Black holes in stellar-mass binary systems

expiating original spin?

King, A.; Nixon, C.

Link to publication

Black holes in stellar-mass binary systems: expiating original spin?

Andrew King[1,2,3]★ and Chris Nixon[1]★

[1]*Theoretical Astrophysics Group, Department of Physics and Astronomy, University of Leicester, Leicester LE1 7RH, UK*

[2]*Astronomical Institute Anton Pannekoek, University of Amsterdam, Science Park 904, NL-1098 XH Amsterdam, Netherlands*

[3]*Leiden Observatory, Leiden University, Niels Bohrweg 2, NL-2333 CA Leiden, Netherlands*

ABSTRACT

We investigate systematically whether accreting black hole systems are likely to reach global alignment of the black hole spin and its accretion disc with the binary plane. In low-mass X-ray binaries (LMXBs), there is only a modest tendency to reach such global alignment, and it is difficult to achieve fully: except for special initial conditions, we expect misalignment of the spin and orbital planes by ~1 rad for most of the LMXB lifetime. The same is expected in high-mass X-ray binaries. A fairly close approach to global alignment is likely in most stellar-mass ultraluminous X-ray binary systems (ULXs) where the companion star fills its Roche lobe and transfers mass on a thermal or nuclear time-scale to a black hole of lower mass. These systems are unlikely to show orbital eclipses, as their emission cones are close to the hole's spin axis. This offers a potential observational test, as models for ULXs invoking intermediate-mass black holes do predict eclipses for ensembles of $\gtrsim 10$ systems. Recent observational work shows that eclipses are either absent or extremely rare in ULXs, supporting the picture that most ULXs are stellar-mass binaries with companion stars more massive than the accretor.

Key words: accretion, accretion discs – black hole physics – binaries: close – X-rays: binaries.

1 INTRODUCTION

Accreting black holes frequently have their spins at least initially misaligned from the angular momentum of the mass reservoir feeding them. This is generic for supermassive black holes (SMBH) (cf. King & Pringle 2006) and is possible in stellar-mass binary systems, particularly if they have undergone a supernova explosion. But any misalignment must evolve as accretion begins. The differential Lense–Thirring precession of disc orbits produces viscous torques on the accretion disc which try to make everything axisymmetric. In stellar-mass binaries, the flux of mass from the companion with angular momentum parallel to the binary axis usually overwhelms these torques in the outer disc, which stays in the binary plane as a result. But close to the black hole, the Lense–Thirring effect generally wins, and the inner disc plane rapidly co- or counter- aligns with the spin plane on the local precession time (Scheuer & Feiler 1996; King et al. 2005). The transition between the outer disc, aligned with the binary orbit, and the inner disc, aligned with the hole spin, occurs either in a smooth warp (Bardeen & Petterson 1975) or (for larger misalignments) an abrupt break (Nixon & King 2012; Nixon et al. 2012; King & Nixon 2013).

We call this configuration – hole spin and inner disc aligned, but both misaligned from the binary orbit – *central alignment*. We expect this kind of alignment for most discs around compact objects because the Lense–Thirring effect establishes it very quickly in the inner disc after accretion on to the black hole

begins, or resumes. This is also likely for SMBH in active galactic nuclei (King & Pringle 2006, 2007). But if accretion from a binary companion continues for an extended time, the system may also tend towards a state of *global alignment*, where spin, disc and orbital rotation are all parallel or (possibly for the spin) antiparallel.

The relative orientation of the hole's spin and the binary axis has a significant effect on the observable properties of accreting stellar-mass black hole binary systems, so the question of how close a system is to global alignment is important. Studies of it so far either consider individual systems (Martin, Tout & Pringle 2008; Maccarone 2002, 2015) or the effect on one method of trying to measure black hole spin (Steiner & McClintock 2012), which assumes that candidate systems are close to global alignment. Our aim here is to give a systematic picture of whether various types of accreting binaries approach global alignment, including whether this is expected in various models of ultraluminous X-ray sources (ULXs).

2 TORQUES

To check whether a given black hole binary approaches global alignment, we assume that the system has already reached central alignment, i.e. of the spin and inner disc planes. We also assume that the inner disc is connected to the outer disc by a smooth warp – if the inclination is large enough to have caused disc breaking, there is little prospect of global alignment, as even central alignment can be disrupted by rapidly precessing disc rings (disc 'breaking' and 'tearing': Nixon & King 2012; Nixon et al. 2012).

★ E-mail: ark@le.ac.uk (AK); cjn@le.ac.uk (CN)

The torque between the disc and the black hole trying to bring about global alignment transfers to the hole a fraction $\beta \lesssim 1$ of the Kepler specific angular momentum $j_w = (GMR_w)^{1/2}$ at the characteristic warp radius

$$R_w \simeq (a\alpha)^{2/3} \left(\frac{2R}{H}\right)^{4/3} R_g, \tag{1}$$

(cf. Natarajan & Pringle 1998), so we write it as

$$\boldsymbol{G}_{\mathrm{align}} = \beta \dot{M} j_w \boldsymbol{e}_{\mathrm{orb}}, \tag{2}$$

where $\boldsymbol{e}_{\mathrm{orb}}$ is the unit vector parallel to the orbital rotation. Here $\dot{M}$ is the disc accretion rate (strictly, at the warp radius, but usually equal to the mass transfer rate from the companion star), a is the Kerr spin parameter, $\alpha \sim 0.1$ is the standard disc viscosity parameter, $H/R \sim 0.02$ is the local disc aspect ratio, and $R_g = GM/c^2$ is the hole's gravitational radius. From a geometric view, $\beta \sim \sin\theta$ (where θ is the angle between the spin and orbital axes) and we shall adopt this for simplicity, so that β decreases as alignment proceeds. Using (1), we find

$$j_w = (a\alpha)^{1/3} \left(\frac{2R}{H}\right)^{2/3} \frac{GM}{c}. \tag{3}$$

There is a second (spin-up) torque on the black hole as it gains mass from the innermost stable circular disc orbit (ISCO). This has magnitude

$$G_{\mathrm{spinup}} = \dot{M}_h j_{\mathrm{isco}}, \tag{4}$$

where $\dot{M}_h \leq \dot{M}$ is the accretion rate at the black hole (which cannot, for example, exceed the Eddington value) and $j_{\mathrm{isco}} \sim GM/c < j_w$ is the specific angular momentum at the ISCO. This acts to increase or decrease the black hole angular momentum

$$J_h = \frac{GM^2 a}{c} \tag{5}$$

accordingly as accretion is, respectively, prograde or retrograde.

3 GLOBAL ALIGNMENT

We can now check the evolution of the black hole spin vector towards global alignment after the companion star has transferred a mass M_{tr} through the accretion disc. The calculation below complements the derivation in King et al. (2005). That paper explains the geometry of the alignment process, but does not specify the time-scale for it to occur in a given system. In contrast, we give here an estimate of the time-scale, independently of the details of warped disc dynamics (see Nixon & King 2016).

After the transfer of a mass M_{tr}, the alignment torque (2) has added a component $M_{\mathrm{tr}}j_w$ parallel to the orbital rotation by interacting with the spin at the warp radius. We note that this torque is a combination of Lense–Thirring precession and viscous damping (King et al. 2005). Central alignment means that the spin-up torque (4) has simultaneously increased the magnitude of the black hole spin as

$$J_h = J_{h0} + M_{\mathrm{acc}} j_{\mathrm{isco}}, \tag{6}$$

where J_{h0} was the original value, and $M_{\mathrm{acc}} \leq M_{\mathrm{tr}}$ is the mass accreted by the black hole. (This may be smaller than M_{tr}, as the accretion rate may be super-Eddington, for example.) This spin-up does not change the original angle θ_0 of $\boldsymbol{J}_h$ to the orbital axis, but the align-ment torque $\boldsymbol{G}_{\mathrm{align}}$ does. So after the mass transfer, the angle θ_f of the spin vector to the orbital axis is given by

$$\tan\theta_f \simeq \frac{J_h \sin\theta_0}{J_h\cos\theta_0 + M_{\mathrm{tr}} j_w \sin\theta_0}. \tag{7}$$

It is straightforward to show (by induction, see Appendix A) that as mass is added iteratively and θ decreases this equation holds exactly for constant J_h, and to first order in the transferred mass if spin magnitude evolution is included. Equation (7) can be re-arranged to give

$$\frac{M_{\mathrm{tr}}}{M} \simeq \frac{0.1a^{2/3}}{(10\alpha)^{1/3}} \left(\frac{50H}{R}\right)^{2/3} [\cot\theta_f - \cot\theta_0]. \tag{8}$$

This shows that a modest approach to global alignment ($\theta_f \sim 1$ rad) requires the transfer of a mass

$$M_{\mathrm{tr}} \sim 0.1a^{2/3}M, \tag{9}$$

but a tighter approach ($\theta_f \sim 0.1$ rad) requires

$$M_{\mathrm{tr}} \sim a^{2/3}M. \tag{10}$$

We see that complete global alignment ($\theta_f = 0$) is impossible for any transferred mass unless $\theta_0 = 0$. The only realistic way of arranging this with $\theta_0 \neq 0$ is for the accretion torque (4) to spin the hole up from an initially retrograde value $J_{h0} < 0$ through zero.

We show the solutions of these equations for a variety of parameters in Fig. 1. These show the evolution of the misalignment as mass is accreted, transferring misaligned angular momentum to the hole, for (a) different initial spins and (b) different initial misalignment angles. For different initial black hole masses, the evolution is invariant for the same fraction of transferred mass M_{tr}/M_0. As predicted by (10), a mass of the order of 0.1 M is required to move the spin angle significantly. These basic results (6, 8) have straightforward consequences for the various types of black hole binaries.

3.1 Standard X-ray binaries

In low-mass X-ray binaries (LMXBs), the companion mass M_2 is small compared with M, so $M_{\mathrm{tr}} < M_2 \ll M$. The same result holds for wind-fed high-mass X-ray binaries (HMXBs), as the black hole accretes only a tiny fraction of the mass lost by the companion star (even though this may have a mass $>M$). So we have $M_{\mathrm{tr}} \lesssim \dot{M}_{\mathrm{Edd}} t_{\mathrm{HMXB}} \lesssim 0.1\,M_\odot$, where we have taken an Eddington rate $\dot{M}_{\mathrm{Edd}} \lesssim 10^{-7}\,M_\odot\,\mathrm{yr}^{-1}$ appropriate for a $10\,M_\odot$ black hole, and a generous HMXB lifetime of 10^6 yr. Then (6) shows that J_h remains effectively constant in both HMXBs and LMXBs. Equations (9 and 10) show that without rather contrived initial conditions, only a modest approach to global alignment (i.e. $\theta_f \sim 1$ rad) is possible in LMXBs, while HMXBs do not move significantly to global alignment at all. Observations of the slightly evolved LMXB GRO 1655-40 also agree with our conclusions, as these show that the spin axis – revealed by the direction of the jet in this system – is far from the binary axis (cf. Martin et al. 2008, and references therein). We note that this difficulty in reaching full alignment leaves these types of binaries susceptible to disc breaking and tearing, which may explain a variety of the observed properties of LMXBs, including state transitions and QPOs (Nixon & Salvesen 2014).

3.2 Ultraluminous X-ray sources

The HMXB systems considered above naturally evolve to the point where the companion star fills its Roche lobe. Because
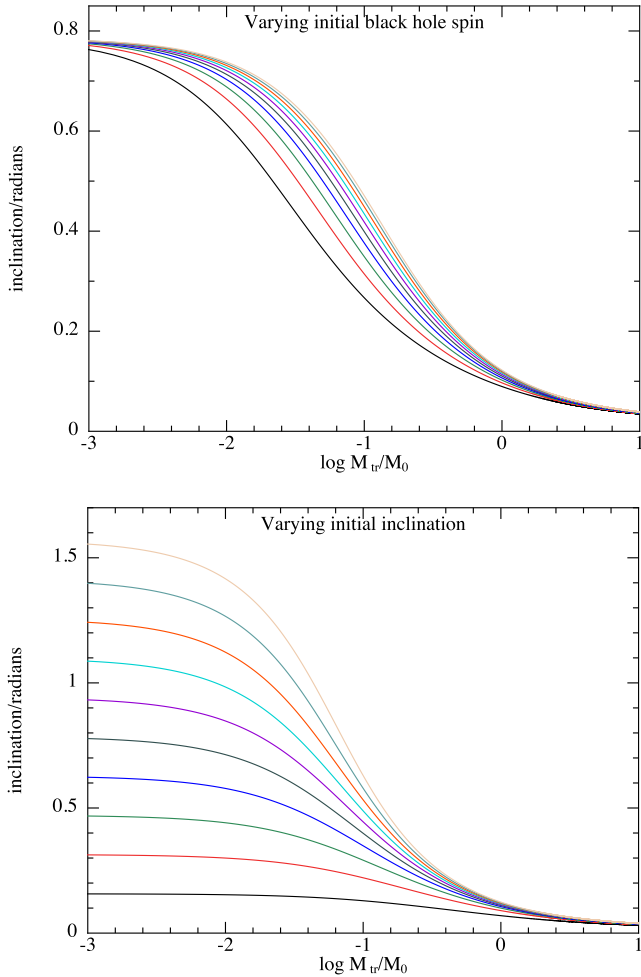
Figure 1. The two panels describe the evolution of the disc–BH inclination angle as mass is transferred following (7). The default parameters are an inclination of $\theta_0 = \pi/4$ and spin $a = 0.5$, and we have also assumed $\beta \sim \sin\theta$. The evolution of the inclination angle depends only on M_{tr}/M_0, rather than the specific value of M_0. Top panel: the curves correspond to varying the initial BH spin from 0.1 to 1 in steps of 0.1. Bottom panel: the curves correspond to varying the initial misalignment angle from $\pi/20$ to $\pi/2$ in steps of $\pi/20$. In each case the hole's spin does not move significantly until $\sim 0.1M$ ($0.5\,\mathrm{M_\odot}$ for $M_0 = 5\,\mathrm{M_\odot}$) has been transferred. Complete alignment requires a mass $\sim M_0$, as predicted.

the companion is generally more massive than the black hole, mass transfer shrinks the binary, and so ultimately proceeds on the thermal time-scale of the companion. (This also happens in the non-ULX microquasar GRO 1655–40 because the companion is expanding across the Hertzsprung gap – see Martin et al. 2008 for a discussion.) This gives very high mass transfer rates, which are strongly super-Eddington for the black hole (cf. King, Taam & Begelman 2000) and offers a natural model for ULXs (cf. King et al. 2001). Similar mass transfer rates occur in long-period binaries where the companion is less massive than the black hole, but massive enough for rapid nuclear evolution (Rappaport, Podsiadlowski & Pfahl 2005). In both cases, we expect $M_{tr} \sim M$. Then (8) shows that the black hole spin is likely to move significantly towards global alignment. The spin behaviour is less clear, as in both cases the Eddington limit may mean that the black hole accretes rather little mass and angular momentum during the relatively short (thermal or nuclear time-scale) ULX phase.

The movement towards global alignment is important, as the ULX property comes from tight geometric collimation of the accretion luminosity around the black hole spin axis (cf. King et al. 2001; Begelman, King & Pringle 2006; King 2009). Since the spin moves towards the binary axis, it is unlikely that any ULX of this type would show orbital eclipses.

The other class of models for ULXs invokes accretion on to an intermediate-mass black hole, with mass $M \gtrsim \text{few} \times 100\,\mathrm{M_\odot}$, large enough to make the luminosity of the ULX both isotropic and sub-Eddington (cf. Colbert & Mushotzky 1999). This probably requires rapid nuclear – time-scale mass transfer from a fairly massive evolved companion (similar to the picture by Rappaport et al. 2005, who considered stellar-mass black holes). For such systems, the binary mass ratios are ~ 0.01–0.1, implying companion Roche lobe radii R_2 which are fractions ~ 0.1–0.2 of the binary separation a, since $R_2/a \simeq 0.462(M_2/M)^{1/3}$.

A simple geometric argument now shows that an ensemble of more than about 10 such systems should have eclipses in at least one case. For binary inclination i, we need $\cos i < R_2/a$ for an eclipse. So the probability of no eclipse in a given case is $1 - R_2/a$, and for n such systems is $(1 - R_2/a)^n \simeq 1 - nR_2/a$. This no-eclipse probability becomes small for sample sizes

$$n \gtrsim \frac{a}{R_2} \gtrsim 2\left(\frac{M}{M_2}\right)^{1/3} \sim 10 - 20. \qquad (11)$$

4 CONCLUSIONS

We have investigated whether various accreting black hole systems are likely to reach global alignment of the black hole spin and its accretion disc with the binary plane. A fairly close approach to this state is likely in systems where the companion star fills its Roche lobe and transfers mass to a lower mass black hole. Such systems are promising candidates for ULXs, and are unlikely to show eclipses as their emission cones are close to the hole's spin axis. This offers a potential observational test, as models for ULXs invoking accretion from stellar-mass companions on to intermediate-mass black holes do predict eclipses for an ensemble of $\gtrsim 10$ systems. Middleton & King (2016) recently showed that eclipses are either absent or extremely rare in among all ULXs for which variability has been measured, in agreement with our result that stellar-mass ULXs should not eclipse because they are close to global alignment.

In standard low-mass X-ray binaries, there is a modest tendency to reach global alignment, so except for special initial conditions (such as initially retrograde black hole spin) we would expect a misalignment of the spin and orbital planes $\gtrsim 1$ rad. This agrees with the conclusions of Maccarone (2002, 2015), and weakens those of Steiner & McClintock (2012). It increases the systematic error in attempting to measure black hole spin by comparing the area of the event horizon with that expected from the measured black hole mass. Finally, in high-mass X-ray binary systems, neither spin-up nor global alignment is likely.

REFERENCES

Bardeen J. M., Petterson J. A., 1975, ApJ, 195, L65
Begelman M. C., King A. R., Pringle J. E., 2006, MNRAS, 370, 399
Colbert E. J. M., Mushotzky R. F., 1999, ApJ, 519, 89
King A. R., 2009, MNRAS, 393, L41
King A., Nixon C., 2013, Class. Quantum Gravity, 30, 244006
King A. R., Pringle J. E., 2006, MNRAS, 373, L90
King A. R., Pringle J. E., 2007, MNRAS, 377, L25
King A. R., Taam R. E., Begelman M. C., 2000, ApJ, 530, L25
King A. R., Davies M. B., Ward M. J., Fabbiano G., Elvis M., 2001, ApJ, 552, L109
King A. R., Lubow S. H., Ogilvie G. I., Pringle J. E., 2005, MNRAS, 363, 49
Maccarone T. J., 2002, MNRAS, 336, 1371
Maccarone T. J., 2015, MNRAS, 446, 3162
Martin R. G., Tout C. A., Pringle J. E., 2008, MNRAS, 387, 188
Middleton M., King A., 2016, preprint (arXiv:1606.07811)
Natarajan P., Pringle J. E., 1998, ApJ, 506, L97
Nixon C. J., King A. R., 2012, MNRAS, 421, 1201
Nixon C., King A., 2016, in Haardt F., Gorini V., Moschella U., Treves A., Colpi M., eds, Lecture Notes in Physics, Vol. 905, Astrophysical Black Holes. Springer-Verlag, Berlin, p. 45
Nixon C., Salvesen G., 2014, MNRAS, 437, 3994
Nixon C., King A., Price D., Frank J., 2012, ApJ, 757, L24
Price D. J., 2007, Publ. Astron. Soc. Aust., 24, 159
Rappaport S. A., Podsiadlowski P., Pfahl E., 2005, MNRAS, 356, 401
Scheuer P. A. G., Feiler R., 1996, MNRAS, 282, 291
Steiner J. F., McClintock J. E., 2012, ApJ, 745, 136

APPENDIX A

Equation (7) is exact if the spin magnitude evolution is neglected, and valid to first order in dM_{tr} if this effect is included. We can show this by induction. Thus

$$\tan\theta_1 = \frac{J_{h1}\sin\theta_0}{J_{h1}\cos\theta_0 + dm\, j_w \sin\theta_0} \,, \tag{A1}$$

where $J_{h1} = J_{h0} + dm\, j_{isco}$, and

$$\tan\theta_2 = \frac{J_{h2}\sin\theta_1}{J_{h2}\cos\theta_1 + dm\, j_w \sin\theta_1} \,, \tag{A2}$$

which both follow from (7). Now we substitute the equation for $\tan\theta_1$ re-arranged as

$$\cos\theta_1 = \frac{\sin\theta_1\,(J_{h1}\cos\theta_0 + dm\, j_w \sin\theta_0)}{J_{h1}\sin\theta_0} \tag{A3}$$

into the equation for $\tan\theta_2$ to get

$$\tan\theta_2 = \frac{J_{h2}\sin\theta_0}{J_{h2}\cos\theta_0 + 2dm\, j_w \sin\theta_0 + dm^2 \frac{j_{isco}}{J_{h1}} j_w \sin\theta_0} \,, \tag{A4}$$

which to first order in dm, or exactly if the spin magnitude evolution is ignored, is as if the equation were evaluated with $M_{tr} = 2dm$. Neglecting the spin magnitude evolution holds for $M_{tr}j_{isco} \ll J_{h0}$, which implies $M \gg f(a)M_{tr}/a$ (where $f(a)$, the angular momentum of the ISCO in units of GM/c, is of order unity). When this requirement is breached, the equation must be solved iteratively with the spin magnitude evolution included.

This paper has been typeset from a TeX/LaTeX file prepared by the author.