On the Misalignment of Jets in Microquasars

Thomas J. Maccarone

ABSTRACT
We discuss the timescales for alignment of black hole and accretion disc spins in the context of binary systems. We show that for black holes that are formed with substantial angular momentum, the alignment timescales are likely to be at least a substantial fraction of the systems' lifetimes. This result explains the observed misalignment of the disc and the jet in the microquasar GRO J 1655-40 and in SAX J 1819-2525 as being likely due to the Bardeen-Petterson effect. We discuss the implications of these results on the mass estimate for GRS 1915+105, which has assumed the jet is perpendicular to the orbital plane of the system and may hence be an underestimate. We show that the timescales for the spin alignment in Cygnus X-3 are consistent with the likely misalignment of disc and jet in that system, and that this is suggested by the observational data.

Key words: accretion:accretion disks – X-rays:individual:GRO J 1655-40 – X-rays:individual:V4641 Sag – X-rays:individual:Cygnus X-3 – X-rays:individual:GRS 1915+105 – galaxies:jets

1 INTRODUCTION
It is often stated that astrophysical black holes present one of the best laboratories available for the study of general relativity. At the same time, relatively few concrete tests of general relativity have been made with observations of accreting black holes. The Lense-Thirring effect is the distortion of space in the presence of a rotating compact object through the dragging of inertial frames. When the effect is important, the central part of an accretion disc is forced to rotate in the same plane as the black hole (the Bardeen-Petterson effect - see Bardeen & Petterson 1975). The geometry of the accretion flow changes significantly in the vicinity of the black hole and hence to allow for sensitive tests of general relativity.
The radius out to which this effect is observed is such that the Lense-Thirring precession period due to the warping of the disc is equal to the timescale for angular momentum to drift through the disc. Past claims of evidence for the BP effect have come from interpretations of the quasi-periodic oscillations in X-ray binaries (Stella & Vietri 1998; see also Fragile, Mathews & Wilson 2001 for a more recent discussion).

The jets of radio galaxies are often seen to show a constant spatial direction over their 10^8 year lifetimes (Alexander & Leahy 1997; Liu, Pooley, & Riley 1992). Until recently, the origin for this stability had been suggested to be that the spin of the black hole provides a "flywheel" effect. Assuming that the jets are powered by disc accretion, the jets should be perpendicular to the discs. The BP effect requires that the disc plane near the black hole be perpendicular to the black hole's spin vector. Given the suggestion that relativistic jets may be powered by extracting the spin energy of the central black hole (Blandford & Znajek 1977) and the expectation that the timescale for the black hole to align itself with the disc by accreting matter with net angular momentum should be at least 10^8 years (Rees 1978), this picture became commonly accepted.

More recent observational and theoretical work challenged this picture for the case of active galactic nuclei. The inner dust discs of some samples of nearby Seyfert galaxies are found to be perpendicular to their radio jets (van Dokkum & Franx 1995; but see Kinney et al. 2000 for contradictory results). The jets in radio galaxies, on the other hand, appear not to be perpendicular to the dust discs (Schmitt et al. 2002). If the Bardeen-Petterson effect is important and the black hole spins are not intrinsically correlated with the dust discs' angular momentum vectors, then alignment should be observed only in the case of the initial alignment of black hole and disc spins, as the size scales on which HST can resolve the discs are substantially larger than the BP radius. The observations of alignments in the early work on Seyferts prompted theorists to explain the steady directions of AGN jets by making the accretion disc, rather than the black hole the "flywheel" (Natarajan & Pringle 1998) and showing that the black hole's spin should be much more quickly aligned with the disc's angular momentum if one took into account the efficient transfer of angular momentum in the disc plane (Papaloizou & Pringle 1983) as shear perpendicular to the disk place can be transported more efficiently than shear within the disk plane, so warp in a nonplanar disc may decay on a timescale much faster than the accretion timescale for a planar disk. Additional theoretical support for the basic assumptions in Natarajan & Pringle (1998) has come from more detailed calculations, both analytical (Ogilvie 1999) and
numerical (Torkelsson et al. 2000; Gammie, Goodman & Ogilvie 2000) but see also Nelson & Papaloizou (2000) who suggest a longer timescale; all of these papers note that the exact timescales depend on details of angular momentum transport which are currently poorly understood. The angular momentum evolution of black holes in binary systems was studied by King & Kolb (1999), where it was found that black hole spins are unlikely to change substantially due to accretion, but has not been re-visited given the hypothesis of efficient warp transfer suggested by Papaloizou & Pringle (1983), and the specific problem of the change in the spin direction of a rapidly rotating black hole has not been considered.

In two X-ray binaries, GRO J 1655-40 and SAX J 1819-2525 (also known as V4641 Sag), measured binary orbital plane inclination angles differ substantially from the measured jet inclination angles, providing strong evidence that the Bardeen-Petterson effect may be relevant. A third system, SS 433, shows precessing jets (Hjellming & Johnston 1981) which imply that either the jets are not perpendicular to the orbital plane, or that the orbital plane itself precesses, which could occur if the system is a hierarchical triple (e.g. Fabian et al. 1986). With this motivation, we compute the timescale for a black hole in a binary system to align its spin with the angular momentum of the binary orbit, and show that in contrast to active galactic nuclei, X-ray binaries containing black holes should routinely have misaligned jets. We consider the implications for the mass estimate of GRS 1915+105, which assumes that the jet is perpendicular to the binary plane. We discuss the case of Cygnus X-3, whose orbital inclination angle is not well constrained, and show that its jet would have become aligned with the orbital plane only for an unlikely range of parameters. We do not apply this model to SS 433, because the nature of its binary companion is not well known and it is often speculated that this system is undergoing thermally unstable, highly super-Eddington mass transfer (e.g. Verbunt & van den Heuvel 1995 and references within), for which our thin disc approximations are highly invalid.

2 APPLICATIONS TO BINARY SYSTEMS

Assuming a thin disc model (Shakura & Sunyaev 1973; Collin-Souffrin & Dumont 1990), NP calculated the timescale for alignment of the black hole’s angular momentum vector with that of the accretion disc:

\[ t_{\text{align}} = 5.6 \times 10^5 a^{11/16} \left( \frac{\alpha}{0.03} \right)^{13/8} \left( \frac{L}{0.1L_\odot} \right)^{-7/8} M_8^{-1/16} (\frac{\epsilon}{0.3})^{7/8} \text{years}, \]  

(1)
where $a$ is the dimensionless angular momentum parameter for the black hole, $\alpha$ is the viscosity parameter of the accretion disc in the Shakura-Sunyaev (1973) formalism, $L$ is the steady luminosity of the accretion flow, $L_E$ is the Eddington luminosity for the central black hole, $M_8$ is the black hole mass in units of $10^8$ solar masses, and $\epsilon$ is the efficiency of the accretion flow, i.e. $L/\dot{m}c^2$, where $\dot{m}$ is the accretion rate. This timescale represents a decay timescale for the separation between the disc’s angular momentum axis and the jet’s axis, and if a system’s age is less than a few alignment timescales, some observable separation between disc and jet axes is to be expected if the initial separation was large.

We re-write this in terms of the accretion timescale, $t_{\text{acc}} = M/\dot{m}$ and set the fiducial value of the black hole mass to 10 solar masses, a more typical value for binary systems.

$$\frac{t_{\text{align}}}{t_{\text{acc}}} = 1.3 \times 10^{-2} a^{11/16} \left( \frac{\alpha}{0.03} \right)^{13/8} \left( \frac{L}{0.1 L_E} \right)^{1/8} M_8^{1/16} \left( \frac{\epsilon}{0.3} \right)^{-1/8}$$  

(2)

The lifetimes, $\tau_{\text{bin}}$ of Roche lobe overflow binary systems have as an upper bound the timescale to accrete the entire donor star - $M_{\text{don}}/M_{\text{CO}} t_{\text{acc}}$, where $M_{\text{don}}$ is the mass of the donor star and $M_{\text{CO}}$ is the mass of the accreting compact object. Making this substitution, we find:

$$\frac{t_{\text{align}}}{\tau_{\text{bin}}} = 0.13 a^{11/16} \left( \frac{\alpha}{0.03} \right)^{13/8} \left( \frac{L}{0.1 L_E} \right)^{1/8} M_8^{15/16} \left( \frac{\epsilon}{0.3} \right)^{-1/8} \left( \frac{M_{\text{don}}}{M_\odot} \right)^{-1}.$$  

(3)

In fact, the lifetimes of binary systems may be quite a bit shorter than $\tau_{\text{bin}}$. Winds from the donor star, perhaps driven by X-ray heating from the accretion flow, may accelerate the mass loss of the donor star without changing the accretion rate on the compact object. Such a scenario has been suggested for reducing the lifetimes of low mass X-ray binaries containing neutron stars in order to match the LMXB birth rate with the millisecond pulsar birth rate (e.g. Tavani 1991; Podsiadlowski 1991).

A substantial fraction of black hole binaries in the Galaxy are transient systems. These induce significant complications in applying the above formulae. First, their time averaged luminosities are not always well known, as the recurrence timescales for the outbursts are poorly constrained for most systems. Secondly, the transfer of angular momentum of a warp is enhanced in large scale height flows. Since a prominent model for the quiescent states of accreting binaries is the advection dominated accretion flow model, where the scale height goes roughly as the radius, the above formulae become invalid.

Two other issues make the problems related to geometrically thick flows less worrisome. First, despite the fact that transient systems spend most of their time in the quiescent state, they emit the vast majority of their luminosity in the outbursts. If we assume the relation of
Narayan & Yi (1995) that $\epsilon \sim \dot{m}/\dot{m}_{\text{EDD}}$, a $\sim 6$ year recurrence timescale, a 30% efficiency in outburst, and that the outbursts consist of emission at $\sim L_{\text{edd}}$ for a few months, while the quiescent periods consists of emission at $10^{-7}L_{\text{edd}}$, then only a few percent of the matter is accreted during the quiescent states. Thus even if the accretion flow is 10 times more efficient at transferring warps in quiescence, the transferring of warps during the outbursts dominates. The second issue is that much recent theoretical work has suggested that outflows from the accretion flow may be extremely important in the quiescent states (Blandford & Begelman 1999; Quataert & Narayan 1999; di Matteo et al. 1999; Meyer, Liu & Meyer-Hofmeister 2001). If matter is expelled from the accretion flow because it retains excess angular momentum, then obviously, the efficiency of this matter in transferring angular momentum from the disc to the black hole is reduced.

Thus it is safe to assume that for transient black hole systems, the accretion history can be approximated as a series of discrete events where the system accretes at $\epsilon \sim 30\%$ efficiency and $L \sim L_{\text{edd}}$. The expressions then become:

\[
\frac{t_{\text{align}}}{\tau_{\text{bin}}} = 0.10a^{11/16} \left(\frac{\alpha}{0.03}\right)^{13/8} \left(\frac{L_{\text{out}}}{L_{\text{edd}}}\right)^{1/8} M_{10}^{15/16} \left(\frac{\epsilon}{0.3}\right)^{-1/8} \left(\frac{M_{\text{don}}}{M_{\odot}}\right)^{-1}.
\]  

For systems with low mean accretion rates, the Hubble time and/or the stellar evolution timescale for the companion star may be shorter than the binary lifetime and/or the alignment timescale. In particular, for high mass X-ray binaries (i.e. wind-fed accreting systems), the system lifetime will almost always be determined by the stellar evolution timescale for the donor star. Many transient systems with low mean accretion rates will also have donor stars with lifetimes shorter than $\tau_{\text{bin}}$. Thus we wish to know the alignment timescale in years as well as in terms of $\tau_{\text{bin}}$, so we can compare with the Hubble time and with the main sequence lifetime of the companion star. Expressing $\tau_{\text{bin}}$ explicitly, we find:

\[
\tau_{\text{bin}} = 1.3 \times 10^8 \left(\frac{M_{\text{don}}}{M_{\odot}}\right)\left(\frac{L_{\text{out}}}{L_{\text{edd}}}\right)^{-1} \left(\frac{t_{\text{recur}}}{t_{\text{out}}}\right)^{-1} \text{years.}
\]  

Thus for binaries which spend a small fraction of their time in outburst, and hence have low mean mass accretion rates, $\tau_{\text{bin}}$ can be of order the Hubble timescale. The alignment timescale can then be expressed as:

\[
t_{\text{align}} = 1.0 \times 10^7 a^{11/16} \left(\frac{\alpha}{0.03}\right)^{13/8} \left(\frac{L_{\text{out}}}{L_{\text{edd}}}\right)^{-7/8} M_{10}^{1/16} \left(\frac{\epsilon}{0.3}\right)^{7/8} \left(\frac{t_{\text{recur}}}{t_{\text{out}}}\right)^{1/8} \text{years.}
\]
3 IMPLICATIONS FOR THE MISALIGNMENT OF THE JET IN GRO J 1655-40 AND SAX 1819-2525

The first known and one of the strongest candidates for the Bardeen-Petterson effect is GRO J 1655-40. Its misalignment between binary plane (70 degrees - Greene, Bailyn & Orosz 2001) and jet (85 degrees - Hjellming & Rupen 1995) of at least 15 degrees has been suggested to be evidence for the Bardeen-Petterson effect (Fragile, Matthews & Wilson 2001). Based on the observations of 300 Hz and 450 Hz quasi-periodic oscillations in this source (Strohmayer 2001a), thought to be in a resonance, its value of \(a\) has been estimated to be between 0.2 and 0.67 (Abramowicz & Kluzniak 2001), with most of the uncertainty from the uncertainty in the mass estimate of the black hole. Alternatively, if the 300 Hz QPO represents a diskoseismic \(g\)-mode, and the 450 Hz represents its corresponding \(c\)-mode (Wagoner, Silbergleit, & Ortega-Rodriguez 2001 - WSO), then \(a = 0.92 \pm 0.02\). Taking the relatively conservative case of 6.3 solar mass black hole, a spin parameter value of 0.4, \(\alpha = 0.05, \epsilon = 0.3\), a companion star mass of 2.4 solar masses and \(L = L_{\text{EDD}}\) in outburst, we find that the ratio of alignment timescale to binary lifetime is about 0.3, without invoking any winds, and with the binary lifetime assumed to be the timescale to accrete the whole companion star, not the stellar evolution timescale of the companion star.

We now check the lifetime in years rather than the ratio of the two timescales to test whether stellar evolution may place a more stringent limit on the lifetime of the system than accretion does. The outburst history of GRO J 1655-40 is somewhat complicated - it has shown several outbursts over the last 10 years, but previously seems to have been quiescent for quite some time. As a southern hemisphere source, it is not well observed in the optical plate archives often used to find past outbursts of novae. The typical recurrence timescale is thus rather uncertain, so we take the mean values for outburst duration and recurrence timescales for transient objects (e.g. Chen, Shrader, & Livio 1997 - CSL). The recurrence timescale is assumed to be about 6 years. The outburst durations for observability are seen to be about 100 days by CSL, but the peaks during which \(L \sim L_{\text{EDD}}\) are somewhat shorter. We thus take a 30 day recurrence timescale. This gives us an alignment timescale of about \(8 \times 10^8\) years.

Assuming that a star’s main sequence lifetime is \(\sim 10^{10}(M/M_\odot)^{-3}\) years for stars below 30 solar masses (e.g. Kippenhahn & Weigert 1990), then the main sequence lifetime of the 2.4 \(M_\odot\) secondary star in GRO J 1655-40 should be about \(7 \times 10^8\) years. The secondary
appears to be somewhat evolved (Greene, Bailyn, & Orosz 2001), so the age of the system is likely to be a substantial fraction of the star’s main sequence lifetime. Thus for our best guess regarding the recurrence timescale (and hence the mean luminosity), we find that the system should be \( \sim \) one alignment timescale in age, and hence the black hole’s spin should not have become fully aligned with that of the accretion disc. If the diskoseismic model, rather than the epicycle-resonance model, is correct, the spin parameter value will be a factor of \( \sim 2.5 \) higher and the alignment timescale will then be about twice the system’s age. It should be noted that the age estimate for the secondary star is an upper limit; if the star has undergone significant mass loss through stellar winds, then its initial mass was larger than the current measurement shows and its stellar evolution timescale will be shorter than our estimate. We caution alternatively that the value of \( \alpha \) could be substantially smaller than 0.05 and that the dependence of alignment timescale on \( \alpha \) is rather strong. In this case, the system could be misaligned despite have an age of more than one alignment timescale. Such a result could be explained by outflows and/or jets taking away a substantial fraction of the system’s angular momentum, and could have important implications for the observed misalignments of AGNs which are several alignment timescales old. Figure 1 shows the three timescales - the stellar evolution timescale, the timescale to accrete the donor star, and the alignment timescale as a function of the duty cycle.

A similar line of reasoning shows that if the black hole in SAX 1819-2525 (V4641 Sag) was formed with a substantial spin, it, too should spend the whole binary lifetime unaligned. Orosz et al. (2001) find that the mass donating star in this system is a late B type star of about 6 \( M_\odot \), meaning that its main sequence lifetime is of order \( 10^8 \) years or less (as the star has likely undergone significant mass loss). They find a 10 solar mass black hole and a distance of about 10 kpc. The jet’s spatial extent within one day of the start of the X-ray outburst then implies an apparent velocity of \( \sim 10c \) (Hjellming et al. 2001). Thus the jet must be strongly beamed (with the Lorentz factor of the jet projected along the line of sight, \( \delta, \sim 10 \)), implying an inclination angle of less than about 10 degrees (Orosz et al. 2001), while measurements of the May 2002 outburst show even larger proper motions, implying \( \delta \sim 17 \) and hence an inclination angle less than 7 degrees (M. Rupen, private communication). Orosz et al. (2001) also find strong ellipsoidal variations, indicating a binary plane inclination angle of at least \( \sim 60 \) degrees. The angle between the orbital plane and the jet must then be at least \( \sim 50 \) degrees. Since the system appears to be a transient that even in outburst emits at a small fraction of its Eddington luminosity (with the exception of the brief, beamed
Figure 1. The three relevant timescales, as a function of the ratio of recurrence timescale to outburst timescale. The solid line is the timescale to accrete the entire donor star. The dot-dashed line is the main sequence stellar lifetime of the $2.4M_\odot$ donor star. The three dashed lines are the alignment timescales for spins of 0.92, 0.4, and 0.2, from top to bottom. The other parameters are chosen as specified in the discussion of the parameter values for GRO J 1655-40.

jet episode - see Wijands and van der Klis 2000), its alignment timescale should be well in excess of $10^8$ years unless it was formed with a very low value of the spin parameter $a$ (one less than $10^{-3}$, assuming that the mean luminosity of V4641 Sag is ten times lower than that of GRO J 1655-40). If the black hole spin affects the production of jets (as suggested, for example, by Blandford & Znajek 1977), we would then not see jets from a source with such a low spin.

4 IMPLICATIONS FOR MASS ESTIMATES IN GRS 1915+105

For GRS 1915+105, the disc and jet have often been assumed to be perpendicular, both for purpose of computing the binary inclination (Greiner, Cuby, & McCaughrean 2001 - GCM) and for purposes of computing the inner disc radii given a normalization to the disc component of the spectrum (e.g. Muno, Remillard & Morgan 1999; Klein-Wolt et al. 2001). The companion star’s mass is estimated to be about $1.2 M_\odot$ and the black hole’s mass is estimated to be about $14 \pm 4$ solar masses. The inclination angle given from jet measurements is 70 degrees (Mirabel & Rodriguez 1994), so the black hole mass cannot
have been overestimated by much more than 5% if the inclination angle of the binary plane is not the direction perpendicular to the jets. The black hole mass could, however, be severely underestimated if the jet is not perpendicular to the accretion disc.

We thus consider other estimates of the black hole mass and attempt to determine whether the spin vectors of the orbit and the black hole should be aligned given these masses and the expected values of the spin parameter. WSO present two estimates for the mass of GRS 1915+105 from diskoseismology based on the measurements of two high frequency QPOs (Strohmayer 2001b). The first, based on the identification of the 67 Hz QPO with the g-mode, as suggested by Nowak et al. (1997), gives a mass of $18.2 \pm 3.1$ solar masses and $a = 0.70 \pm 0.04$. The 42 Hz QPO is then the c-mode. The second estimate consists of switching the identifications. If the more rapid QPO is the c-mode, as seen in GRO J 1655-40, then the mass of the black hole is $42.4 \pm 7.0$ solar masses and $a = 0.93 \pm 0.02$. In either case, the spin alignment timescale for the black hole should be substantially longer than the lifetime of the system. The 18 solar mass estimate is within the error bars of the measurement of GCM, while the 42 solar mass estimate would require the inclination angle of the binary plane to be about 20 degrees, implying a misalignment of disc and jet of at least 50 degrees. WSO state that the higher mass estimate is consistent with the findings of Strohmayer (2001b) that the relative spectral properties of high and low frequency QPOs in the two microquasars systems are the same.

More recent measurements of additional high frequency QPOs in GRS 1915+105 at 162 and 324 Hz, with an additional possible detection at 486 Hz (Remillard et al. 2002, in preparation) cast serious doubt on the diskoseismic model. A consistent set of values for the mass and spin cannot reproduce both the 67 and 40 Hz QPOs as diskoseismic modes and the higher frequency QPOs as a 1:2 or 1:3 resonance between orbital and epicyclic frequencies. The resonance model rules out a large misalignment between the disc and jet inclination angles. Figure 2 shows the curves for the 1:2 and 1:3 resonances which give an epicyclic frequency of 162 Hz (with orbital frequencies of 324 and 486 Hz respectively), along with the curve where the disc and jet are misaligned. We compute the relation between the minimum spin and mass needed for a misaligned system by assuming $L = 3 \times 10^{38}$ ergs/sec (the mean value as estimated from the RXTE All Sky Monitor data), a 30% efficiency, $\alpha=0.05$. Since the initial mass of the companion star is not known, we take the as an upper limit the mass where the time to accrete all but $1.2 M_\odot$ at 30% efficiency at the current mean luminosity equals the stellar evolution timescale for a star at that mass. For
these parameter values, the maximum initial mass of GRS 1915+105’s companion is about 3.6 $M_\odot$. The system has then lived at most $1.5(M/14M_\odot)^{13/16}a^{11/16}$ alignment timescales, under the assumptions that all the matter accreted makes it into the hole, that mass loss by the companion star is unimportant, and that the system has been in outburst for its entire lifetime. The third assumption here is known to be false and makes the estimate an upper limit. If we require three alignment timescales for full alignment, then the system may be aligned only for $a < 0.36(M/14M_\odot)^{-13/11}$, bearing in mind that this is a conservative estimate since we know that the luminosity of the system was much lower before its discovery in 1992 than it has been during the RXTE era. We plot in Figure 2 three curves - two showing the loci of points allowed by the 1:2 and 1:3 resonance models for the QPOs and the third showing the loci of points where the black hole has had time to align its spin with that of the binary plane. From inspection of the curves, one can see that the strong upper bound on the mass of GRS 1915+105 comes from the QPO frequencies, and not from the measurement of the orbital parameters, as the alignment timescale is substantially longer than the expected lifetime of the system. The inclination angle of the orbital plane of GRS 1915+105 cannot be more than $\sim 25$ degrees offset from the jet angle if the resonance model of the quasi-periodic oscillations is correct. Thus while the mass of GRS 1915+105 itself cannot be too seriously in error due to disc-jet misalignment, this system should serve as a cautionary tale when future mass measurements are made assuming that the disc and jet are aligned.

We also note that misalignment of disc and jet in GRS 1915+105 has already been speculated on the basis of the enhanced Fe and Si abundances in the system’s absorption column (Lee et al. 2002). In their scenario, polar ejecta (which are richer in heavy elements than the non-polar ejecta) from a supernova/hypernova that produced the black hole in GRS 1915+105 may have contaminated the atmosphere of the companion star. While we find that a jet inclined in the binary plane of the system is inconsistent with the allowed parameter space (due to the maximum black hole mass allowed by the QPO measurements), the fact that the companion star occupies a rather small fraction of the binary plane (as its radius is only about 1/10 of the binary separation) and that the orbital period is longer than the ejection phase implies that a rather large opening angle for the polar ejection would be required for this scenario to work anyways. Furthermore, if the misalignment of the jet is in the position angle, rather than in the inclination angle, the jet could still be parallel to the plane of the binary orbit. At present there are no constraints on the position angles of
Figure 2. The spin-mass curves for GRS 1915+105. The solid curve represents the locus of points which provide a 162 Hz epicyclic frequency in resonance with a 324 Hz orbital frequency. The dotted line provides a 162 Hz epicyclic frequency in resonance with a 486 Hz orbital frequency. The dashed line shows where the timescale for alignment of the black hole’s spin equals its maximum age as calculated in the text. Above the line, the inclination angle of the system can deviate substantially from the jet inclination angle, and the mass measurement based on the orbital parameters may be substantially in error.

5 APPLICATION TO CYG X-3

Cygneus X-3 is a persistent emitter in the X-rays and in the radio, with flaring episodes where it is one of the brightest sources in the sky in both those wavebands. It has been recently found to have a one-sided radio jet with an inclination angle of about 14 degrees (Mioduszewski et al. 2001). That only one side of the jet is seen suggests that the velocity of the jet is at least 0.8c. Like GRS 1915+105, its optical and infrared properties are rather poorly constrained because of the high column density to the source and because of the contaminating emission from the accretion flow. Cyg X-3 is known to be a high mass X-ray binary accreting from the stellar wind of a Wolf-Rayet star of somewhere between 5 and 20 solar masses. A 4.8 hour period has been seen in both the infrared and X-ray emission and is assumed to be the orbital period. The physically simplest and statistically best fitting model...
for the orbital parameters - that of a constant strength wind and an elliptical orbit, requires an inclination angle of $51 \pm 2$ degrees (Ghosh et al. 1981). In this case, there is at least a 37 degree angle between the jet and the direction perpendicular to the binary plane. Hanson et al. (2000) also find that the system is unlikely to be at an inclination angle as low as the 14 degrees of the radio jet. Attempts to measure the orbital plane through polarimetry have been unsuccessful, probably because the jet emission contaminates the infrared light curve (Jones et al., 1994). Using the 51 degree inclination angle, the estimated mass of the compact object is 17 solar masses (Schmutz et al. 1996), and in fact, if the inclination angle of the binary system is 14 degrees, the mass of the compact object would be about $50 \, M_\odot$. Given a typical luminosity of approximately 5% of Eddington (as estimated from the RXTE All Sky Monitor public data) and a stellar lifetime for the presumed 20 solar mass progenitor of the Wolf-Rayet companion star, we estimate that the initial spin of the black hole would have to have been only about $a = 5 \times 10^{-4}$ in order not to have been aligned. Even given the much smaller mass estimate of Hanson et al. (2000), which states that the system may contain a much less massive black hole, $a$ must be less than about $10^{-3}$ for the black hole’s spin to have aligned with that of the binary plane.

The compact star in Cyg X-3 may be a neutron star (Hanson et al. 2000). Since the angular momentum of a maximally rotating neutron star is about the same as that for a maximally rotating black hole of $1.4 \, M_\odot$, we use the same formula as for the black hole case to estimate that the alignment timescale will be about $10^7$ years, which is substantially longer than the estimated $10^6$ year lifetime of the companion star. Thus there is no strong constraint on the inclination angle of the binary plane from the jet inclination angle, and a neutron star primary, which would require $i > 60$ degrees, is still permitted by the data. The only way to force alignment is if the characteristic spin-down timescale for the neutron star is sufficiently fast that its initial angular momentum when accretion begins is substantially smaller than that of a maximally rotating neutron star. The spin-down timescale is $10^6$ years for a magnetic field of $4 \times 10^{12}$ Gauss, after which the pulsar period is of order 1 second. This is also roughly the equilibrium period for a $4 \times 10^{12}$ Gauss neutron star accreting near the Eddington limit (e.g. Bhattacharya 1995). Thus a only a very high magnetic field neutron star can be ruled out, as its inner disc would be aligned with the neutron star’s spin axis. High magnetic field neutron stars accreting in high mass X-ray binaries are generally observed to be accretion powered pulsars, and coherent pulsations have not been seen in Cyg X-3, so this system is unlikely to contain such an object.
6 CONCLUSIONS

We have shown that the timescale for the black hole spin to align with the accretion disc’s angular momentum in binary systems is often longer than the lifetime of the binary system. The Bardeen-Petterson effect should then be important in these systems if the black holes were formed with substantial angular momentum. This represents a fundamental difference between black holes in binary systems and the black holes in active galactic nuclei which should align in a relatively short fraction of their lifetimes (as shown by NP). Strong evidence of this effect is seen from GRO J 1655-40 and SAX J1819-2525.

That the timescale for spin alignment in GRO J 1655-40 is so close to the main sequence lifetime of the companion star hints at a possible explanation for the difference between radio galaxies (which are unaligned) and Seyfert galaxies (which are often aligned). The strong jets in the radio galaxies may carry away a substantial amount of angular momentum, keeping the matter and its angular momentum from reaching the black hole and making the spin changing estimate of NP98 a severe underestimate. The Seyfert galaxies have a much lower fraction of their total power taken away by the radio jets, so this effect will not be as severe for them. Secondly, if the Blandford-Znajek mechanism is responsible for powering the radio jets, it is likely that the dimensionless spin parameter values of the black holes in radio galaxies are higher than those in the Seyfert galaxies, giving another reason why the timescales for the radio galaxies’ black holes to change their spins might be longer.

The dynamical mass estimate for GRS 1915+105 depends upon the inclination angle of the system being such that the disc is perpendicular to the jets. We have shown that for high mass, high spin black hole primaries in GRS 1915+105, the alignment timescale of the black hole’s spin with that of the accretion flow can be longer than the characteristic age of the system. On the other hand, the orbital/epicyclic resonance model for the quasi-periodic oscillations recently discovered in this system suggest that the black hole mass cannot be too far outside the error bars from the dynamical measurement. As a result, the inclination angle separation between the disc and the jet is likely to be less than about 25 degrees. Thus the system must have either been formed with a small offset between disc and jet angle, or the offset between the two angles is largely in the plane of the sky rather than in the inclination angle. Future planned X-ray interferometry missions such as MAXIM may have the potential for measuring the position angles of systems such as GRS 1915+105 by imaging the plane of the “hot spot” where accretion stream hits the accretion disc.
We discuss suggestive evidence that the disc and jet are unaligned in Cygnus X-3, and show that this is a result to be expected in wind-fed accreting black holes even with very small initial angular momenta. A neutron star origin is also consistent with the binary orbital data, since even a rapidly rotating neutron star would have too much angular momentum to be aligned in the lifetime of the donor star. It is likely that the system will need to be observed in quiescence before polarization measurements can tell us its true orbital inclination angle. Future observations of inclination angles in microquasars should help determine whether the results for these four systems are common.

7 ACKNOWLEDGEMENTS

I wish to thank Priya Natarajan and Annalisa Celotti for useful discussions and for critical reviews of this manuscript. I also wish to thank Arun Thampan and Wlodk Kluźniak for interesting discussions regarding high frequency QPOs from accreting black holes. I wish to thank Julia Lee for discussions regarding the abundance anomalies in GRS 1915+105. Finally, I thank the anonymous referee for useful suggestions.

REFERENCES

Abramowicz, M.A., & Kluźniak, W., 2001, A&A, 374, 19L
Alexander, P. & Leahy, J.P., 1987, MNRAS, 225, 1
Bailyn, C.D. & Grindlay, J.E., 1990, ApJ, 353, 159
Bardeen, J.M. & Petterson, J.A., 1975, ApJ, 195, L65
Bhattacharyya, D., 1995, in X-Ray Binaries, Lewin, van Paradijs, & van den Heuvel editors, Cambridge University Press : Cambridge
Blandford, R.D. & Begelman, M.C., 1999, MNRAS, 303, L1
Blandford, R.D. & Znajek, R.L., 1977, MNRAS, 179, 433
Chen, W., Shrader, C., & Livio, M., 1997, ApJ, 491, 312
Collin-Souffrin, S. & Dumont, A.M., 1990, A&A, 229, 292
di Matteo, T., Fabian, A.C., Rees, M.J., Carilli, C.L., & Ivison, R.J., 1999, MNRAS, 305, 492
Fabian, A.C., Eggleton, P.P., Hut, P., & Pringle, J.E., 1986, ApJ, 305, 333
Fragile, P.C., Mathews, G.J., Wilson, J.R., 2001, ApJ, 553, 955
Gammie, C.F., Goodman, J., Ogilvie, G.I., 2000, MNRAS, 318, 1005
Ghosh, P., Elsner, R.F., Weisskopf, M.C. & Sutherland, P.G., 1981, ApJ, 251, 230
Greene, J., Bailyn, C.D. & Orosz, J.A., 2001, ApJ, 554, 1290
Greiner, J., Cuby, J. G. & McLaughren, M. J., 2001, Nature, 414, 522
Hanson, M.M., Still, M.D., & Fender, R.P., 2000, ApJ, 541, 308
Hjellming, R.M. & Rupen, M.P., 1995, Nature, 375, 464
Hjellming, R.M., et al., 2001, ApJ, 544, 977
Hjellming, R.M. & Johnston, K.J., 1981, ApJL, 246, L141
On the Misalignment of Jets in Microquasars

Israelian, G., Rebolo, R., Basri, G., Caseres, J. & Martin, E.L., 1999, Nature, 401, 142
Jones, T.J., Gehrz, R.D., Kobulnicky, H.A., Molnar, L. & Howard, E.M., 1994, AJ, 108, 605
Kinney, A. L., Schmitt, H. R., Clarke, C. J., Pringle, J. E., Ulvestad, J. S. & Antonucci, R. R. J., 2000, ApJ, 537, 152
King, A.R. & Kolb, U., 1999, MNRAS, 305, 654
Kippenhahn, R. & Weigert, A., Stellar Structure and Evolution, Springer-Verlag, New York
Klein-Wolt, M., Fender, R. P., Pooley, G. G., Belloni, T., Migliari, S., Morgan, E. H., & van der Klis, M., 2001, ApSSS, 276, 291
Lee, J.C., Reynolds, C.S., Remillard, R., Schulz, N.S. & Blackman, E.G. & Fabian, A.C., 2002, ApJ, 567, 1102
Liu, R., Pooley, G. & Riley, J.M., 1992, MNRAS, 257, 545
Meyer, F., Liu, B.F., & Meyer-Hofmeister, E. 2001, A&A, 354, 67L
Mioduszewski, A.J., Rupen, M.P., Hjellming, R.M., Pooley, G.G. & Waltman, E.B., 2001, ApJ, 553, 766
Mirabel, I.F., & Rodriguez, L.F., 1994, Nature, 371, 46
Muno, M.P., Remillard, R.A. & Morgan, E.M., 1999, ApJ, 527, 321
Narayan, R. & Yi, I., 1995, ApJ, 444, 231
Natarajan, P. & Pringle, J.E., 1998, ApJL, 506, L97
Nelson, R.P. & Papaloizou, J.C.B., 2000, MNRAS, 315, 570
Nowak, M.A., Wagoner, R.V., Begelman, M.C., & Lehr, D.E., 1997, ApJL,477, 91L
Ogilvie, G.I., 1999, MNRAS, 304, 557
Orosz, J.A., et al., 2001, ApJ, 555, 489
Papaloizou, J.C.B., & Pringle, J.E., 1983, MNRAS, 202, 1181
Podsiadlowski, P., 1991, Nature, 350, 136
Quataert, E. & Narayan, R., 1999, ApJ, 520, 298
Rees, M.J., 1978., Nature, 275, 516
Remillard, R.A., Muno, M.P., McClintock, J.E. & Orosz, J.A., 2002, submitted to ApJ [astro-ph/0202032]
Schmitt, H.R., Pringle, J.E., Clarke, C.J. & Kinney, A.L., 2002, ApJ, in press [astro-ph/0204247]
Schmutz, W., Geballe, T.R., & Schindl, H., 1996, A&A, 311, L25
Shakura, N. I. & Sunyaev, R. A. 1973, A&A,24,337
Stella, L. & Vietri, M., 1998, ApJL, 492, 59
Strohmayer, T., 2001, ApJL, 552, 49L
Strohmayer, T., 2001, ApJL, 554, 169L
Tavani, M., 1991, ApJL, 366, L27
Torkelsson, U., Ogilvie, G.I., Brandenburg, A., Pringle, J.E., Nordlund, A. & Stein, R.F., 2000, MNRAS, 318, 47
van den Heuval, E.P.J. & van Paradijs, J.A., 1988, Nature, 334, 227
van Dokkum, P.G. & Franx, M., 1995, AJ, 110, 2027
Verbunt, F. & van den Heuvel, E.P.J., 1995, in X-Ray Binaries, Lewin, van Paradijs,& van den Heuvel editors, Cambridge University Press : Cambridge
Wagoner, R.V., Silbergleit, A.S., & Ortega-Rodriguez, M., 2001, ApJL,559, 25
Wijnands, R. & van der Klis, M., 2000, ApJL, 528, L93