SPIN-INDUCED DISK PRECESSION IN SAGITTARIUS A*  
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ABSTRACT  

In Sgr A* at the Galactic center, by far the closest and easiest supermassive black hole we can study, the observational evidence is increasingly pointing to the presence of a compact, hot, magnetized disk feeding the accretor. In such low Mach number plasmas, forces arising, e.g., from pressure gradients in the plasma, can altogether negate the warping of disks around Kerr black holes caused by the Bardeen-Petterson effect and can lead to coherent precession of the entire disk. In this paper, we present for the first time highly detailed three-dimensional smoothed particle hydrodynamics (SPH) simulations of the accretion disk evolution in Sgr A*, guided by observational constraints on its physical characteristics, and conclude that indeed the Bardeen-Petterson effect is probably absent in this source. Given what we now understand regarding the emission geometry in this object, we suggest that a ∼ 50–500 days modulation in Sgr A*’s spectrum, arising from the disk precession, could be an important observational signature; perhaps the ∼ 106 days period seen earlier in its radio flux, if confirmed, could be due to this process. On the other hand, if future observations do not confirm this long modulation in Sgr A*’s spectrum, this would be an indication either that the disk size or orientation is very different from current estimates, that the black hole is not spinning at all (unlikely), or that our current understanding of how it produces its radiative output is incorrect.  

Subject headings: accretion, accretion disks — black hole physics — Galaxy: center — radiation mechanisms: nonthermal — radiation mechanisms: thermal — relativity  

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1. INTRODUCTION  

At the Galactic center, the compact radio source Sgr A* appears to be the radiative manifestation of an accreting 3.7 × 106 M☉ supermassive black hole (Ghez et al. 2005). Its radio to millimeter spectrum is thought to be a composite of two principal components, a slightly inverted power law with a notable bump at millimeter/submillimeter wavelengths. The latter is somewhat reminiscent of the “big blue bump” seen in many active galactic nuclei (AGNs), evidently produced by an accretion disk feeding the supermassive black hole (see, e.g., Brotherton et al. 2001). But unlike the blackbody emission process that gives rise to the optical/UV thermal feature in an AGN spectrum, the radiative mechanism responsible for Sgr A*’s millimeter/submillimeter spectral excess appears instead to be a combination of thermal and nonthermal synchrotron emission within the inner portion (r < 10rS) of a hot, magnetized Keplerian flow (Melia et al. 2001; Liu & Melia 2001). (The Schwarzschild radius, rS, for an object of this mass M is 2GM/c² ≈ 1012 cm, or roughly 1/15 AU.) The inferred characteristics of the compact region surrounding Sgr A* are also consistent with the ∼ 10% linear polarization detected from this source at millimeter wavelengths (Melia et al. 2000; Bromley et al. 2001). Given the complex spatial arrangement of the mass-losing stars that feed this object, it is unlikely that the disk angular momentum axis is aligned with the spin axis of the black hole.  

The possible (but currently unconfirmed) detection of a 106 days cycle in Sgr A*’s radio variability (Zhao et al. 2001) has added significant intrigue to this picture, since it could indicate precession of the disk induced by the spin of the black hole (Liu & Melia 2002b). The dynamical timescale near the marginally stable orbit around an object with this mass is ∼ 20 minutes. Thus, since the physical conditions associated with the disk around Sgr A* imply unwarped, coherent precession, a precession period of 106 days could be indicative of a small black hole spin (a ∼ 0.1) if the circularized flow is confined to a region within ∼ 30rS. (Throughout this paper, we define a to be the black hole angular momentum divided by GM²/c².) The precession of a larger structure at the same rate would require a greater black hole spin; alternatively, for a given black hole spin, a larger disk would precess with a longer period. Liu & Melia (2002b) also noted that a small value of a (< 0.1) would be favored if the nonthermal (1–20 cm) portion of Sgr A*’s spectrum is powered by energy extracted via a Blandford-Znajek type of process, for which the observed luminosity would correspond to an outer disk radius rout ∼ 30rS. In addition, a small disk size was suggested by earlier hydrodynamic and magnetohydrodynamic simulations (Coker & Melia 1997; Igumenshchev & Narayan 2002) and is implied by Sgr A*’s spectral and polarimetric characteristics.  

For a thin, cold disk, the differential Lense-Thirring precession dominates the internal coupling of the plasma at small radii and therefore leads to the so-called Bardeen-Petterson effect (Bardeen & Petterson 1975), in which the inner region flattens toward the equatorial plane, producing a warped accretion pattern. As shown by Nelson & Papaloizou (2000) and confirmed recently by Fragile & Aminos (2005), however, thicker disks with a midplane Mach number of ∼ 5 or less can suppress warping effects due to the coupling provided by pressure gradients and viscosity in the gas. The midplane Mach number in Sgr A* is ∼ 3 (for detailed comparisons of model disks to observations, see, e.g., Melia et al. 2001; Igumenshchev & Narayan 2002), so it seems that the disk in this system may be precessing as one unwarped structure (Liu & Melia 2002b). In this paper, we report
the results of smoothed particle hydrodynamics (SPH) simulations we have carried out to test these ideas at a higher level of sophistication than was attempted earlier by Liu & Melia (2002b).

2. PHYSICAL PRINCIPLES AND METHOD

We evolve gaseous disks in the gravitational potential of the black hole at the Galactic center using the three-dimensional SPH code described in Fryer et al. (2005). The inner boundary of the calculation is placed at a radius corresponding to the innermost stable circular orbit, as a function of $a$. For simplicity in this first generation of calculations, particles crossing the inner boundary carry all of their mass and angular momentum into the black hole, and no additional infalling material enters the simulation at the outer edge of the disk. We also do not model the magnetic field or evolve the equations of magnetohydrodynamics, but we include a prescription for the role of the magnetorotational instability in transporting angular momentum (see below). In principle, infalling material can exert an additional torque on the disk with a tendency to align the disk’s angular momentum vector with that of the accreting plasma. However, the angular momentum flow through the disk is also subject to magnetic coupling effects at its inner boundary (Krolik & Hawley, 2002), which can either offset or enhance the effect of the external torque, depending on the configuration of the magnetic field (see Liu & Melia 2002b). We do not fully explore the range of inner and outer boundary conditions in this first treatment and instead leave this important survey to future publications. Consequently, our simulated disks mediate an outward viscous transport of angular momentum, which causes them to slowly grow in radius.

We construct disks based on current estimates of flow properties in the Galactic center (Melia et al. 2001), and we incorporate important effects of general relativity in a Kerr metric and an anomalous viscosity due to the magnetorotational instability that the observations strongly indicate is active in this system. The gravomagnetic force per unit mass and the anomalous viscosity dominate the dynamics of the disk; even at its turbulent saturation point, the magnetic field energy represents only about 15% of the equipartition value. Since the adoption of a post-Newtonian approach to handle the general relativistic effects (see below) introduces $\sim 10\%$ errors, it is reasonable to ignore the dynamical impact of the magnetic field for the first set of simulations. Advancing this study to the next level of sophistication will entail the use of a more elaborate magnetohydrodynamic treatment, which is currently in development. In the final analysis, we will indeed follow the evolution of the inner disk in Sgr A* with all effects included in the simulation: the magnetic field and associated anomalous viscosity and the gravomagnetic force per unit mass. The calculations we describe here will provide a powerful baseline against which the later calculations can be compared and tested.

2.1. The Conservation Equations and SPH Code

Since the gravitational influence of interest simulated here occurs many Schwarzschild radii from the black hole, we follow Nelson & Papaloizou (2000) and include the relativistic effects only in a post-Newtonian approximation. Our momentum equation therefore takes the form

$$\frac{dv}{dt} = -\frac{1}{\rho} \nabla P + v \times h - \nabla \Phi + F_{\text{visc}},$$

(1)

where $\rho$ is the density, $v$ is the velocity, $P$ is the pressure, $\Phi$ is the gravitational potential, and $F_{\text{visc}}$ is the viscous force per unit mass. The term $v \times h$ is the lowest order post-Newtonian approximation to the gravomagnetic force per unit mass near a rotating black hole (see, e.g., Blandford 1996). In this equation, $h$ is defined as

$$h \equiv \frac{2S}{r^3} - \frac{6(S \cdot r)r}{r^5},$$

(2)

where

$$S = \frac{GJ}{c^2}$$

(3)

in terms of the (cylindrical) coordinate vector $r = (\eta, \phi, z)$ and $r = |r|$. The spin angular momentum of a Kerr black hole (using our definition of $a$; see above) is given by

$$J = \frac{aGM^2}{c} \hat{k},$$

(4)

where $\hat{k}$ denotes the unit vector in the z-direction. We calculate the gravitational acceleration due to the black hole using

$$-\nabla \Phi = \frac{GM}{r^3} \left(1 + \frac{6r_\gamma}{r} \right) r,$$

(5)

where $r_\gamma \equiv r_\gamma / 2 = GM/c^2$, which produces the correct apsidal precession frequency at large distances from the black hole (Nelson & Papaloizou 2000).

We use an equation of state of the form $P = k \rho^\gamma$, where $P$ is the pressure, $\gamma = 5/3$ is the heat capacity ratio, and $k$ is a constant chosen to set the midplane Mach number. Energy dissipated through artificial viscosity is allowed to leave the system.

2.2. The Anomalous Viscosity

Many of the properties derived by Balbus & Hawley (1991, 1992) for weakly magnetized accretion disks appear to be present in Sgr A*. One of the most important defining characteristics is the existence of an anomalous viscosity arising from the Maxwell stress, which in Sgr A* easily dominates over the Reynolds stress. In our calculations, we model the effect of this anomalous viscosity using the $\alpha$-disk prescription,

$$\nu = \frac{\alpha c_s^2}{\Omega},$$

(6)

where $c_s$ is the local sound speed and $\Omega$ is the Keplerian angular velocity. Earlier quasi-analytical fits to Sgr A*'s spectrum and analysis of X-ray flares detected from this object by Chandra X-Ray Observatory (Liu & Melia 2002a) concluded that the ratio $\beta_0$ of Maxwell stress to thermal pressure is $\sim 0.05$. Since the viscosity $\nu$ can also be written as

$$\nu = \frac{2 \beta_0 c_s^2}{3 \Omega},$$

(7)

we relate $\alpha$ and $\beta_0$ using $\alpha = \frac{\gamma}{3} \beta_0$ and find that $\alpha$ should be approximately 0.03 in our model disks.

We implement the viscosity using the same technique used by Nelson & Papaloizou (2000), i.e., we adjust the bulk viscosity coefficient $\alpha_{\text{SPH}}$ and the Von Neumann–Richtmyer viscosity coefficient $\beta_{\text{SPH}}$ of the standard SPH artificial viscosity prescription. Following Nelson & Papaloizou (2000), we set $\alpha_{\text{SPH}} = 0.5$ and $\beta_{\text{SPH}} = 0.0$. By tracking the motion of particles in our calculations, measuring the ratio of the orbital period $P$ to the accretion timescale $\tau_{\text{acc}}$, and relating the ratio of timescales to the
viscosity parameter $\alpha \simeq \dot{P}/\dot{P}_{\text{acc}}$, we find that a value of $\alpha_{\text{SPH}} = 0.5$ corresponds to a value of $\alpha \simeq 0.02$.

3. RESULTS

The characteristics of the three simulations we ran that directly address the questions we wish to answer in this paper are summarized in Table 1. Simulation E1 is a direct comparison with the calculation of the same name reported by Nelson & Papaloizou (2000). Simulation GC20 was constructed with an initial outer radius of $20r_S$; the parameters of this model were chosen to be fully consistent with the physical conditions outlined above. It is the contrast between this model and E1 that we expect to highlight the difference between the behavior of a cold disk that is subject to the Bardeen-Petterson effect and the low Mach number disk that we believe is present at the Galactic center. According to earlier semianalytical analysis, the Galactic center disk ought not to experience this effect. However, because we have chosen not to feed the disk from outside, the viscous transport of angular momentum leads to a slow growth in its size. To test the dependence of the disk’s temporal behavior on the initial conditions, we also carried out simulation GC30, which has an initial size of $30r_S$ and is otherwise identical to GC20.

Figure 1 shows the three-dimensional arrangement of SPH particles in our reproduction of test E1 by Nelson & Papaloizou (2000). In this image, the black hole spin axis points in the vertical direction. The outer portion of the disk has maintained its original $10^\circ$ inclination relative to this direction. However, due to the Bardeen-Petterson effect, the inner portion of the disk has become warped and now lies in the equatorial plane of the black hole. By this time in the simulation, which corresponds to four Keplerian orbital periods at $30r_S$, the central portion of the disk lies in the same plane as the rest of the disk, not in the equatorial plane of the black hole. Nelson & Papaloizou (2000) also considered one case in which the midplane Mach number was low (specifically, $M = 5$) and found that that particular disk did not warp. Our result for model GC30, which has a midplane Mach number of 3, is consistent with their finding. Simulation GC20 behaves in exactly the same way. A principal result of this work is that the physical conditions inferred from Sgr A*’s spectrum evidently imply that the entire disk precesses coherently around the black hole spin axis, confirming the prediction of Liu & Melia (2002b).

An important observational signature of this effect is the dependence of the precession period on the size of the disk for a given value of the black hole spin parameter. The size of the disk provides a measure of the moment of inertia of the structure, whose response to the applied gravomagnetic torque determines the rate of precession.

Liu & Melia (2002b) argued that the precession period of a coherently precessing simplified model disk should vary as $r_{\text{out}}^{5/2}$, under the assumption that the surface density in the disk is constant. To test this predicted dependence, we evolved the disk over many orbital periods, tracing its growth in size and corresponding change in precession period; the relationship is summarized in Figure 3. Note that the disk radius plotted along the horizontal axis is actually the radius of the thickest portion of the disk, not the radius of the outermost particle in the simulation. The low number density of particles at the outer disk edge inhibits a consistent and accurate determination of what actually constitutes the disk size. Choosing the radius where the disk is thickest, on the other hand, provides a more stable and reliable determination of the disk size.

Starting with an outer radius of $20r_S$ and assuming that $a = 0.1$ (see Table 1), the precession period is 69 days. The period grows smoothly and monotonically as the disk expands under the action of viscous angular momentum transport and reaches approximately 600 days when the outer radius is $46r_S$. In Figure 3, the solid curve indicates the calculated behavior of the period as a function of outer disk radius; the dashed curve gives a strict $P \propto r_{\text{out}}^{5/2}$ dependence. Our simulations clearly exhibit a period that varies as $r_{\text{out}}^{5/2}$; this is a consequence of the fact that our GC20 and GC30 disks precess coherently.

Future work will include the effect of infalling material and a more thorough survey of the dependence of disk evolution on black hole parameters such as $a$. Very importantly, we will study another potentially significant signature: the prograde-retrograde flip that might occur due to sudden changes in the accreted angular momentum $L$. Past hydrodynamic simulations (Coker & Melia 1997) have hinted that the complex, clumpy structure of

![Figure 1](image-url)
the infalling plasma can lead to significant fluctuations in both the magnitude and direction of $L$.

4. CONCLUDING REMARKS

We find that the physical conditions associated with accretion onto Sgr A* imply the presence of a compact accretion disk that precesses as a coherent, unwarped structure about the black hole spin axis. Our simulations confirm the general results of Nelson & Papaloizou (2000); specifically, we find that the low Mach number disk in Sgr A* would not be subject to the Bardeen-Petterson effect. Given the observed constraints on disk parameters, we provide an accurate determination of the precession period of such a disk. The fact that this period varies as $r_{\text{out}}^{5/2}$ could eventually lead to a compelling determination of the black hole spin; alternatively, if other independent techniques or observations can provide accurate estimates of the spin, our results determine the radius of the disk around Sgr A*.

Observationally, our work provides some motivation for expecting a modulation in Sgr A*'s flux with a period of $\sim 50$–500 days; we have found that the precession period is in this range as long as the disk size is $\sim 20r_S$–$30r_S$. Such a modulation might arise in portions of Sgr A*'s spectrum produced by an occulted emitter; for example, it is known that Sgr A*'s radio emission is produced on scales of $20r_S$–$100r_S$ (see, e.g., Bower et al. 2004). Thus, since this disk is optically thick to centimeter radiation (Liu & Melia 2002b; Prescher & Melia 2005), its precession could lead to a variable aspect that periodically attenuates the total radio flux from this region.

This effect may already have been observed; Zhao et al. (2001) report a detection of a $\sim 106$ days cycle in Sgr A*'s radio emission. If this result is eventually confirmed, and if indeed it appears that only a disk precessing in a nonisotropic gravitational field can account for it, we may eventually be able to use it as a probe of the spacetime within the inner $\sim 10r_S$ of a Kerr metric and, more importantly, as a means of directly measuring the black hole's spin.

On the other hand, a nonconfirmation of such a modulation on a $\sim 50$–500 days timescale would tell us either that no disk is present in Sgr A*, that its properties—specifically, its size and orientation—are different from what we now understand, or that the geometry of the emission region has not yet been identified. The fact that such a determination can be made points to the predictive power of detailed numerical simulations such as those reported here and argues for the need for more sophisticated calculations incorporating the effects we have ignored thus far.

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