BARDEEN-PETTERSON EFFECT AND THE DISK STRUCTURE OF THE SEYFERT GALAXY NGC 1068

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ABSTRACT

VLBA high spatial resolution observations of the disk structure of the active galactic nucleus (AGN) NGC 1068 have recently revealed that the kinematics and geometry of this AGN is well characterized by an outer disk of H$_2$O maser emission having a compact milliarcsecond- (parsec-) scale structure, which is encircling a thin rotating inner disk surrounding a $\sim 10^7 M_\odot$ compact mass, likely a black hole. A curious feature in this source is the occurrence of a misalignment between the inner and outer parts of the disk, with the galaxy’s radio jet being orthogonal to the inner disk. We interpret this peculiar configuration as due to the Bardeen-Petterson effect, a general relativistic effect that warps an initially inclined (to the black hole equator) viscous disk and drives the angular momentum vector of its inner part into alignment with the rotating black hole spin. We estimate the timescale for both angular momenta to get aligned as a function of the spin parameter of the Kerr black hole. We also reproduce the shape of the parsec- and kiloparsec-scale jets, assuming a model in which the jet is precessing with a period and aperture angle that decrease exponentially with time, as expected from the Bardeen-Petterson effect.

Subject headings: accretion, accretion disks — black hole physics — galaxies: active — galaxies: individual (NGC 1068) — galaxies: jets — relativity

1. INTRODUCTION

Recent mid-infrared interferometric observations (Jaffe et al. 2004) were able to resolve the inner dust torus of the nearby (14.4 Mpc; Bland-Hawthorn et al. 1997) Seyfert 2 galaxy NGC 1068. The emission distribution along this torus showed a small emission distribution similar to a warped disk, with the inner parts almost perpendicular to the jet, but deviating from this configuration as the distance to the core increases. Gallimore et al. (2004) proposed a configuration in which the thin hot disk is perpendicular to the radio jet, while the misaligned maser disk points toward the parsec-scale dusty torus.

In this work we investigate the possibility that both the bent jet and warped accretion disk are a consequence of the Bardeen-Petterson effect, which results from the misalignment between the angular momenta of the Kerr black hole and disk. In $\S$ 2, we discuss the Bardeen-Petterson mechanism, used to calculate the timescale for alignment between the two angular momenta. In $\S$ 3, we present the physical parameters of the accretion disk of NGC 1068, as constrained by the observations found in the literature, and we use them to model the warping of the accretion disk due to the Bardeen-Petterson effect as a function of the alignment timescale. In $\S$ 4, we show how jet morphology can be used independently to estimate the alignment timescale. Conclusions are presented in $\S$ 5.

2. THE BARDEEN-PETTERSON EFFECT AND THE ALIGNMENT TIMESCALE

Frame dragging produced by a Kerr black hole causes precession of a particle if its orbital plane is inclined in relation to...
the equatorial plane of the black hole. The precession angular velocity $\Omega_{\text{LT}}$ due to the Lense-Thirring effect is given by (e.g., Wilkins 1972)

$$\Omega_{\text{LT}} = \frac{2G J_{\text{BH}}}{c^2 r^3},$$

(1)

where $G$ is the gravitational constant, $c$ is the light speed, and $r$ is the radial distance from a black hole of mass $M_{\text{BH}}$ and angular momentum $J_{\text{BH}}$, defined as $J_{\text{BH}} = a GM_{\text{BH}}^2/c$, with $a$, the ratio between the actual angular momentum and its maximum possible value.

The combined action of the Lense-Thirring effect and the internal viscosity of the accretion disk forces the alignment between the angular momenta of the Kerr black hole and the accretion disk. This is known as the Bardeen-Petterson effect (Bardeen & Petterson 1975) and affects only the innermost part of the disk, because of the short range of the Lense-Thirring effect, while its outer parts tend to remain in its original configuration. The transition radius between these two regimes is known as Bardeen-Petterson radius $R_{\text{BP}}$ shown schematically in Figure 1; its exact location depends mainly on the physical properties of the accretion disk (Bardeen & Petterson 1975; Kumar & Pringle 1985; Ivanov & Illarianov 1997; Nelson & Papaloizou 2000; Lubow et al. 2002; Fragile & Anninos 2005).

The timescale for alignment can be calculated as (e.g., Natarajan & Armitage 1999)

$$T_{\text{align}} = J_{\text{BH}} \left( \frac{dJ_{\text{BH}}}{dt} \right)^{-1} \sin \varphi,$$

where $\varphi$ is the angle between the black hole spin axis and the direction perpendicular to the outer disk. The time derivative of $J_{\text{BH}}$ has the form

$$\frac{dJ_{\text{BH}}}{dt} = -2\sin \varphi \int_{R_{\text{out}}}^{R_{\text{in}}} \Omega_{\text{LT}}(r)L_{\text{d}}(r)r^2 dr,$$

(3)

where $R_{\text{out}}$ is the outer disk radius and $L_{\text{d}}(r) = \Sigma_d(r)\Omega_d(r)r^2$ is its differential angular momentum (e.g., Caproni et al. 2004). Here $\Omega_d$ is the disk angular velocity and $\Sigma_d$ is the surface density of the accretion disk integrated over its semithickness $H_d$, derived following Sakimoto & Coroniti (1981; see also Bardou et al. 1998):

$$H_d(r) = \frac{H_{\text{mag}}(r)H_{\text{sg}}(r)}{\sqrt{H_{\text{mag}}^2(r) + H_{\text{sg}}^2(r)}},$$

(4)

where $H_{\text{mag}} = c_s/\Omega_d$, $H_{\text{sg}} = c^2_s/(\pi G\Sigma_d)$, and $c_s$ is the sound speed, defined as

$$c_s(r) = \sqrt{1 - \frac{d \ln \Omega_d(r)}{d \ln r} \frac{\Omega_d(r)}{\alpha}},$$

(5)

where $\Gamma$ is the polytropic index of the gas, which we have assumed equal to 5/3.

A rough estimate of $R_{\text{BP}}$ can be obtained comparing the timescales for Lense-Thirring precession and warp transmission through the disk (e.g., Natarajan & Armitage 1999) that, on the other hand, will depend on how the warps are being communicated along it. If they are transmitted diffusively,

$$R_{\text{BP}}^{\text{diff}} = \sqrt{\nu_2/\Omega_{\text{LT}}},$$

(6)

where $\nu_2$ is the viscosity acting on the direction perpendicular to the disk; both parameters must be calculated at $R_{\text{BP}}^{\text{diff}}$. If the timescales for the warp and surface density evolution are similar, then $\nu_2 \approx \nu_1$, where $\nu_1$ is the viscosity along the disk; otherwise $\nu_2 \sim f(\alpha)\nu_1$, where $f(\alpha)$ is a function of the dimensionless viscosity parameter $\alpha$ introduced by Shakura & Sunyaev (1973); we adopted $f(\alpha) = 2(1 + 7\alpha^3)/[\alpha(4 + \alpha^2)]$ as derived by Ogilvie (1999). Assuming that the inner radius of the accretion disk is the marginally stable orbit $R_{\text{ms}}$, the viscosity $\nu_1$ can be written as

$$\nu_1 = \frac{-M}{2\pi \Sigma_d(r)} \left[ \frac{d \ln \Omega_d(r)}{d \ln r} \right]^{-1} \left[ 1 - \left( \frac{R_{\text{ms}}}{r} \right)^2 \frac{\Omega_d(R_{\text{ms}})}{\Omega_d(r)} \right],$$

(7)

where $\dot{M}$ is the accretion rate, which is related to the bolometric luminosity $L_{\text{bol}}$ through $M/\dot{M}_{\text{Edd}} = L_{\text{bol}}/L_{\text{Edd}}$, $M_{\text{Edd}}$ and $L_{\text{Edd}}$ are the Eddington mass accretion rate and luminosity, respectively.

In the wavelike regime, $R_{\text{BP}}^{\nu}$ can be written as

$$R_{\text{BP}}^{\nu} = c_s/\Omega_{\text{LT}}.$$

(8)

The transition from the diffusive to wavelike regime occurs at a radius $R_T \sim H_d/\alpha$ (Papaloizou & Lin 1995).

3. APPLICATION TO THE ACCRETION DISK OF NGC 1068

The physical parameters of the black hole accretion disk system of NGC 1068 were determined by Huré (2002) and Lodato & Bertin (2003) from the analysis of the maser line velocities; they are presented in Table 1 and were used in our calculations of the Bardeen-Petterson radius and the alignment timescale.

| Parameter       | Model A                  | Model B                  |
|-----------------|--------------------------|--------------------------|
| $M_{\text{BH}}$ (M$_\odot$) | (1.2 ± 0.1) × 10$^6$    | (8.0 ± 0.3) × 10$^6$    |
| $s$             | -1.05 ± 0.10             | -1.05 ± 0.10             |
| $M_d(r = 1$ pc) (M$_\odot$) | (9.4 ± 1.6) × 10$^6$    | (8.6 ± 0.6) × 10$^6$    |
| $\Sigma_d$ (g cm$^{-2}$)  | (1.06 ± 0.23) × 10$^6$  | (1.49 ± 0.18) × 10$^6$  |
| $L_{\text{Edd}}$ (ergs s$^{-1}$) | (1.5 ± 0.1) × 10$^{45}$ | (1.0 ± 0.3) × 10$^{45}$ |
| $M_{\text{Edd}}$                  | 0.46 ± 1.0               | 0.71 ± 1.0               |
| $\alpha(c_d)$                | (4.4–9.4) × 10$^{-4}$    | (4.4–6.3) × 10$^{-4}$    |

Note.—The quoted errors in $M_{\text{BH}}$ and $s$ are given by Huré (2002) and Lodato & Bertin (2003), while those for $\Sigma_d$ were obtained from error propagation.
The maser velocities present signatures of sub-Keplerian motion; however, in equation (3) we used the relativistic Keplerian angular velocity (Abramowicz et al. 1978), since at the radius in which this assumption is not valid, the angular momentum $L_d$ becomes negligible.

We assumed a power-law surface density distribution for the accretion disk $\Sigma(r) = \Sigma_0(r/R_g)\alpha$, where $R_g = GM_\text{BH}/c^2$ is the gravitational radius and $s = -1.05$ (Hüre 2002). The constant $\Sigma_0$ was determined from the mass of the disk $M_d$, derived by Hüre (2002) and Lodato & Bertin (2003), integrating $\Sigma(r)$ from the inner to the outer disk radius.

The $\alpha$-parameter was obtained from the expression $M = (28.1 \pm 0.2)\alpha M_\odot$ yr$^{-1}$ given by Lodato & Bertin (2003). The accretion rate can be calculated from the bolometric luminosity $L_{\text{bol}} = \epsilon Mc^2$, given the accretion efficiency $\epsilon$, which depends on the black hole spin parameter $a_*$. We used as lower limit for the bolometric luminosity $\sim 7 \times 10^{44}$ ergs s$^{-1}$, as found by Gallimore et al. (2004) from the observed free-free emission, and the Eddington luminosity $L_{\text{Edd}}$ as upper limit.

The Bardeen-Petterson radius was obtained from either equation (6) or equation (8), depending on whether it obeys the diffusive or wave regimes, respectively.

The calculations were performed for the disk models A and B defined in Table 1, considering several values of the black hole spin and the extreme values of the accretion rate and $\alpha$-parameter, the latter depending also on the spin value. The results show that the Bardeen-Petterson radius for NGC 1068 depends weakly on the accretion rate, being limited by the variation of the black hole spin and $\alpha$-parameters between $10^{-5}$ and $10^{-4}$ pc (about 20 and 200 $R_g$, respectively), as shown in the left panel of Figure 2.

For the lower limit of the $\alpha$-parameter and both black hole masses, $R_{\text{BP}} = R_{\text{BP}}^\text{diff}$ when $|a_*| > 0.1$. For the upper limit of $\alpha$, $R_{\text{BP}} = R_{\text{BP}}^\text{diff}$ for $a_* < 0.1$, turning gradually into $R_{\text{BP}}^\text{diff}$ for larger values of $a_*$ at a rate that depends on the $\alpha$-parameter.

We calculated the alignment timescale as a function of the black hole spin by solving the integral given in equation (3), using as integration limits the Bardeen-Petterson radius and an arbitrary outer radius. The results, which are independent of the outer radius value, are presented in the right panel of Figure 2.

The alignment timescale turned out to vary between 100 and $10^5$ yr, while the lifetime of the radio jet in NGC 1068 is $\lesssim 1.5 \times 10^5$ yr (Capetti et al. 1999), similar to the lifetimes of AGN activity. Therefore, it indicates that the Bardeen-Petterson effect can perfectly warp the inner part of the accretion disk.

It is important to emphasize that warped accretion disks produced by the Bardeen-Petterson effect can be probed by features in relativistically broadened emission iron-line profiles (Fragile et al. 2005), but unfortunately, since NGC 1068 is a type 2 Seyfert galaxy, relativistically broadened iron lines are unlikely to be observed due to the obscuring dust torus.

4. PROBING ALIGNMENT FROM JET KINEMATICS

The current angular resolution provided by interferometric techniques is not capable to resolve structures with sizes comparable to the Bardeen-Petterson radius in NGC 1068. However, the orientation of the inner part of the disk can be traced from the jet, which is usually thought (sometimes supported by observations; Ray et al. 1996; Jones et al. 2000) to be ejected in the perpendicular direction. In NGC 1068, the jet is not continuous but presents discrete features, the upper limit to their expanding velocities being $0.17c$ (Gallimore et al. 1996a).

The Bardeen-Petterson effect forces the disk to align gradually with the black hole, producing precession and a progressive change in the jet direction (Caproni et al. 2004). According to Scheuer & Feiler (1996), the solution of equation (3) gives an exponential time variation for the inclination angle between black hole spin and the jet direction, as well as for the precession period $P_{\text{prec}}$:

$$\varphi(t) = \varphi_0 e^{-(t-t_0)/T_{\text{align}}},$$

$$P_{\text{prec}}(t) = P_0 e^{-(t-t_0)/T_{\text{align}}},$$

where $\varphi_0$ and $P_0$ are, respectively, the inclination angle and precession period at time $t_0$ when the disk was formed ($t_0 \leq 0$, measured in the past from the present time). Scheuer & Feiler (1996) found that the timescales for precession and realignment are identical, implying that $P_0 = T_{\text{align}}$, which we also consider in our approach.

We assumed that the jet originated at time $t_0$ and that afterward each plasma element was ejected with constant speed $v_{\text{jet}}$ at a time $t$ in a direction that forms an angle $\varphi(t)$ with the black hole spin axis, in a plane that rotates with velocity $\omega(t) = 2\pi/P_{\text{prec}}(t)$. We introduced two additional parameters: the viewing and position angle of the black hole spin in relation to the line of sight $\theta$ and on the plane of the sky $\eta$. 

![Figure 2](image-url)
In order to compare our model with the observations, we calculated the right ascension and declination offsets ($\Delta \alpha$ and $\Delta \delta$, respectively) of each jet element as a function of time through

$$\Delta \alpha(t) = \frac{v_{\text{jet}}}{D} \left[ A(t) \cos \eta + B(t) \sin \eta \right],$$

$$\Delta \delta(t) = \frac{v_{\text{jet}}}{D} \left[ -A(t) \sin \eta + B(t) \cos \eta \right],$$

where $D$ is the distance to the observer, $A(t) = \sin \varphi(t) \cos \omega t$, and $B(t) = \sin \varphi(t) \sin \omega t \cos \theta + \cos \varphi(t) \sin \theta$.

We found solutions for several combinations of the input parameters, in the ranges $25^\circ \leq \varphi_0 \leq 45^\circ$, $70^\circ \leq \theta \leq 90^\circ$, and $14^\circ \leq \eta \leq 20^\circ$. The parameters $t_0$ and $T_{\text{align}}$ are scaled by the jet velocity and have ranges $-1.7 \times 10^5 \leq t_0 \leq -9600$ (where $t_0$ is in yr) and $7500 \leq T_{\text{align}} \leq 1.3 \times 10^5$ (where $T_{\text{align}}$ is in yr) for $0.01 \leq v_{\text{jet}} \leq 0.17c$ (Wilson & Ulvestad 1987; Gallimore et al. 1996a). The limits found for $T_{\text{align}}$ are perfectly compatible with those derived in § 3.

In Figure 3 we present the comparison between the parsec- and kiloparsec-scale radio maps (Wilson & Ulvestad 1987; Gallimore et al. 2004) and a model with parameters $\theta = 80^\circ$, $v_{\text{jet}} = 0.17c$, $t_0 = -9800$ yr, $T_{\text{align}} = 7580$ yr, $\varphi_0 = 40^\circ$, and $\eta = 17^\circ$. We can see that our simple kinematic approach reproduces satisfactorily the inverted S-shape of the kiloparsec jet, as well as the location of its jet components; at parsec scales, the position of the jet components C and NE, as well as the counterjet knot S2, are also well reproduced by the same model. As can be seen in the left panel of Figure 3, at larger distances from the core, the full range of position angles provided by our precessing model is not found in the observational data, in the sense that the amplitude of the helix toward the northern and southern regions are systematically larger than the observed jet aperture. This may be due to the implicit assumption of accretion disk rigid-body precession during all the jet-time evolution, which might not be totally true, especially close to the initial time $t_0$. In fact, numerical simulations have shown a period of differential precession preceding the rigid-body configuration (Nelson & Papaloizou 2000; Fragile & Anninos 2005). In addition, the galactic medium will influence the jet propagation, as can be seen from the [O iii] and mid-infrared images of NGC 1068 (Gallimore et al. 1996c; Capetti et al. 1997; Galliano et al. 2003), showing the existence of jet-ambient interaction.

In all cases considered in this work, the inner disk is not completely aligned with the equator of the black hole, since $\varphi \sim 11^\circ$ at the present time. Interestingly, Galliano et al. (2003) proposed the existence of a slight tilt of $\sim 15^\circ$ between the Compton-thick central absorber and the molecular disk in order to reproduce the observed distribution of H$_2$ and CO emission in this object.

5. CONCLUSIONS

We studied the possibility that the Bardeen-Petterson effect is responsible for the warping of the accretion disk in NGC 1068, as derived from the radio continuum and water maser observations (e.g., Greenhill & Gwinn 1997; Gallimore et al. 2004). Such a mechanism arises from the frame dragging produced by a Kerr black hole whose rotation axis is not parallel to that of the accretion disk.

Using an analytical approach similar to that suggested by Scheuer & Feiler (1996) and Natarajan & Armitage (1999), we calculated the Bardeen-Petterson radius and the alignment timescale between the accretion disk and the equatorial plane of the black hole for different values of the black hole spin. We showed that the general form of the parsec- and kiloparsec-scale jets can be reproduced by the model in which the jet is precessing with a period $P_{\text{prec}}$ and aperture angle $\varphi$ that decrease exponentially with a timescale $T_{\text{align}}$, as expected from the Bardeen-Petterson effect.
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