THE INFLUENCE OF GAS DYNAMICS ON MEASURING THE PROPERTIES OF THE BLACK HOLE IN THE CENTER OF THE MILKY WAY WITH STELLAR ORBITS AND PULSARS

DIMITRIOS PSALTIS
Astronomy Department, University of Arizona, 933 N. Cherry Ave., Tucson, AZ 85721, USA
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ABSTRACT

Observations of stars and pulsars orbiting the black hole in the center of the Milky Way offer the potential of measuring not only the mass of the black hole but also its spin and quadrupole moment, thereby providing observational verification of the no-hair theorem. The relativistic effects that will allow us to measure these higher moments of the gravitational field, however, are very small and may be masked by drag forces that stars and pulsars experience orbiting within the hot, tenuous plasma that surrounds the black hole. The properties of this plasma at large distances from the central object have been measured using observations of the extended X-ray emission that surrounds the point source. At distances comparable to the black hole event horizon, the properties of the accretion flow have been constrained using observations of its long-wavelength emission and polarization, as well as of the size of the emitting region at 1.3 mm. I use models of the plasma density and temperature at various distances from the black hole to investigate the effect of hydrodynamic drag forces on future measurements of the higher moments of its gravitational field. I find that hydrodynamic drag does not preclude measurements of the black hole spin and quadrupole moment using high-resolution observations of stars and pulsars that orbit within a few thousand gravitational radii from its horizon.

Key words: accretion, accretion disks – black hole physics – Galaxy: center

Online-only material: color figures

1. INTRODUCTION

The black hole in the center of the Milky Way, Sgr A*, has a number of characteristics that make it an ideal candidate for testing general relativity in the strong-field regime. It is surrounded by a swarm of young stars at very close orbits, the tracking of which has already led to a direct measurement of its mass (see Ghez et al. 2008; Gillessen et al. 2009 for recent work). It is accreting from the surrounding medium at rates high enough to make it a detectable source both in the X-rays (e.g., Baganoff et al. 2003) and at long wavelengths (e.g., Falcke et al. 1998; Yusef-Zadeh et al. 2009). It is also the black hole with a horizon that subtends the largest angle in the sky, making it possible to directly image the region very close to its horizon (e.g., Doeleman et al. 2008).

Three distinct technological advances in the next decade offer the possibility of not only improving the accuracy of our knowledge of the black hole’s mass but also of measuring directly its spin and quadrupole moment. This last quantity of the gravitational field is not an independent quantity in the Kerr metric; instead it depends in a very particular way on the mass and spin of the black hole, as required by the no-hair theorem (see, e.g., Ryan 1995). Measuring all three moments of the gravitational field, however, will interact with the hot surrounding plasma, which is thin at such wavelengths (Doeleman et al. 2008) and has led to the first constraints on the orientation and properties of the black hole (Broderick et al. 2009). Future observations with 5–10 baselines will provide the first direct image of horizon-scale structures in the vicinity of a black hole (Fish & Doeleman 2009) and allow for a model-independent measurement of the black hole’s spin and quadrupole moment (Johannsen & Psaltis 2010).

Measuring the mass, spin, and quadrupole moment of the black hole in the center of the Milky Way with three independent techniques is crucial in distinguishing relativistic effects from other astrophysical complications. Indeed, the presence of gas and stars in the vicinity of the black hole introduces perturbations to the orbits of stars and pulsars, that may mask or even bias the measurements. The cluster of stars (known and anticipated) in orbit around Sgr A* introduces multipole components to the gravitational field, which in turn cause precession of their orbits. In order for this classical effect to be negligible compared to the relativistic precession that depends on the spin and quadrupole of the black hole spacetime, the orbital separations of the stars from the black hole have to be less than a milliparsec (Merritt et al. 2010).

Stars and pulsars orbiting very close to the black hole, however, will interact with the hot surrounding plasma, which is
provided by the stellar winds of the more distant stars and powers the accretion luminosity of the black hole. This interaction will cause them to leave their geodesic orbits and very slowly spiral toward the black hole. If any of the various components of hydrodynamic drag is comparable to or larger than the perturbation to the Newtonian gravitational acceleration due to relativistic effects, then tracking the orbits of stars or pulsars around the black hole will not lead to a clean measurement of the moments of its spacetime.

In this article, I first infer the density and temperature of the hot plasma at different distances from Sgr A* using models of the accretion flow and of its feeding region that are consistent with current X-ray and millimeter observations. I then estimate the effect of hydrodynamic drag on the orbits of objects in this plasma and show that it is negligible for stars and pulsars orbiting within a few thousand gravitational radii from the black hole (dashed line). The range of orbital separations of the S2 star from the black hole horizon is provided by the millimeter observations of Sgr A∗ (Falcke et al. 1998; Marrone et al. (2007), the polarization of its emission (Marrone et al. 2007), and the size of the emitting region at 1.3 mm (Doeleman et al. 2008). In their model, the electron density and temperature of the extended emission around the black hole. At small distances, the model of Broderick & Loeb (2005) fits the long-wavelength spectrum of the accretion flow, is consistent with polarization measurements, and agrees with the size of the emitting region at 1.3 mm. The dashed portion of each curve represents an extrapolation of each model to distances far beyond its intended range of validity.

(A color version of this figure is available in the online journal.)

Figure 1. Inferred electron (top) density and (bottom) temperature at different distances from Sgr A*. At large distances, the model of Quataert (2004) was designed to fit the Chandra observations by Baganoff et al. (2003), who inferred the electron density and temperature of the extended emission around the black hole. In this article, I first infer the density and temperature of the hot plasma at different distances from Sgr A* using models of the accretion flow and of its feeding region that are consistent with current X-ray and millimeter observations. I then estimate the effect of hydrodynamic drag on the orbits of objects in this plasma and show that it is negligible for stars and pulsars orbiting within a few thousand gravitational radii from the black hole (dashed line). The range of orbital separations of the S2 star from the black hole horizon is provided by the millimeter observations of Sgr A∗ (Falcke et al. 1998; Marrone et al. (2007), the polarization of its emission (Quataert & Gruzinov 2000; Agol 2000), and the size of the emitting region (Özel et al. 2000). Alternatively, the same properties have also been modeled using jet models launched in the vicinity of the black hole (Falcke & Markoff 2000).

Broderick & Loeb (2005; see also Broderick et al. 2009, 2011) constructed a semi-analytic model of radiatively inefficient accretion flows based on the earlier works and determined its parameters by fitting simultaneously the latest millimeter-to-centimeter spectra observed from Sgr A∗ (Falcke et al. 1998; Marrone et al. 2007), the polarization of its emission (Marrone et al. 2007), and the size of the emitting region at 1.3 mm (Doelman et al. 2008). In their model, the electron density $n_e$ and temperature $T_e$ in the accretion flow scale with radius $r$ as

$$n_e = n_0 \left( \frac{r c^2}{G M_{BH}} \right)^{-1.1}$$

(1)
The best-fit parameters of the model to the observations are $G$, the gravitational constant, and $M_{BH}$, the mass of the black hole. At large distances, where the electrons are expected to be only weakly coupled with the ions, the ion temperature is believed to be $\sim 1-5$ times the electron temperature. At small distances, it is set equal to the inferred electron temperature. At large distances, ions and electrons are expected to have the same temperatures. On the other hand, close to the black hole, the combination of MHD simulations, which follow the dynamics of the ions, and of radiative transfer calculations, which model the electron properties, indicate that the ion temperature is $\sim 1-5$ times the electron temperature (see, e.g., Mościbrodzka et al. 2009; Dexter et al. 2010).

Figure 2 compares the Broderick & Loeb (2005) model of the inner accretion flow to the Quataert (2004) model of the feeding region at large distances from the black hole. Remarkably, the inferred density of the inner accretion flow is only a factor of $\sim 3$ lower than the extrapolation of the Quataert (2004) model at distances that are smaller by four orders of magnitude compared to its intended region of validity (see also similar remarks in Shcherbakov & Baganoff 2010). This suggests that the estimates presented below are not very sensitive on the details of the particular model used for the inner accretion flow, be it a radiatively inefficient flow or a jet. In order to be conservative in calculating the effect of hydrodynamic drag on the orbits of objects around Sgr A*, I will use the extrapolation of the Quataert (2004) model throughout the vicinity of the black hole. Moreover, because in the regions of interest the electron temperature is in excess of $10^7$ K (see below), I will assume that the plasma is fully ionized.

The electron temperature of the inner accretion flow is higher than the extrapolation of the Quataert (2004) model and has a steeper radial profile. This is not unexpected, however, as turbulent heating in the accretion flow will heat the plasma to temperatures higher than what is calculated in the analytical work, which takes into account only compressional and adiabatic heating. The discontinuity between the models is not a serious handicap for this calculation since I will use the plasma temperature only to infer whether the motion of objects through the plasma is subsonic or supersonic. In order to achieve this, however, I will need to make an assumption regarding the ratio of ion-to-electron temperatures, as the models of both the inner accretion flow and of the feeding region provide an estimate of only the electron temperature in the plasma surrounding Sgr A*.

At large distances, ions and electrons are expected to have the same temperatures. On the other hand, close to the black hole, the combination of MHD simulations, which follow the dynamics of the ions, and of radiative transfer calculations, which model the electron properties, indicate that the ion temperature is $\sim 1-5$ times the electron temperature (see, e.g., Mościbrodzka et al. 2009; Dexter et al. 2010). For the purposes of this work, I will use the temperature of the model by Quataert (2004) in the outer region of the plasma and an ion temperature that is $\sim 1-5$ times the electron temperature of the Broderick & Loeb (2005) model in the inner region, where the latter is higher, as shown in Figure 2.

Figure 3 compares the sound speed in the models shown in Figure 2 to the characteristic orbital speed $u_{orb} = (G M_{BH}/r)^{1/2}$ at different distances from the black hole. In all regions of interest, i.e., for distances $\lesssim 10^2 M$, the orbital speed is larger than the local sound speed. As a result, the motion of stars and pulsars through the plasma surrounding Sgr A* will be mildly to highly supersonic.

### 3. THE INTERACTION OF STARS AND PULSARS WITH THE HOT PLASMA

The motion of a star or a pulsar in the vicinity of Sgr A* will be affected by its interaction with the surrounding plasma to the degree that it will preclude a clean gravitational experiment, if the interaction results in accelerations that are comparable to that of gravity. As a scale against which I will compare the hydrodynamic accelerations, the Newtonian gravitational acceleration at a distance $r$ away from the central black hole is

$$a_N = \frac{G M_{BH}}{r^2} \simeq 1.4 \times 10^9 \left( \frac{M_{BH}}{4.5 \times 10^6 M_\odot} \right) \left( \frac{G M_{BH}}{r c^2} \right)^2 \text{cm s}^{-2}. \quad (3)$$
Described by the Kerr solution, are proportional to \( M \) (Merritt et al. corrections to the Newtonian acceleration that depend on the spin of the black hole are proportional to (see Merritt et al. 2010) acceleration that depend on the spin and its quadrupole moment of the black hole and verifying whether to the Newtonian acceleration that is proportional to the spin and due to the gravitational interaction of the star with its wake \( (a_{\text{eq}}; \text{green line}) \). The black hole is assumed to be described by the Kerr solution and to be mildly spinning \( (\chi \approx 0.1) \). At radii \( \lesssim 10^5 \) times the gravitational radius, hydrodynamic interactions are not large enough to preclude a successful measurement of the spin and quadrupole moment of the black hole. (A color version of this figure is available in the online journal.)

An observational verification of the no-hair theorem around \( \text{Sgr A}^* \) will involve measuring the magnitude of the correction to the Newtonian acceleration that is proportional to the spin and the quadrupole moment of the black hole and verifying whether these lowest three multipole moments of its spacetime obey the relation of the Kerr metric. Corrections to the Newtonian acceleration that depend on the spin of the black hole are proportional to (see Merritt et al. 2010)

\[
a_i \equiv \frac{4 \chi G^2 M_{\text{BH}}^2}{c^3} \left( \frac{\mu_{\text{orb}}}{r^3} \right)^2 \approx 5.4 \times 10^9 \chi \left( \frac{M_{\text{BH}}}{4.5 \times 10^6 M_\odot} \right)^{-1} \left( \frac{GM_{\text{BH}}}{rc^2} \right)^{7/2} \text{ cm s}^{-2},
\]

where \( \chi \) is the dimensionless spin of the black hole. Finally, corrections to the Newtonian acceleration that depend on the quadrupole moment of the spacetime, assuming that the latter is described by the Kerr solution, are proportional to (Merritt et al. 2010)

\[
a_Q \equiv \frac{3}{2} \chi^2 \left( \frac{GM_{\text{BH}}}{c^2 r} \right)^4 \approx 2.0 \times 10^9 \chi^2 \left( \frac{M_{\text{BH}}}{4.5 \times 10^6 M_\odot} \right)^{-1} \left( \frac{GM_{\text{BH}}}{rc^2} \right)^4 \text{ cm s}^{-2}.
\]

Figure 4 shows the magnitude of the various contributions to the gravitational acceleration at different distances from the central black hole, for an assumed spin of \( \chi = 0.1 \).

An orbiting object in the vicinity of \( \text{Sgr A}^* \) interacts with the surrounding plasma in at least two distinct ways (see also Narayan 2000), which I will now consider in some detail.

First, as the object plows through the plasma, it scatters away the plasma particles or it gravitationally captures them, depending on its compactness. In the former case, the orbiting object transfers some of its linear momentum to the plasma particles, thereby feeling a hydrodynamic drag. In the latter case, the gravitational focusing of the trajectories of the plasma particles toward the back side of a small orbiting object leads to an increase of its linear momentum (Ruffert 1996). Which of the two cases dominates depends on the ratio of the Bondi radius to the radius of the object itself. Given that the motion of stars and pulsars in the vicinity of \( \text{Sgr A}^* \) is supersonic everywhere in the region of interest, I estimate the Bondi radius around such objects to be

\[
R_B = \frac{2GM_\star}{u_{\text{orb}}^2} = \frac{2GM_\star}{\frac{c^2}{r}} \left( \frac{r c^2}{GM_{\text{BH}}} \right) \sim 4 \times 10^{-5} \left( \frac{M_\star}{10 M_\odot} \right) \left( \frac{r c^2}{GM_{\text{BH}}} \right) R_\odot \sim 6 \times 10^5 \left( \frac{M_\star}{2 M_\odot} \right) \left( \frac{r c^2}{GM_{\text{BH}}} \right) \text{ cm.}
\]

In other words, the Bondi radius around a \( 10 M_\odot \) star is smaller than its stellar radius and, therefore, such a star will always feel a hydrodynamic drag. On the other hand, the Bondi radius around a neutron star is comparable to its size even at the smallest orbital separations from the central black hole and rapidly increases for larger orbits. As a result, Bondi accretion onto the neutron star will dominate the scattering of the plasma particles and lead to an increase of its orbital velocity.

I will estimate the magnitude of the acceleration due to the hydrodynamic drag \( a_d \) using the relation

\[
a_d \approx \pi R_{\text{eff}}^2 \rho u_{\text{rel}}^2.
\]

where \( \rho \) is the density of the plasma that I inferred in Section 2, \( u_{\text{rel}} \) is the relative velocity of the object with respect to the plasma, which I will set equal to the orbital velocity, and \( R_{\text{eff}} \) is the effective radius at which the moving object interacts with the plasma. For a normal star, the Bondi radius is much smaller than the stellar radius. I will, therefore, set the effective radius equal to the stellar radius \( R_\star \) and obtain

\[
a_d \approx 1.1 \times 10^{-9} \left( \frac{M_\star}{10 M_\odot} \right)^{-1} \left( \frac{R_\star}{10 R_\odot} \right)^2 \times \left( \frac{n_e}{10^4 \text{ cm}^{-3}} \right) \left( \frac{GM_\odot}{c^2 r} \right) \text{ cm s}^{-2}.
\]
The hydrodynamic drag on a pulsar has a different dependence on the distance from the black hole compared to that of a 10 $M_\odot$ star. The effective radius in this case is the Bondi radius, which increases linearly with increasing distance from the black hole. Setting $R_{\text{eff}} = R_B$ in Equation (7), I obtain, for a 2 $M_\odot$ neutron star,

$$a_d \simeq 6.2 \times 10^{-14} \left( \frac{M_*}{2M_\odot} \right)^{-1} \left( \frac{n_e}{10^4 \text{ cm}^{-3}} \right) \times \left( \frac{r c^2}{G M_B} \right) \text{ cm s}^{-2}. \quad (9)$$

Figure 5 compares the hydrodynamic drag exerted on the neutron star to the various terms of the gravitational acceleration. Because the electron density in the region of interest scales as $n_e \sim r^{-1}$, the acceleration due to the hydrodynamic drag on the neutron star is nearly independent of the distance from the black hole. It becomes comparable to the quadrupole contribution to the gravitational acceleration at $\sim 10^5$ gravitational radii.

As an object moves through the plasma in the vicinity of the black hole, it will also generate a wake behind it. The gravitational interaction between the object and the wake will result in an additional drag on the object, which will decelerate its motion (Chandrasekhar 1943). The magnitude of this effect has been calculated by Ostriker (1999) and Sánchez-Salcedo & Brandenburg (1999) for the uniform motion of a star in a medium of constant density and more recently by Kim & Kim (2007, 2009) and Kim (2010) for the case of a circular motion in a stratified medium. The results of these papers were used by Narayan (2000) and by Barausse (2007) and Barausse & Rezzolla (2008) to estimate the effect of hydrodynamic drag on the properties of gravitational waves emitted during extreme mass-ratio inspirals.

Following these works, I estimate the magnitude of the resulting acceleration using the expression

$$M_* a_{d_w} \simeq 4\pi \ln \left( \frac{R_{\text{max}}}{R_{\text{min}}} \right) \left( \frac{G M_*}{u_{\text{rel}}^2} \right) \rho. \quad (10)$$

Note that the drag due to the gravitational interaction with the wake decreases with increasing relative velocity, because as the velocity increases, the opening angle of the wake decreases.

For a 10 $M_\odot$ star in orbit at radius $r$ around the central black hole, the appropriate values for the maximum and minimum distances of the wake are $R_{\text{max}} \simeq r$ and $R_{\text{min}} = R_*$, respectively. Setting, as above, the relative velocity equal to the orbital velocity $u_{\text{orb}}$, I obtain

$$a_{d_w} = 9 \times 10^{-15} \ln \left( \frac{r c^2}{G M_B} \right) \left( \frac{10 R_\odot}{R_*} \right) - 0.046 \times \left( \frac{M_B}{4.5 \times 10^6 M_\odot} \right) \left( \frac{n_e}{10^4 \text{ cm}^{-3}} \right) \left( \frac{r c^2}{G M_B} \right) \text{ cm s}^{-2}. \quad (11)$$

Note that, because the electron density scales as $n_e \sim r^{-1}$, this acceleration is also nearly constant throughout the region of interest. Figure 4 compares the magnitude of this acceleration due to the interaction with the wake of a 10 $M_\odot$ to the gravitational acceleration from the central black hole. Within $\sim 10^6$ gravitational radii from the central black hole, this component of the hydrodynamic drag is negligible compared to the quadrupole component of the gravitational acceleration.

For the case of a 2 $M_\odot$ neutron star, the minimum distance of the wake is the Bondi radius, i.e., $R_{\text{min}} = R_B$ and the acceleration due to the gravitational interaction of the star with its wake is

$$a_{d_w} = 4.1 \times 10^{-21} \times \left\{ \ln \left[ \frac{M_B}{4.5 \times 10^6 M_\odot} \right] \left( \frac{M_*}{2M_\odot} \right)^{-1} - 13.9 \right\} \times \left( \frac{M_*}{2M_\odot} \right) \left( \frac{n_e}{10^4 \text{ cm}^{-3}} \right) \left( \frac{r c^2}{G M_B} \right) \text{ cm s}^{-2}. \quad (11)$$

As before, the acceleration due to the gravitational interaction of the neutron star with its wake depends only weakly on its distance from the black hole. Figure 5 compares the magnitude of this acceleration to the gravitational accelerations from the central black hole demonstrating that the former is again negligible in all regions of interest.

4. CONCLUSIONS

In this paper, I used the most recent models of the X-ray and millimeter observations of the black hole in the center of the Milky Way in order to estimate the density and temperature of the plasma in a wide range of distances from the central black hole. I then calculated the effect of hydrodynamic drag on the orbits of stars and pulsars that can be used to probe relativistic effects and test the no-hair theorem.

I found that in both the case of orbiting stars and of pulsars, the hydrodynamic drag dominates over the gravitational interaction of the object with its wake. For the case of 10 $M_\odot$ stars or 2 $M_\odot$ pulsars around Sgr A*, the hydrodynamic drag is negligible compared to the quadrupole terms of the gravitational acceleration, as long as their orbits are within $\sim 10^7$ and $\sim 10^4$ gravitational radii, respectively, from the central black hole. These estimates were calculated for an average, steady state profile of electrons and ions in the vicinity of the black hole. They may substantially change, if the orbiting object encounters a density inhomogeneity, such as those believed to be responsible for the variability of emission from the black hole. An encounter of this kind will alter the orbital characteristics of the star or pulsar and will become apparent in the orbital solution as a short-lived phase jump as opposed to a sustained precession of the orbital plane and of the longitude of the periastron.
Even though the requirements set above appear to be very tight, they are also comparable to those required for the perturbations in the gravitational field due to the presence of the stellar cluster to be negligible compared to relativistic effects (Merritt et al. 2010). In other words, for those stars and pulsars for which the interactions with the other objects of the stellar cluster are negligible, hydrodynamic drag will not preclude measuring the spin and quadrupole moment of the black hole spacetime.

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