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Observational Evidence for a Correlation Between Jet Power and Black Hole Spin

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ABSTRACT

*We show that the 5 GHz radio flux of transient ballistic jets in black hole binaries correlates well with the dimensionless black hole spin parameter $a$estimated via the continuumfitting method. The data suggest that jet power scales either as the square of a_{H*}or the square of the angular velocityof the horizonΩ. This is the first direct evidence that jets are powered by black hole spin energy.The observed correlation validates the continuum-fittingmethod of measuring spin. In addition, for those black holes that have well-sampled radio observations of ballistic jets, the correlation may be used to obtain rough estimates of their spins.

Key words: accretion, accretion discs – black hole physics – binaries: close – ISM: jets and outflows – X-rays: binaries

In §2, we describe our sample of stellar-mass BHs and collect together the relevant observational data on BH spins and jet power. In §3, we plot radio power against BH spin and demonstrate that there is a significant correlation between the two quantities. We summarize and discuss in §4.

2 THE DATA 2.1 BH sample and spin estimates

*The CF method (see McClintock et al. 2011 for a brief review) fits the X-ray continuum spectrum of an accreting stellar-mass BH using the classic relativistic thin-disc model of Novikov & Thorne (1973). The spectral fit gives an estimate of the radius of the inner edge of the accretion disc. The BH spin parameter $a$is then obtained by assuming that the disc edge is located at the innermost stable circular orbit (ISCO) of the Kerr metric. The CF method has been developed in detail over the last several years and has been shown to produce consistent results when multiple independent observations of the same source are available (e.g., Steiner et al. 2009, 2010). Inaddition, numerical simulations have provided support for a crucial assumption of the model, namely, that the disc inner edge is close to the ISCO (Shafee et al. 2008; Penna et al. 2010; Kulkarni et al. 2011; Noble et al. 2011).

The spins of the BH primaries in nine BH binaries (BHBs) have been measured using the CF method (McClintock et al. 2011; Gou et al. 2011). Five of these BHBs, namely, A0620–00, XTE J1550–564, GRO J1655–40, GRS 1915+105, 4U 1543–47, are

1 INTRODUCTION

Accreting black holes, both supermassive and stellar-mass, are commonly observed to produce powerful relativistic jets (Zensus 1997; Mirabel & Rodr´iguez 1999). Although there now exists a wealth of data and many detailed models describing these jets, the mechanism that powers the jets remains a mystery.

A popular idea is that jets are powered by the black hole (BH) itself. This goes back to the work of Penrose (1969) who showed that a spinning BH has free energy. Blandford & Znajek (1977) proposed a plausible mechanism whereby the free energy could be used to power an astrophysical jet. They suggested that magnetic fields in the vicinity of an accreting BH would be twisted as a result of the dragging of space-time by the rotating BH. The twisted field lines will carry away energy from the BH, producing an electromagnetic jet. The broad outlines of this model have been confirmed in numerical simulations (e.g., Tchekhovskoy et al. 2011).

While a connection between BH spin energy and relativistic jets is theoretically very appealing, there has been no direct observational evidence for such a link. This is because, until recently, there was no BH with a believable measurement of the dimensionless spin parameter $a_{**}=cJ/GM_2$for several stellar-mass BHs. With this sample of spin measure-, where M and $J$are the mass and angular momentum of the BH. The situation has now changed. Methods are now available — one in particular, the continuumfitting (CF) method (Zhang et al. 1997; Gierli´nski et al. 2001; Shafee et al. 2006; Davis et al. 2006; McClintock et al. 2006) — that have enabled us to make plausibly reliable measurements of a ments, we are now in a position to test whether jet power is related to BH spin. Such a test is the goal of this paper.

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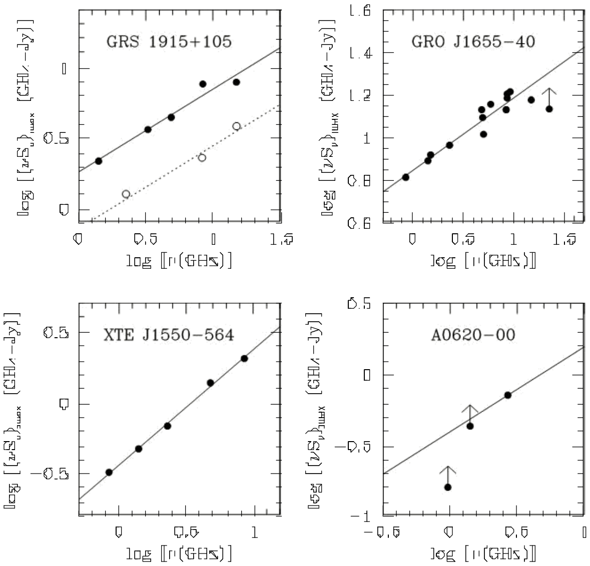

Table 1. Parameters

of Transient BHBs in the Sample

BH Binary a_* M ($M_\odot$) D (kpc) i (deg) $(S_\nu)_{\max,5\,\mathrm{GHz}}$ (Jy) S_0 (γ=2

)(Jy)

References

A0620–00

0.12±0.19

6.61±0.25

1.06±0.12

51.0±0.9

0.203

0.145

1,6,7XT

E

J1550–564

0.34±0.24

9.10±0.61

4.38±0.50

74.7±3.8

0.265

0.859

2,6,8

GRO

J1655–40

0.

7 ± 0.1

6.30 ± 0.27

3.2 ± 0.5

70.2 ± 1.9

2.42

7.74

3,4,6,9,10

GRS

1915+105

0.975 ± 0.025

14.0 ±

4.4 11.0±1.0 66.0±2.0 0.912 2.04 5,6,11,12

4U 1543−07 0.8±0.1 9.4±1.0 7.5±1.0 20.7±1.

5 $>1.16\times10^{-2-4}$ $>4.31\times10$ 3,6,13

References: (1) Gou et al. (2010); (2) Steiner et al. (2

011); (3) Shafee et al. (2006); (4) Davis et al. (2006); (5) McClintock et al. (2006

); (6) Özel et al. (2010); (7) Kuulkers et al. (1999); (8) Hannikainen et al. (2009)

; (9) Hjellming & Rupen (1995); (10) Hannikainen et al. (2000); (11) Rodriguez et al

. (1995); (12) Fender et al. (1999); (13) Park et al. (2004)transient systems (Re millard & McClintock 2006) and are of primary interest to us since they pr oduce transient, ballistic jets (§2.2). The measured spins of these system s, along with the BH mass M, the distance to the binary D, and the inclina tion angle of the binary plane i, are listed in Table 1. In the case of A0

620–00 and XTE J1550–564, the error estimates on the spins are taken from the original papers (Gou et al. 2010; Steiner et al. 2011). The other thre e spins were measured in the early days of the CF method (Shafee et al. 20

06; Davis et al. 2006; McClintock et al. 2006), and we have doubled the pu blished error estimates. An additional four stellar-massBHs have spin estima tes: LMC X-3 (Davis et al. 2006), M33 X-7 (Liu et al. 2008, 2010), LMC X-1

(Gou et al. 2009) and Cyg X-1 (Gou et al. 2011). These are persistent BHB s (Remillard & McClintock 2006) that either do not exhibit ballistic jets or do so only feebly (Fender et al. 2006). We ignore them in this study.

2.

2 Jet radio power

Fender et al. (2004) identified a number of systematic pr operties jet in the radio emission of BHB jets. They showed that there are tw o kinds of jets associated with specific spectral states of the X-ray sourc

e. The first type of jet is consistently observed in the hard spectral stat e as a steady and relatively low-power jet or outflow, which appears not to be very relativistic and is observable only out to a few AU. The second a nd far more dramatic jet, which is central to this paper, is launched when a BHB undergoes a transient outburst. This powerful transient jet appears as the source switches from its initial hard state to a soft state via the “steep power-law” (SPL) state, a violently-variable state characterized b y both strong thermal and power-law components of emission (Remillard & Mc

Clintock 2006). Transient jets manifest themselves as blobs of radio (and o ccasionally X-ray) emitting plasma that move ballistically outward at rela tivistic speeds ($\gamma > 2$). Because these pc-scale jets resemble the kpc-scale jets seen in quasars, BHBs that produce them are called microquasars (Mir abel & Rodríguez 1999).

[2](Markoff et al. 2005) w

here theBallistic jet ejection occurs at a very specific stage during the s pectral evolution of a given system (Fender et al. 2004). As most clearly demonstrated for the prototype microquasar GRS 1915+105 (Fender & Belloni

2004), this stage appears to correspond to the inward-moving inner edge of the accretion disc reaching the ISCO, which results in a shock or some ot her violent event that launches the large-scale relativistic jet. In this scenario, it appears reasonable that the jet is launched within a few grav itational radii and hence plausible that the BH’s spin energy could power the jet. In contrast, the small steady jet in the hard state is thought to originate much further out at ~10-100GM/c

Figure 1. Plot of the maximum observ

ed radio power $(\nu S_\nu)_{max}$ as a function of frequency ν for transient ballistic jet outbu rsts in four BHBs. Two separate outbursts are shown for GRS 1915+105. Best-fit lines (two separate ones in the case of GRS 1915+105) are indicated, except in the case of

A0620–00 where the line slope is fixed at 0.6. effects of spin are relatively we ak. Another virtue of the ballistic jets for our purposes is that they occ ur at a sharply defined luminosity (i.e., near Eddington) compared to the h ard state steady jets, which occur over a wide range of luminosity. For th ese reasons, we restrict our attention to ballistic jets. A typical ballist ic jet blob is initially optically thick and has a low radio power. As the blob moves out and expands, the larger surface area causes its radio powe r to increase. This continues until the blob becomes optically thin, after which the flux declines rapidly. The overall behaviour is generally consis tent with an expanding conical jet (e.g., Hjellming & Johnston 1988). Figur e 1 shows the peak radio flux $(S_\nu)_{max}$ versus $\nu_{observed}$ at different radio freq uencies ν for four of the five transient BHBs in our sample. The radio light curves of these four systems were monitored with good time resolution, al lowing us to obtain reasonably accurate estimates of the peak fluxes. The t op left panel shows data for two separate outbursts of GRS 1915+105 (the s olid and open circles correspond respectively to the outbursts studied

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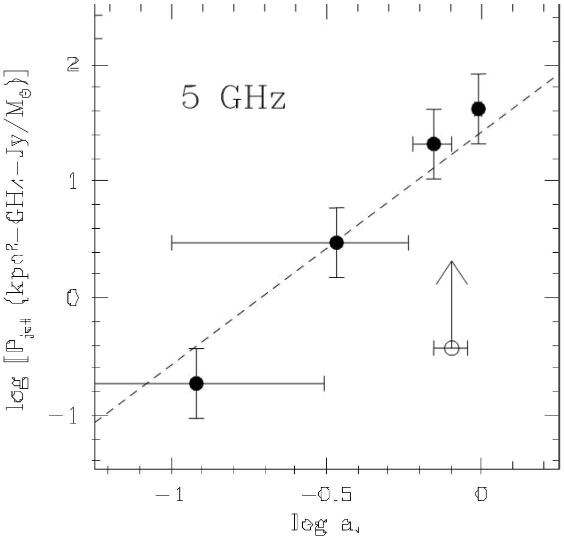

as estimated from the maximum radio flux of ballistic jets (eq. 1) vs the measured spin parameter of the BH $a\propto a$for the transient BHBs in our sample. Solid circles correspond to the first four objects listed in Table 1, which have high quality radio data, and the open circle corresponds to 4U 1543–47, which has only a lower limit on the jet power. The dashed line corresponds to P, the theoretical scaling derived by Blandford & Znajek (1977). The data confirm that ballistic jets derive their power from the spin of the central BH.

power accurately. For instance, the properties of the ISM in the vicinity of the BHB may play a role and is likely to vary from one object to another. Also, the energy released in these roughly Eddington-limited events will vary (e.g., see GRS 1915+105 in Fig. 1). Below, we arbitrarily assume that the uncertainty in P is 0.3 in the log, i.e., a factor of 2 each way.

jet**3 JET POWER VS BH SPIN** Figure 2 shows jet power Pplotted against BH spin parameter a_* jetfor the five transient BHBs in our sample. The data are taken from Table 1. The dashed line has a slope of 2, motivated by the theoretical scaling, $P\propto a_2{}_*$, derived by Blandford & Znajek (1977). The data points agree remarkably well with this theoretical prediction.

$_*$Blandford & Znajek (1977) assumed a slowly spinning BH: $a_{jet}\ll 1$. Tchekhovskoy et al. (2010) obtained a more accurate theoretical scaling which works up to spins fairly close to unity: $P\propto\Omega_2{}_H$, where $\Omega_H$is the angular frequency of the BH horizon,

cGM

$_H$, with the dashed line corresponding to a slope of 2. The agreement is again very good.

We need to consider one additional effect: relativistic beaming. Assuming a typical jet Lorentz factor $\gamma_V= 2$(Fender et al. 2004) and using the inclination angles $i$given in Table 1, we have corrected the values of $(S)_{max,5GHz0}$. The beaming-corrected radio fluxes S(computed using the relations given in Mirabel & Rodr´iguez 1999 with the values of $a$given in §2.2) are listed in

Figure 3 shows a plot of P_{jet} ^{2} $_{*}$)

vs Ω

jet

$_H$ = a_* ^{3} . (2)

$_\nu$by Rodriguez et al. 1995 and Fender et al. 1999). The two lines are fits to the respective data and have a slope of 0.59; writing the spectrum as $S \propto \nu^{a1}$, the fit corresponds to $a = -0.41$. The top right panel combines the observations of Hjellming & Rupen (1995) and Hannikainen et al. (2000) during an outburst of GRO J1655–40. The best-fit line has a slope of 0.34, or $a = -0.66$.

$_\nu$The lower two panels show data for XTE J1550–564 (Hannikainen et al. 2009, slope 0.82, a=-0.18) and A0620–00 (Kuulkers et al. 1999). For the latter source, we do not have enough data points to determine theslope; the line in the plot corresponds to aslope of 0.6 (a = -0.4), which is an average of the slopes for the other three BHBs. In order to enable a fair comparison of the different objects, we use the fitted lines in the four panels to estimate the peak fluxes $(S)_{max}$at a standard frequency of 5 GHz. These 5 GHz peak flux values are listed in Table 1.

$_{jet}$The transient BHB 4U 1543–47 was unfortunately not monitored well at radio frequencies during any of its several outbursts. The only radio data we know of when the source was bright are those for the 2002 outburst summarized in Park et al. (2004). The strongest radio flux was 0.022 Jy at 1.02675 GHz. Assuming $a = -0.4$, this gives a flux of 0.0116 Jy at 5 GHz (or only 0.00043 Jy if one corrects for beaming with γ=2). We list this result separately in Table 1 and plot it as a lower limit in Figs. 2 and 3 because of the sparse radio coverage. In addition, there was an anomaly in the 2002 X-ray outburst of this source.

The anomalous behaviour of 4U 1543–47 is apparent by an inspection of Figs. 4–9 in Remillard & McClintock (2006), which summarize in detail the behaviour of six BH transients scrutinized by *RXTE*. In panel bof these figures, which displays light curves of the PCA model flux coded by X-ray state, one sees that only 4U 1543–47 failed to enter the SPL state (green triangles) near the peak of its outburst, i.e., at the time of the radio coverage reported by Park et al. Rather, it remained locked in the thermal state (red crosses) after its rise out of the hard state. This behaviour contrasts sharply with the behaviour of the other five transients which displayed the strongly-Comptonized SPL state during both the late phase of their rise to maximum and during their early decay phase. Thus, because of (1) the sparse radio coverage of 4U 1543–47, and (2) the failure of the source to transition out of the jet-quenched thermal state (Gallo et al. 2003) to the SPL state (which is closely associated with the launching of ballistic jets), we treat the maximum observed flux of 0.022 Jy as a lower limit. Finally, in sharp contrast to our finding, we note that Figs. 5 and 6 in Fender et al. (2004) indicate a very high jet power for 4U 1543–47. Although we are unsure how they arrived at this result, we believe it was based on infrared data and their equipartition model (see §4).

To measure jet power, we scale the 5 GHz peak flux of each BHB by the square of the distance to the source D. We also divide by the BH mass M since we expect the power to be proportional to M (this scaling is not important since the range of masses is only a factor ~2). We thus obtain from the radio observations the following quantity, which we treat as a proxy for the jet power:

/M. (1) It is hard to assess the uncertainty in the estimated values of P. There is some uncertainty in the values of Dand M, but these are not large. Potentially more serious, the radio flux may not track jet

Figure 2. Plot of the jet power P_{jet}

In the case of GRO J1655–40, the 22 GHz observations did not cover the peak of the light curve. Hence this point is shown as a lower limit. Similarly, in A0620–00, the peak was not observed at 0.962 GHz and 1.14 GHz.

jet

$P^{*}_{jet} = D^{2}_{jet}(\nu S_{\nu})_{max,5GHz}$ $\quad {}^{2\,*}_{jet}$ $\quad \Omega \quad 2(1+ \quad 1-a$

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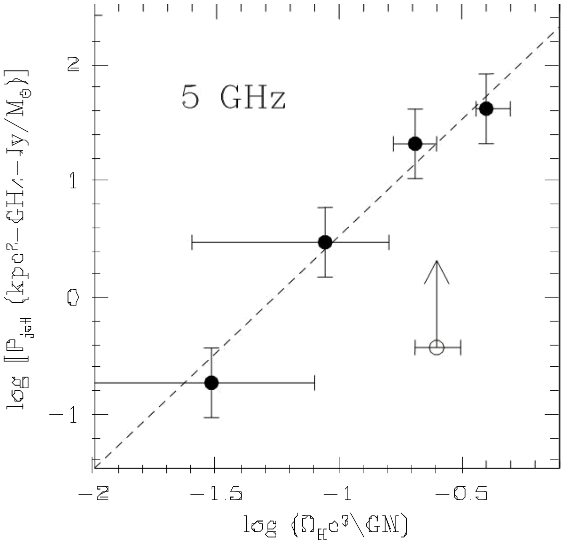

Figure 3. Similar t

o Fig. 2, but showing the angular velocity of the BH horizon Ω (eq. 2) along the abs cissa. The dashed line corresponds to $P_{jet} \propto \Omega_{H}^{2}{}_{H}$ (Tchekhovskoy et al. 2010). $_{jet}$

Table 1

. The inferred jet power of A0620–00 (the left-most point in Figs. 2 and 3

) decreases by a small factor, whereas the other three jet powers increase by a larger factor. As a result, the spread in P_{jet} among the four objects becomes ~3.0 orders of magnitude, compared to ~ 2.4 orders in Figs. 2, 3. Th us, allowing for beaming enhances the range of P in the sources and solidifi es further the connection between jet power and BH spin.

4 DISCUSSION

Since

the correlations shown in Figs. 2 and 3 are based on only four objects, on e wonders whether we are merely seeing chance alignment of intrinsically u ncorrelated data. The chief argument against this hypothesis is that a_{H}^{*} var ies over the full allowable range of prograde spins, Ω varies by more than a factor of 10, and P_{jetjet} varies by 2.4 orders of magnitude (or 3 orders of magnitude if one corrects for beaming assuming $\gamma = 2$). Also, the plotted po ints differ from one another by several standard deviations, which is not statistically likely. We therefore conclude that the evidence in Figs. 2 a nd 3 indicates rather strongly that the power of ballistic jets depends on the spin of the accreting BH. At the same time, and as a corollary, the st rong apparent correlation validates the CF method of measuring spin. The C

F method is based on a number of assumptions, most of which have been inde pendently validated (see McClintock et al. 2011). The results presented he re provide yet another validation.

*The existence

of a correlation between jet power and BH spin does not necessarily mean t hat the energy source for the jet is BH spin. The power could possibly be supplied by the accretion disc (Ghosh & Abramowicz 1997; Livio et al. 1999

). Since the binding energy of a particle at the ISCO increases with incre asing a, the disc power increases with BH spin and this might cause the ob served correlation. However, we note that the radiative luminosity of a th in accretion disc varies by only a modest factor with BH spin; the radiativ e efficiency $\eta = 0.061$ for $a_{**} = 0.12$ (the spin of A0620–00) and $\eta = 0.23$ for a

= 0.98 (the spin of GRS 1915+105). If jet power scales similarly, we expec t no more than a factor of 4 variation in the radio powers in our sample.

Instead, we see a factor ~ 250-1000. Moreover, the observed spread is rath er close to what is expected theoretically if jets are powered by BH spin.

The evidence thus strongly suggests that ballistic jets are powered direc tly by the spin energy of the accreting BH.Based on the above arguments, w e view our results as a confirmation of the Penrose-Blandford-Znajek mechan ism of powering relativistic jets by BH spin energy. Theoretically, this m echanism depends on both the BH spin and the magnetic field strength at the horizon. The latter is believed to depend on the mass accretion rate. M (

e.g., Ghosh & Abramowicz 1997; Livio et al. 1999; Tchekhovskoy et al. 2011)

. Since ballistic jets are seen during a very specific phase of the evoluti on of a transient BHB, it is reasonable to assume that. M(normalized by th e BH mass) is roughly the same in different objects when they exhibit balli stic jets, or indeed in different ballistic jet episodes in the same objec

t. This allows us to eliminate. M from our analysis, and makes the compari sons shown in Figs. 2 and 3 meaningful. In addition to the CF method, a seco nd method based on fitting* the profile of the relativistically broadened Fe line has been used to estimate BH spins (Reynolds & Nowak 2003; Miller 200

7). The method has the advantage that it does not require estimates of M a nd D(which the CF method does). However, obtaining secure results via the

Fe-line method is a challenge. CF spins are obtained rather simply by mode ling a (typically) strongly dominant thermal disc component, while Fe-line spins require modelling the thermal disc plus a strong Compton component p lus a disc reflection component that includes the Fe K line. Both methods r equire models of spectral hardening, as well as numerical simulations to i nvestigate conditions near the ISCO. However, the Fe-line method additiona lly entails detailed atomic physics and requires a complex model of reproc essing in the disc, ideally with a self-consistent determination of the di sc’s ionization state as a function of radius. It further requires charact erizing a luminous corona of unknown geometry. In practice, while the CF m ethod has been shown to give consistent values of a for dozens (even hundre ds) of observations of a single BH (Steiner et al. 2010), the Fe-line meth od has not yet been demonstrated to give consistent results for multiple o bservations of a single BHB. In the absence of such a consistency check, i t is hard to quantify uncertainties in this method. For these reasons, we have considered only CF spin estimates in this paper.[*] After considering se parately both ballistic and hard state steady jets, Fender et al. (2010) fi nd no evidence for a correlation between jet power and BH spin. We have al ready given in §2.2 a plausible reason for the absence of evidence in the case of the steady jets. We now focus on rationalizing the very different results obtained by Fender et al. (presented in their §2.2.1 and Fig. 6) a nd ourselves for the ballistic jets. Their source sample is identical to o urs, namely the BH transients listed in Table 1. Concerning the data used and limiting ourselves to CF-derived spin estimates, the only significant d ifference is that for GRO J1550–564 we use the new spin value of Steiner e t al. (2011), $a_* = 0.34 \pm 0.24$, while they used the earlier Davis et al. (200

6) limit of $a<0.8$. The substantial difference between our results and thos

e of Fender et al. (2010) is, in the end, determined by the choice of the q uantity used to represent jet power. We simply use the observed flux densit y at 5 GHz expressed as a luminosity. Fender et al. compute jet power from the peak radio luminosity and the rise time of some particular synchrotro n event. The authors clearly

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state that their 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.” Their estimates of jet luminosity for three sources are given in Table 1 of Fender et al. (2004), but it is not clear how the luminosities of A0620–00 and 4U 1543–47 were estimated. The authors further adopt a formula relating jet power to X-ray luminosity, $\log_{10}L_{jet}=c+0.5(\log_{10}L_x-34)$, and estimate the normalization constant $c$in the preceding formula, which they treat as their proxy for jet power. In short, their proxy for jet power is heavily model dependent and ours is model independent.

$\odot$(¨ Ozel et al. 2010), we obtainThe correlation shown in Fig. 2 can be used to obtain rough estimates of spin for any transient BH that has undergone a major outburst cycle and that has been closely monitored at radio wavelengths. For instance, radio observations of Nova Muscae 1991 (GRS 1124–68) by Ball et al. (1995) suggest a maximum 5 GHz radio flux ˜ 1Jy. Assuming a distance D ˜ 6kpc and a typical BH mass M ˜ $8M$
$\log[P_{jet}]$˜0.65 ± 0.3. Fig. 2 then gives $a_{\odot *}$˜$0.3-0.6$. In the case of GX 339-4, the brightest X-ray and radio outburst (Gallo et al. 2004) had a maximum 5 GHz flux of 0.055 Jy. Taking D˜9kpc, M ˜ $8M$(¨ Ozel et al. 2010), we find $\log[P_{*jet}]$ ˜ -0.25 ± 0.3 and $a_*<0.2$. The latter estimate is consistent with the strict upper limit $a<0.9$derived by Kolehmainen & Done (2010) using the CF method with conservative assumptions.

These examples illustratethe importance of obtaining good radio coverage for all future transient BHBs, including especially the recurrent system 4U 1543–47. Those systems that have

CF-based spin measurements will flesh out the correlations plotted in Figs. 2 and 3. For the many other BH transients that lack a sufficientlybright optical counterpart and are therefore out of reach of the CF method, the radio data can either be used as a check on Fe-line measurements of spin or serve as our only estimate of spin.

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