there may be evidence for the requirement of an additional parameter determining jet power in hard state BH binaries, such a parameter in no way correlates with reported estimates of the BH spin. It is worth noting that there may be some unknown systematics, which may exceed our 0.3 dex estimate, it seems very unlikely indeed that these systematics could be enough to hide a genuinely strong trend with the reported spin.
In Fig. 6, we compare these fitted normalizations with the reported measurements of the BH spin. While the disc measurements again show no correlation with the estimated jet power, there is an intriguing apparent correlation between the jet power and spin for the reflection measurements. We caution the reader not to overinterpret this, given all the uncertainties outlined above, and discuss it further in Section 3.

2.2.2 Transient jet speed

As discussed already in Fender (2003) and FBG04, in nearly all cases it is only possible to place a lower limit on the speed of jets from XRBs when basing the estimates on measurements of proper motions alone. This is because the distance uncertainties typically encompass a range of possible solutions for the Lorentz factor from $2 \leq \Gamma \leq \infty$. A different approach was taken in Miller-Jones, Fender & Nakar (2006) in which estimates of the jet Lorentz factor were made under the assumption of free relativistic expansion in the rest frame of the jet, with time dilation causing the apparently very small opening angles (i.e. retarded apparent expansion). A third approach to estimating the Lorentz factor of jets is available from the ratio of approaching to receding jets. Unfortunately, in all cases we still end up with lower limits on the Lorentz factor.

All of these three approaches have their uncertainties; we summarize these estimates, for sources with reported spin measurements, in Table 3. Once again, there is no evidence for any correlation with reported BH spin measurements. Furthermore, it is worth noting that currently the highest speed measured for a jet from an XRB is that from the neutron star system Circinus X-1 (FBG04; Tudose et al. 2008), although this may be a jet quite unlike those observed from accreting BHs.

Because these measurements are all lower limits, it is more or less impossible to attempt any correlation with the reported spin measurements. Nevertheless, it is worth bearing in mind that there is evidence that transient jets are faster than the hard state jets (FBG04) and so it may be that this boost in speed is somehow connected to the BH spin (but in this case, the jet in Cyg X-1 should be slower than those from other transients).

3 DISCUSSION

We have clearly demonstrated that for the BH XRBs in the hard X-ray state, there is no correlation between the reported spin measurements and either jet power or speed. If the spin measurements are correct then any dependence on spin which does exist in the hard state must be very weak, less than about an order of magnitude across the whole range of spins from 0.05 to 0.98. Recall that in McKinney (2005), a jet with $a_\ast \geq 0.9$ should have a jet efficiency more than $10^4$ greater than the one with $a_\ast \leq 0.2$ [although also recall that Livio et al. (1999) argue the opposite position that the spin cannot be efficiently tapped via this process]. Note that McKinney’s $a_\ast^4$ dependence of jet power on spin is much steeper than the $a_\ast^2$ originally estimated by Blandford & Znajek (1977).

3.1 Different types of jets – only one spin-powered?

It has been suggested (e.g. Meier 1999; FBG04; see also Tchekhovskoy, Narayan & McKinney 2010) that the two apparently different types of jets in BH XRBs (slow and steady in the hard state, fast and transient at hard $\rightarrow$ soft state transitions; both very powerful) may be powered in different ways. In particular it has been suggested that the hard state jet may be powered by the disc (via e.g. the centrifugal mechanism of Blandford & Payne 1982), while only the transient jets arise close enough to the BH to be affected by spin, and possibly the Blandford–Znajek (or related) process. This suggestion is interesting in the context of AGN, because lower Eddington ratio systems seem in fact to be responsible for most of the kinetic feedback in the Universe (e.g. Kording, Jester & Fender 2008; Heinz, Merloni & Schwab 2007). In other words, even if the transient jets are in some way spin-powered, kinetic feedback in the
A comparison of the jet power normalizations found from radio (upper) and near-IR (lower) with reported BH spin measurements, from reflection (left) and disc fits (right). Despite reportedly sampling the entire range of BH spins, there is clearly no dependence of jet power on these reported values. The left-oriented arrows in the disc fits indicate the upper limit of ≤0.8 reported for the spin of XTE J1550−564 based on disc measurements. Note that in the near-IR jet power panels, XTE J1550−564 has two measurements, based on the different apparent jet power normalizations in the rise and decay phases of an outburst; these are indicated by dotted circles (and are included to demonstrate the range of currently inexplicable apparent changes in jet production efficiency). GRS 1915+105 has three reported spin measurements, which are all plotted, indicated by solid red circles.

With these caveats in mind, we can still explore if there might be a transition to spin-powered jets in transient states, as possibly suggested by the left-hand panel of Fig. 6, with the contribution from spin (as measured via reflection) increasing the jet power by about an order of magnitude for the extreme Kerr BHs. Such an interpretation would not be arrived at, obviously, if the disc fits were also included. If this hypothesis were the case, then we would expect a step up in jet power for the transient systems at the point at which they ‘connect’ to the spin. Whether or not such a step-up in jet power between hard states and transient jets existed was explored in FBG04 (their fig. 5), which shows that if the lower limit to jet power of Fender, Gallo & Jonker (2003) is correct, then there may be a boost of about an order of magnitude in jet power for the transient events. However, in the same figure the jet power normalization from Malzac et al. (2004) is also plotted, which does not require any step-up in jet power. Since then, the jet power estimates for Cyg X-1, based upon the apparently jet-blown cavity in the interstellar medium, are very close to the normalization of Malzac et al. (Gallo et al. 2005; Heinz 2006; Russell et al. 2007a). Surveying all of the available evidence, we conclude that there is no strong evidence for a dependence of jet power on the reported BH spin although there is room for a weak dependence in the case that only the reflection measurements are correct.
3.2 Changing jet power without changing the spin

In BH XRBs there are two well-established circumstances in which the jet power can change significantly in the same source on short time-scales, i.e. without any possible significant change in the BH spin. The first of these is well established for a decade now and was in fact observed during the very first BH state change, that of Cygnus X-1 in 1972 (Tananbaum et al. 1972). It is the observation that the radio emission in many BH systems drops dramatically in the soft X-ray state, compared to the same levels of X-ray emission in the hard X-ray state (Fender et al. 1999; FBG04; Corbel et al. 2005; Russell et al. 2006; see also Russell & Fender 2010). In addition to this, there are two less well-known effects which have only more recently become clear. The first is that even in hard X-ray states, in the same BH XRB, there can apparently be a range of jet powers at the same X-ray luminosity. This is well observed in the near-IR jet emission of XTEJ1550–564 (Russell et al. 2007), where the near-IR emission from the jet returns at a higher level post-outburst, at the same X-ray luminosity in the same state, by a factor of ~5 (Russell et al. 2007; this effect is visible in our Fig. 3). The same physical effect, this time of the same source making ‘parallel tracks’ in the hard state radio versus X-ray correlation, is also in the case of GX 339–4 (Corbel et al. in preparation; see also Coriat et al. 2009).

Thirdly, it has been shown in recent years that several BH XRBs seem to be a long way below the ‘universal’ radio:X-ray correlation reported for the hard state by Gallo et al. (2003). Gallo (2007) and Cadolle-Bel et al. (2007) present clear examples of this, and it is apparent in our Fig. 2. The origin of these discrepancies is unclear but could be related to errors in distance estimates, combinations of orientation and beaming, or simply efficiency of jet production (which may in turn be related to the magnetization of the jet – see Casella & Pe’er 2009). Interestingly, two of the sources which lie significantly below the correlation, i.e. are apparently ‘radio-quiet’, have spin measurements reported by Miller et al. (2009). XTEJ1650–500 (a = 0.79 ± 0.01) and 4U 1543–57 (a = 0.3 ± 0.1) both lie significantly below the correlation. Unfortunately, these spins lie between those measured by the same authors for GX 339–4 (a = 0.94 ± 0.02) and Cyg X-1 (a = 0.05 ± 0.01), both of which have a higher normalization in the $L_{\rm radio}/L_X$ plane.

In summary, based on XRBs, there is evidence for at least one further parameter which affects the efficiency of jet and/or radiation production in an accreting BH system, but this parameter is not associated with the BH spin.

3.3 Relation to AGN

The strongest case made in recent years for spin-powering of some AGN jets is that put forward by Sikora et al. (2007), who demonstrate an apparent bimodality in the relation of radio loudness as a function of the Eddington ratio for different classes of AGN (see also e.g. Lal & Ho 2010). They find that while there is an overall trend of decreasing radio loudness with increasing luminosity for all classes of AGN, there appear to be two distinct, approximately parallel tracks, with broad-line radio galaxies (BLRGs), radio-loud quasars and Fanaroff–Riley type I objects on the upper track and Palomar–Green (PG) quasars, Seyferts and low-ionization nuclear emission-line regions (LINERs) on the lower track. This effect is most evident at the lower Eddington ratios – above ~0.01 Eddington, some BLRGs are actually radio-quiet and some PG quasars radio-loud. Sikora et al. attribute the parallel tracks to representing populations of high-spin (radio-loud) and low-spin (radio-quiet) BHs, respectively; a key point is that all of the objects on the high-spin track reside in large ellipticals. The partial mixing of radio loudnesses at the highest Eddington ratios they attribute to a distribution of states, in analogy with the behaviour of XRBs...
(FBG04). Therefore in their scenario, radio loudness above about 1 per cent Eddington results from a combination of both spin and accretion state, whereas below this level it is dominated by spin. There are reasonable arguments for the evolution of BH spin resulting from merger histories to support such an interpretation (e.g. Volonteri et al. 2007, and references therein).

However, as noted in Sikora et al. (2007), the apparent bimodality in radio loudness at low luminosities probably only arises when total and not core radio luminosities are taken into account (see Terashima & Wilson 2003). The implication is therefore that somehow high-spin systems produce the same core radio luminosity and only reveal their more powerful jets by their stronger interaction with the ambient medium (see e.g. discussion in Zirbel & Baum 1995). This seems at first counter-intuitive to us, based on our experience with X-ray binaries, and would require that the relation between jet power and radio emission (which seems so evident in the hard state of BH X-ray binaries) becomes ‘saturated’ above some luminosity. The ‘Fundamental Planes of BH activity’ presented by Merloni et al. (2003) and Falcke et al. (2004) similarly only use core radio luminosity and do not find strong evidence for a radio-loudness bimodality. Presumably, other factors such as jet lifetime and the properties of the surrounding medium must also play a role in the strength of the extended emission (it is worth noting that the strongest such ‘lobe’ emission from a BH X-ray binary is probably that associated with the apparently low-spin BH in Cyg X-1).

4 CONCLUSIONS

So, is there any case for the reported BH spins being correlated with jet power or jet velocity in BH X-ray binaries? Almost certainly no. Our view on the evidence is summarized in Table 4. This leads us to conclude that either

(i) one or more of the methods used for estimating jet power or velocity is in error;
(ii) one or more of the methods used for estimating BH spin is in error;
(iii) jet power and/or velocity are not related to BH spin.

In addition to this lack of observational evidence for a relation between the BH spin and jet power or speed, we have highlighted the fact that there appear to be at least three different ways in which the jet power and/or radiative efficiency – both of which in the context of AGN are used as estimators of spin – from a BH XRB may vary, two of which are certainly independent of spin because they occur in the same source on relatively short time-scales and the third which does not correlate with any reported measurements of the BH spin.

In this paper, we do not intend to argue that the BH spin does not, in some cases, affect the power or speed of jets formed by that BH. However, current estimates of all three parameters (spin, jet power, jet speed) of BH XRBs show no evidence for a strong relation between them. Furthermore, it is suggested that as well as pursuing the spin–jet connection, researchers working on AGN populations should consider more carefully the fact that observations of BH binaries suggest that there may be parameters other than spin which determine the radio loudness of a system.

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Table 4. A summary of our conclusions on any relation between reported BH spin measurements (mainly for XRBs) and the power and speed of observed jets. There is no good evidence for a connection in any aspect, although some are poorly tested.

| Jet power | Hard state jet | Transient jet | Soft state (suppressed) jet |
|-----------|---------------|--------------|-----------------------------|
| Jet power | Strong evidence against (from radio:X-ray correlations) | Moderate evidence against (from jet power:X-ray correlations) | Weak evidence against (from radio:X-ray correlations and AGN) |
| Jet speeds | Strong evidence against (narrowness of radio:X-ray sample distribution) | Weak evidence against (but only lower limits to speed) | No evidence |
