THE ALIGNMENT OF DISK AND BLACK HOLE SPINS IN ACTIVE GALACTIC NUCLEI

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ABSTRACT

The inner parts of an accretion disk around a spinning black hole are forced to align with the spin of the hole by the Bardeen-Petterson effect. Assuming that any jet produced by such a system is aligned with the angular momentum of either the hole or the inner disk, this can, in principle, provide a mechanism for producing steady jets in active galactic nuclei (AGNs) whose direction is independent of the angular momentum of the accreted material. However, the torque that aligns the inner disk with the hole, also by Newton’s third law, tends to align the spin of the hole with the outer accretion disk. In this Letter, we calculate this alignment timescale, \( t_{\text{align}} \), for a black hole powering an AGN, and we show that it is relatively short. This timescale is typically much less than the derived ages for jets in radio-loud AGNs and implies that the jet directions, in general, are not controlled by the spin of the black hole. We speculate that the jet directions are most likely controlled either by the angular momentum of the accreted material or by the gravitational potential of the host galaxy.

Subject headings: accretion, accretion disks — black hole physics — galaxies: active — galaxies: jets — galaxies: nuclei

1. INTRODUCTION

The classic double radio sources, the FR II galaxies (Faranoff & Riley 1974), are thought to be powered by narrow beams or jets of energy emanating from a nuclear black hole in the center of the host galaxy (Rees 1971, 1984; Longair, Ryle, & Scheuer 1973). In many, though not all, of these sources, the spatial direction of the jets has remained unchanged throughout the lifetime of the radio source. In the most luminous sources, the lengths of the jets reach up to scales of around 1 Mpc, and the source lifetimes are as long as around 10^8 yr (Alexander & Leahy 1987; Liu, Pooley, & Riley 1992). The degree of collimation of the beams, often on the order of 0.1 rad or less, implies that whatever physical mechanism gives rise to the beam stability is unchanged in the direction it defines on comparable timescales, which is at least 10^8 yr. In this Letter, we address the question of what might give rise to such stability.

This problem was considered by Rees (1978), who came to the conclusion that the most likely cause of the stability of the jet directions is the fact that it is determined by the spin of the nuclear black hole. Any accretion disk flow that might power the nuclear activity is aligned with the hole spin direction by the Bardeen-Petterson effect (Bardeen & Petterson 1975) out to a disk radius of \( R_{\text{BP}} \gg R_s \), where \( R_s \) is the Schwarzschild radius. Thus, if the jet is disk powered, it will be strictly aligned with the spin of the hole. Furthermore, this idea also fits into the current theoretical paradigm in which jets are powered directly by the spin energy of the hole (Blandford 1991 and references therein; Rawlings & Saunders 1991), although this paradigm is open to debate (see, for example, Livio, Ogilvie, & Pringle 1998). Rees (1978) pointed out, however, that the couple exerted by the black hole as it aligns the disk with the spin of the hole also has, by Newton’s third law, the effect of aligning the hole with the spin of the disk. He estimated the timescale for this alignment to occur by assuming that each accreted mass element brings with it to the hole the angular momentum corresponding to its orbital angular momentum at the Bardeen-Petterson radius \( R_{\text{BP}} \). He suggested that this alignment timescale is given by

\[
\tau_a \sim \frac{M J}{M J_{\text{acc max}}} \left( \frac{R_s}{R_{\text{BP}}} \right)^{1/2},
\]

where \( M/M \) is the accretion timescale, \( t_{\text{acc}} \), and \( J/J_{\text{acc max}} \) is the ratio of the angular momentum of the black hole to the maximal angular momentum of a Kerr black hole. Rees (1978) estimated \( t_a \) to be on the order of 10^8 yr.

However, in recent years, there has been considerable theoretical progress in our understanding of how a warped (or nonplanar) accretion disk communicates the warp and evolves in time. This physical process has a direct bearing on the black hole/accretion disk alignment timescale. We show below that, by using current theories, the alignment timescale is considerably shorter than the ages of the radio sources inferred from spectral aging models fitted to the observations, and consequently it is also less than the timescale on which the jet direction changes.

2. ALIGNMENT PROCESS

The timescale for disk/hole alignment depends directly on the timescale on which an accretion disk can transfer a warp in the radial direction. In an accretion disk, the component of angular momentum parallel to the spin of the disk is transferred at radius \( R \) in the disk in a diffusive manner on a timescale \( t_\nu \sim R^2/\nu_r \), where \( \nu_r \) is the usual disk kinematic viscosity (Pringle 1981; Frank, King, & Raine 1992). Using the dimensionless viscosity parameter \( \alpha \) (Shakura & Sunyaev 1973), this timescale can be written approximately as

\[
t_\nu = \Omega^{-1} \left( \frac{R_s}{H} \right)^2 \alpha^{-1},
\]

where \( H \) is the local disk semithickness and \( \Omega \) is the local angular velocity. It was originally assumed (Bardeen & Petterson 1975; Rees 1978) that the component of the disk
angular momentum lying in the plane of the disk (i.e., the warp) is transferred radially on a similar timescale. However, it was discovered by Papaloizou & Pringle (1983) that consideration of the propagation of disk warp must necessarily take into account the internal hydrodynamics of the disk itself. In the regime in which $H/R < \alpha \ll 1$, and in which the disk is close to being Keplerian, they found (see also Kumar & Pringle 1985) that the disk behavior is somewhat complicated but that, to a first approximation, the component of angular momentum in the disk plane is transferred within the disk on a timescale of order $R^2/v_\phi$, where $v_\phi/v_r = 1/2\alpha^2$ (assuming that $\alpha \ll 1$). Thus, the relevant timescale for communication of the disk warp is

$$t_{\text{warp}} \sim \alpha^2 t_R \ll t_R.$$  

(2.2)

The original calculations by Papaloizou & Pringle (1983) were carried out using the Eulerian linear perturbation theory about an initially flat disk, and so they were formally valid only for disk warp angles, $\beta$, much less than for the disk opening angle $H/R$. For disks in active galactic nuclei (AGNs) for which $H/R \sim 10^{-5} \sim 10^{-3}$ (see below), this is somewhat limiting. Recent work by Ogilvie (1998a, 1998b), however, has shown that similar conclusions remain valid for radii of significant amplitude. These results have a considerable effect on the so-called Bardeen-Petterson radius, $R_{\text{BP}}$, the radius out to which the disk is aligned with the spin of the hole, as well as on the hole/disk alignment timescale. Since the disk turns out to be far more efficient at transferring warp in the radial direction than the initial estimates, which ignored the internal disk hydrodynamics, it follows that both $R_{\text{BP}}$ (Kumar & Pringle 1985) and the alignment timescale are much smaller than was originally thought.

2.1. Alignment Radius

The timescale, on which a misaligned black hole aligns with its disk, and the radius, out to which the alignment occurs, have been calculated by Scheuer & Feiler (1996). Writing the Lense-Thirring precession rate in the disk as $\Omega_{\text{LT}} = \omega_J/R^3$, they find that the radius out to which the disk is aligned with the spin of the hole is given simply by the radius at which the timescale for radial diffusion of the warp, $t_{\text{warp}}$, is on the order of the local Lense-Thirring precession timescale $\Omega_{\text{LT}}^{-1}$. Equating these, we obtain

$$R_{\text{warp}} \sim \omega_J/v_\phi,$$  

(2.3)

where $\omega_J = 2GJ/c^2$; the angular momentum of the hole, $J$, is given by $J = aMc(GM/c^2)$, where $M$ is the mass of the hole and $a$ ($0 < a < 1$) is the dimensionless spin parameter. Using these expressions, together with the fact that $v_\phi/v_r = 1/2\alpha^2$, and writing $v_\phi = \alpha H^2 \Omega$, we find that $R_{\text{warp}}$ may be written as

$$R_{\text{warp}} = 2\alpha^2 c \left(\frac{R}{c}\right)^2 \Omega_{\text{LT}}^{-1} \left(\frac{R}{H}\right),$$  

(2.4)

where $R_e = 2GM/c^2$ is the Schwarzschild radius. Taking account of the fact that far from the hole,

$$\frac{\Omega}{c} = \frac{1}{\sqrt{2}} \left(\frac{R_e}{R}\right)^{1/2},$$  

(2.5)

we find that

$$\frac{R_{\text{warp}}}{R_e} = 2^{1/3} (\alpha \epsilon)^{2/3} \left(\frac{R}{H}\right)^{4/3}.$$  

(2.6)

To proceed further, we need a model for the AGN disk at the relevant radii. We make use of the AGN disk models computed by Collin-Souffrin & Dumont (1990) from which, in the relevant range of radii, we find that

$$\frac{H}{R} = 7.1 \times 10^{-3} \left(\frac{\alpha}{0.03}\right)^{-1/10} \left(\frac{L}{0.1L_\odot}\right)^{1/5} \epsilon^{-1/5} \left(\frac{R}{R_g}\right)^{2/3}.$$  

(2.7)

Here $\epsilon$ is the efficiency of the accretion process defined as $\epsilon = L/M c^2$, and $L_\odot$ is the Eddington luminosity, $L_\odot = 1.4 \times 10^{44} M_\odot$ ergs s$^{-1}$, where $M_\odot$ is the black hole mass in units of $10^8 M_\odot$. Throughout this Letter, we shall take $\alpha = 0.03$ and $L = 0.1L_\odot$ to represent the typically expected standard values.

Using this, we find that

$$\frac{R_{\text{warp}}}{R_e} = 66 \alpha^{3/8} \left(\frac{\alpha}{0.03}\right)^{3/4} \left(\frac{L}{0.1L_\odot}\right)^{-1/4} \epsilon^{-1/8} M_\odot^{1/2}.$$  

(2.8)

This expression is valid provided that

$$\frac{L}{L_\odot} \geq 2.0 \times 10^{-2} \alpha^{9/10} \left(\frac{\alpha}{0.03}\right)^{7/5} \epsilon^{-7/5} M_\odot^{1/2}.$$  

(2.9)

We note that although Scheuer & Feiler (1996) used a simplified set of evolution equations (Pringle 1992) that take into account the difference between $v_\phi$ and $v_r$ but that do not take the full effects of internal disk hydrodynamics into account, their estimates of the alignment radius are in substantial agreement with the full calculations of Kumar & Pringle (1985) for values of $\alpha \sim 0.3$.

2.2. Alignment Timescale

Scheuer & Feiler (1996) find that the effect of the disk on the black hole is to force the spin axis of the hole to precess and to align with the disk. Both precession and alignment take place on the same timescale, which is given by

$$t_{\text{align}} \sim \left(\frac{J}{J_e}\right) \Omega_{\text{LT}}^{-1},$$  

(2.10)

where $J_e$ is the angular momentum of the disk within the warp radius $R_{\text{warp}}$, and $\Omega_{\text{LT}}$ is the Lense-Thirring angular velocity also evaluated at $R_{\text{warp}}$. It should be noted that the transfer of angular momentum between the hole and the disk does not depend in any way on the disk being an accretion disk (i.e., it is independent of $M$). Therefore, the above formula is valid provided that the disk is able to transfer warp, which it may
do purely by diffusion if \( \alpha > H/R \), or by warp waves (Lubow & Pringle 1993; Papaloizou & Lin 1995; Nelson & Papaloizou 1998) if \( \alpha < H/R \), and provided that the disk can act as an adequate sink of angular momentum. In the viscous case (\( \alpha > H/R \)) relevant to AGN disks, this timescale may be rewritten (Scheuer & Feller 1996) as

\[
\tau_{\text{align}} \sim \left( \frac{a \Sigma M}{2 G p_\Sigma} \right)^{1/2} \frac{1}{\pi \Sigma},
\]

(2.11)

where \( \Sigma \) is the surface density of the disk at the warp radius \( R_{\text{warp}} \). For a steady accretion disk far from the center, it can be shown that (Pringle 1981)

\[
\Sigma = \frac{M}{3 \pi \nu_1}.
\]

(2.12)

Thus, for a steadily accreting disk, we may write

\[
\frac{\tau_{\text{align}}}{\tau_{\text{acc}}} = 1.9 \times 10^{-2} \alpha^{1/2} \left( \frac{H}{H} \right)^{1/4} \left( \frac{R_{\text{warp}}}{R_s} \right)^{1/4} \left( \frac{L}{L_\nu} \right)^{3/8} \left( \frac{\epsilon}{0.03} \right)^{-1/8} \left( \frac{1}{0.03} \right)^{3/8} \left( \frac{1}{0.3} \right)^{1/8} \left( \frac{1}{0.1 L_\nu} \right)^{-1/8},
\]

(2.13)

where the accretion timescale \( \tau_{\text{acc}} \) is defined as \( \tau_{\text{acc}} = M/\dot{M} \).

Alternatively, for a steady disk, the accretion timescale can be written in terms of the Salpeter time \( t_s \), which is the growth timescale for the black hole if it is accreting at a rate corresponding to the limiting Eddington luminosity \( L_{\text{E}} \). Thus,

\[
\tau_{\text{acc}} = t_s \left( \frac{L}{L_{\text{E}}} \right)^{-1},
\]

(2.14)

where \( t_s = 1.2 \times 10^4 (\epsilon/0.3) \) yr.

Making use of equations (2.7), (2.8), (2.13), and (2.14), we find that

\[
\frac{\tau_{\text{align}}}{t_s} = 4.7 \times 10^{-3} \alpha^{1/16} \left( \frac{\epsilon}{0.03} \right)^{13/8} \left( \frac{L}{0.1 L_\nu} \right)^{-7/8} \left( \frac{M}{M_8} \right)^{-1/16} \left( \frac{\epsilon}{0.3} \right)^{-1/8} \left( \frac{L}{0.1 L_\nu} \right)^{-7/8} \text{yr},
\]

(2.15)

or, equivalently,

\[
\tau_{\text{align}} = 5.6 \times 10^5 \alpha^{1/16} \left( \frac{\epsilon}{0.03} \right)^{13/8} \left( \frac{L}{0.1 L_\nu} \right)^{-7/8} \left( \frac{M}{M_8} \right)^{-1/16} \left( \frac{\epsilon}{0.3} \right)^{7/8} \text{yr}.
\]

(2.16)

3. DISCUSSION

We have shown that our current understanding of the time evolution of warps in accretion disks leads to the conclusion that a disk that is misaligned with the spin of a central black hole, and whose inner regions are therefore aligned with the spin of the hole by the Bardeen-Petterson effect, brings the spin vector of the hole into alignment with the spin vector of the outer disk on a timescale that is much shorter than had previously been realized. Thus, the idea that the maintenance of the jet directions in extended double radio sources, for timescales up to an order of \( 10^9 \) yr, is due to the “flywheel” effect of the central spinning black hole is no longer a tenable one. In any case, this should not be too surprising since, for some kind of flywheel mechanism to work, one would normally select as the flywheel an object with as large a moment of inertia as possible. Taking cognizance of this, the idea that the smallest object in the system might be the flywheel seems, in retrospect, counterintuitive. Thus, a more likely identification of the flywheel might be the accretion disk itself. For example, the radius at which black hole and disk angular momenta are equal for the Collin-Souffrin & Dumont (1990) AGN models is

\[
R \sim 1.4 \times 10^4 a M_\nu^{-1} \left( \frac{\alpha}{0.03} \right) \left( \frac{\epsilon}{0.3} \right) \left( \frac{L}{0.1 L_\nu} \right)^{-1}.
\]

(3.1)

In this picture, the constancy of the directionality of the jets is due to the fact that the accretion event was of a single gas-rich object. Alternatively, one might consider using the host galaxy as the flywheel, if the galactic potential is such that any accreted gas would soon start to orbit in some preferred plane.

We should note that although the overall conclusions are unlikely to change, the details of the alignment timescales and disk warp structure will depend on the specific accretion disk model applicable in any given case. For illustration, in this Letter, we have used the models by Collin-Souffrin & Dumont (1990). However, it should be borne in mind that even these models need some amendment in order to take account of the asymmetric heating of the disk, because it is twisted, and to take account of the additional internal heating due to the enhanced \( \nu_s \) type of dissipation brought on by the twist. In addition, it may be that the accretion disk structure is quite different from the standard thin-disk structure envisioned by Collin-Souffrin & Dumont (1990). For example, if the flow onto the hole is in the form of an advection-dominated flow, for which \( \alpha \sim H/R \sim 1 \) (Narayan & Yi 1995), then from equation (2.4) we see that we expect \( R_{\text{warp}}/R_s \sim 1 \), together with a consequently reduced alignment timescale. All these issues will need to be addressed in further work.

From an observational point of view, if the jet direction is controlled solely by the black hole spin, then, because the Bardeen-Petterson radius is typically at radii too small to be observed directly, we would not necessarily expect to observe a correlation between the angular momentum vector of gas in the host galaxy and the directions of the jets. In this context, we note that in a survey of nearby radio-loud, early-type galaxies with the Hubble Space Telescope, van Dokkum & Franx (1995) find that the major axes of the dust disks seen in the inner regions (\( \leq 250 \) pc) are aligned perpendicular to the arc-second radio structures in the nuclei. This might be taken as prima facie evidence that the direction of the radio jets in these objects is determined by the galactic potential and/or by the orbital angular momentum of the gas-rich intruder, which presumably produced both the dust disks and the nuclear activity. We also note that for this to occur, and indeed for jets to be able to display long-term directional stability, the radiation-driven (perhaps wind-enhanced) warping mechanism discussed by Pringle (1996, 1997) must be unable to operate in these systems. This can occur either because the mechanism is not powerful enough to operate in galactic nuclei (it seems likely that the effect may well need wind enhancement in this case since it is severely reduced for values of \( \nu_s/\nu_s \gg 1 \)) or because the warping is stabilized by Lense-Thirring precession that is driven by a sufficiently rapidly spinning central black hole.
(Pringle 1997; P. Maloney 1998, private communication). We note that the argument here differs somewhat from that of Wilson & Colbert (1995), who assume that a rapidly spinning black hole is necessary to produce mechanical jet energy. The present line of reasoning would suggest that while we already know from the protostellar case that the presence of a black hole (spinning or not) is not necessary for the production of a jet (see, for example, Pringle 1991), it is the spin of the hole that is required to suppress the warping instability (which only operates effectively in disks around compact objects) and so produce a jet with some directional stability.

In contrast to this, however, is the indication that in the nuclei of Seyfert (spiral) galaxies, the direction of the arcsecond scale radio structure (presumed to be the inner radio jets) is independent of the spin axis of the disk of the spiral galaxy and, indeed, appears to be oriented completely at random in space (Clarke, Kinney, & Pringle 1998). If our estimates of the hole/disk alignment are correct, then there are two obvious possibilities to explain this. First, the radiation-driven warping instability may be able to operate in these nuclei, presumably because the black hole spin is much reduced. We note that if the inner-disk direction is indeed randomly directed over a large timescale, then the net angular momentum accreted by the hole from the disk is much reduced (Moderski & Sikora 1996a), and we also note that at the low accretion rates relevant to Seyfert nuclei, it may be possible to spin the black hole down (Moderski & Sikora 1996b). If this is so, then, in order to produce rapidly spinning black holes in galactic nuclei, it may be necessary, following Wilson & Colbert (1995), to appeal to black hole mergers. And, second, the gas being fed to the hole may come not from the disk of the galaxy but from some other source, such as a small gas-rich intruder on a plunging orbit to the nucleus. In any case, to test these ideas further, it will be important to observe the dynamics of gas on small scales (10–100 pc) around Seyfert nuclei.

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