Measuring the Black Hole Spin in Sgr A*

Fulvio Melia$^{1,2,3}$, Benjamin C. Bromley$^4$, Siming Liu$^2$, and Christopher, K. Walker$^3$

$^2$Physics Department, The University of Arizona, Tucson, AZ 85721

$^3$Steward Observatory, The University of Arizona, Tucson, AZ 85721

$^4$Department of Physics, University of Utah, 201 JFB, Salt Lake City, UT 84112

Received ___________________; accepted ___________________

1Sir Thomas Lyle Fellow and Miegunyah Fellow.
ABSTRACT

The polarized mm/sub-mm radiation from Sgr A* is apparently produced by a Keplerian structure whose peak emission occurs within several Schwarzschild radii \( r_S \equiv 2GM/c^2 \) of the black hole. The Chandra X-ray counterpart, if confirmed, is presumably the self-Comptonized component from this region. In this paper, we suggest that sub-mm timing observations could yield a signal corresponding to the period \( P_0 \) of the marginally stable orbit, and therefore point directly to the black hole’s spin \( a \). Sgr A*’s mass is now known to be \( (2.6 \pm 0.2) \times 10^6 M_\odot \) (an unusually accurate value for supermassive black hole candidates), for which \( 2.7 \text{ min} < P_0 < 36 \text{ min} \), depending on the value of \( a \) and whether the Keplerian flow is prograde or retrograde. A Schwarzschild black hole \( (a = 0) \) should have \( P_0 \approx 20 \text{ min} \). The identification of the orbital frequency with the innermost stable circular orbit is made feasible by the transition from optically thick to thin emission at sub-mm wavelengths. With stratification in the emitter, the peak of the sub-mm bump in Sgr A*’s spectrum is thus produced at the smallest radius. We caution, however, that theoretical uncertainties in the structure of the emission region may still produce some ambiguity in the timing signal. Given that Sgr A*’s flux at \( \nu \sim 1 \text{ mm} \) is several Jy, these periods should lie within the temporal-resolving capability of sub-mm telescopes using bolometric detectors. A determination of \( P_0 \) should provide not only a value of \( a \), but it should also define the angular momentum vector of the orbiting gas in relation to the black hole’s spin axis. By analogy with low-mass X-ray binaries and Galactic black hole candidates, Sgr A* may also display quasi-periodic oscillations, which can reveal additional features in the geometry of the accreting gas. In addition, since the X-ray flux detected by Chandra appears to be the self-Comptonized mm to sub-mm component, these temporal fluctuations may also be evident in the X-ray signal.

Subject headings: accretion—black hole physics—Galaxy: center—hydrodynamics—magnetic fields: dynamo—radiation mechanisms: nonthermal
1. Introduction

It is now thought that the dynamical center of the Galaxy coincides with Sgr A* (Eckart et al. 1995; Menten et al. 1997; Ghez et al. 1998), a compact nonthermal radio source no bigger than $\sim 1$ AU (Krichbaum et al. 1993; Backer et al. 1993; Krichbaum et al. 1998; Lo et al. 1993). With a concentration of dark matter ($2.6 \pm 0.2 \times 10^6 \, M_\odot$) within 0.015 pc of its centroid (Genzel et al. 1996; Ghez et al. 1998), Sgr A* anchors the stars and gas locked in its vicinity, and provides possibly the most compelling evidence for the existence of supermassive black holes. Its time-averaged spectrum is roughly a power-law, $S_\nu \propto \nu^a$, with $a \sim 0.19 - 0.34$ from cm to mm wavelengths. In the sub-millimeter (sub-mm) region, a spectral excess (or “bump”) has emerged (Zylka et al. 1992; Zylka et al. 1995), which now appears to be well established (Falcke et al. 1998). This is interesting in view of the fact that it may be a signature of activity close to the black hole’s event horizon, since the highest frequencies appear to correspond to the smallest spatial scales (e.g., Melia, Jokipii & Narayan; Melia 1992, 1994; Narayan et al. 1995; Falcke et al. 1998; Coker & Melia 2000).

The detection of Sgr A* at X-ray wavelengths (Baganoff et al. 2001), together with the radio polarization measurements reported by Bower et al. (1999) and Aitken et al. (2000), offer the best constraints yet for determining the nature of the emitting gas, and understanding the environment within several Schwarzschild radii ($r_S \equiv 2GM/c^2 = 7.7 \times 10^{11} \, \text{cm}$) of the black hole. This is because the behavior of Sgr A* is dictated by the manner with which plasma accretes onto it from the nearby medium. Through a series of large scale 3D hydrodynamic simulations (e.g., Coker & Melia 1997), it has become apparent that the specific angular momentum $\lambda$ (in units of $c r_S$) accreted with the gas is variable (on a time scale of decades) and rather small, averaging $\lambda < 40$. This is not sufficient for the plasma to form a large disk (such as that required by ADAF disk models; Narayan et al. 1995), but it is expected to circularize the inflow at a radius $r_{circ} = 2\lambda^2 r_S$ before spiraling in through the event horizon.

The existence of a Keplerian structure at small radii should still be viewed as an assumption. The reason for this is that the hydrodynamic simulations conducted thus far have necessarily
employed an inner boundary with a radius ($r_{in} > 1,000r_S$) much larger than $r_{circ}$. However, a small Keplerian structure is implied by the detailed modeling of Sgr A*’s spectrum (from radio to X-rays), which has demonstrated that the sub-mm “excess” of emission seen in its spectrum may be associated with radiation produced within this region of circularized flow (Melia, Liu & Coker 2000, 2001). The sub-mm emission probably represents a transition from optically thick to optically thin emission (Melia 1992, 1994), so that radiation below the peak of the sub-mm bump originates predominantly in front of and behind the black hole, whereas radiation above the peak is produced by (and Doppler boosted within) the orbiting gas to the side of the central object. The implied degree of polarization (about 10%) and a rotation in the position angle (by almost 90°) across the bump are consistent with what has been seen in this source (Aitken et al. 2000).

The Chandra observations are crucial for establishing the viability of this picture because the hot Maxwellian particles producing the cm to sub-mm radiation via thermal synchrotron emission can also self-Comptonize the soft radiation to produce X-rays.

These three pieces of circumstantial evidence (the mm/sub-mm bump, its polarization characteristics and the self-Comptonized X-ray component) now suggest the intriguing possibility that we may be on the threshold of actually measuring the spin of the black hole in Sgr A*. Since its mass is known to such high precision, features seen in the power spectrum for the mm/sub-mm emission can directly yield the factors defining the circum-black hole geometry.

2. A Possible Periodicity in Sgr A*’s Millimeter/Sub-Millimeter Spectrum

The structure of the circularized flow within $\sim 5 - 50 \ r_S$ is developed fully in Melia, Liu & Coker (2000). Central to the modeling of the sub-mm “excess” is the supposition that within the Keplerian flow, a magnetohydrodynamic dynamo produces an enhanced (though still sub-equipartition) magnetic field, dominated by its azimuthal component (Hawley, Gammie & Balbus 1996). Briefly, Melia, Liu & Coker (2000) infer the following physical state of the gas toward small radii (i.e., within $\sim 5r_S$ or so). The polarization data (particularly those presented by Aitken et al. 2000) appear to restrict the accretion rate to values no larger than about $10^{16}$ g
s$^{-1}$, for otherwise the medium would not become transparent at sub-mm wavelengths. In order to account for the sub-mm bump with thermal synchrotron emission, the temperature $T$ (assumed to be the same for the electrons and the protons) should be relativistic. In the best fits, the profile in $T$ shows a steady rise from $\sim 10^{10}$ K at the outer edge of the Keplerian flow to about $10^{11}$ within the last stable orbit. Following the prescription for calculating the magnetic field and the viscosity (e.g., Hawley et al. 1996), Melia, Liu & Coker (2000) determined the corresponding particle density $n$ and magnetic field intensity $B$ self-consistently. In the best fits to the data, they found that $2 \times 10^6$ cm$^{-3} < n < 2 \times 10^7$ cm$^{-3}$, and $6$ G $< B < 17$ G. This range for $B$ is consistent with the result of Beckert & Duschl (1997) and Coker & Melia (2000). In the sub-mm region, the thermal synchrotron flux density produced by this gas peaks at $2.4 \times 10^{11}$ Hz, and the flip frequency (where the position angle shifts by about $90^\circ$) is $2.8 \times 10^{11}$ Hz.

The sub-mm bump represents a transition from optically thick to thin emission. Thus, since the dominant frequency of emission increases with decreasing radius, the peak of this bump is expected to be produced at the smallest stable radius. Above this frequency, the medium is transparent. If this picture is correct, general relativistic effects should significantly influence Sgr A*'s mm/sub-mm spectrum (Bromley, Melia & Liu 2001), which would provide an observational signature that can be tested with high-sensitivity single-dish observations. Chief among these effects is the expected amplification of nonaxisymmetric modulations in the disk or jet flux due to strong light bending and Doppler shift corrections within $\sim 4 - 5$ Schwarzschild radii of the black hole, which might therefore produce a characteristic period, associated with the innermost stable circular orbit. Earlier attempts to see a periodicity in Sgr A*'s spectrum were concerned with its possible infrared emission (Hollywood et al. 1995), which we now know is very weak given the very high temperatures and low density attained by the gas near the event horizon. However, since the X-rays appear to be produced by self-Comptonization of the radio photons, it may be possible to see these temporal variations in the X-ray signal as well.

More rapid disk fluctuations may also be present, which would stand out in the power spectrum as peaks associated with quasi-periodic oscillations (QPO). Reports of periodic or
quasi-periodic oscillations (QPO) in Active Galactic Nuclei have been rare, and in at least one case (NGC6814) were later shown to be due to confusion with a nearby object (Madejski, et al. 1993). But in the case of NGC5548 (Papadakis & Lawrence 1993), the QPOs with period $\sim 500$ s do appear to be intrinsic to the source.

X-ray observations of low-mass X-ray binaries (LMXBs) containing low-magnetic-field neutron stars have revealed two simultaneous quasi-periodic oscillation peaks in the 300-1300 Hz range some 300 Hz apart (van der Klis et al. 1996; Strohmayer et al. 1996). The characteristics of these frequencies argue strongly in favor of a beat-frequency interpretation, in which the higher frequency ($\nu_{\text{orb}}$) is associated with some preferred radius in the accretion disk, while the lower one is the beat frequency ($\nu_{\text{orb}} - \nu_s$) between $\nu_{\text{orb}}$ and the neutron star's spin frequency $\nu_s$. However, the fact that the separation between the two peaks (which is supposed to be equal to $\nu_s$) is not exactly constant, has triggered other possible interpretations. The so-called relativistic precession model (Stella & Vietri 1998) takes the upper frequency to be an orbital frequency, whereas the lower one is now the frequency of a general-relativistic precession mode of a free particle orbit at that radius. Regardless, all models of the LMXBs QPO are based on the interpretation that one of the kHz frequencies is an orbital frequency in the disk.

The idea of using kHz QPO to constrain neutron-star masses and radii, and to test general relativity, traces its roots to the work of Kluzniak & Wagoner (1985), Paczyński (1987), and Biehle & Blandford (1993), among others. Interestingly, the maximum kHz QPO frequencies observed in each source are constrained to a narrow range. Zhang et al. (1997) proposed that this narrow distribution is caused by the limit set by the innermost stable circular orbit. Miller et al. (1998) have suggested that when the inner edge of the accretion disk reaches this orbit, the QPO frequency should level off and remain constant even when other accretion parameters (such as the accretion rate) continue to change. Some evidence for this has been seen in 4U 1820-30 (Zhang et al. 1998; Kaaret et al. 1999).

The situation with the black hole candidates (BHCs) in binary systems is more complex and not as well understood. Oscillations with frequencies in the range $100 - 300$ Hz have been
seen in several sources (including Cyg X-1), and they tend to be constant. This has motivated interpretations in which these frequencies depend mostly on black-hole mass and angular momentum, e.g., through the orbital motion at the innermost stable circular orbit (Morgan et al. 1997), the Lense-Thirring precession at that radius (Cui et al. 1998), and trapped-mode disk oscillations (Nowak et al. 1997). The situation with Sgr A* is unique, and presumably better suited for such studies, for several reasons, not the least of which is the fact that its mass is known very accurately. In addition, whereas the X-ray emitting gas in LMXBs and BHCc is presumably thick over a large range of radii, the sub-mm bump in Sgr A* is produced at the smallest radius (see above), which should confine the variability frequency to that of the innermost stable circular orbit. We caution, however, that the inferences we draw from the timing observations of Sgr A* may still be somewhat ambiguous given the theoretical uncertainties regarding the structure of the emission region in this source. For example, if the range of radii associated with the temporal variations is afterall larger than what we are hypothesizing here, identification of the compact object’s spin would be subject to the same limitations as those described above for the LMXB. As we shall see below, it may nonetheless be possible not only to infer Sgr A*’s spin, but also to identify whether the Keplerian flow is in prograde or retrograde rotation.

### 3. Identifying the Observed Variability

The most rapid variability is expected to occur at the marginally stable (circular) orbit, \( r_{ms}(a) \) (see Bardeen, et al. 1972) where \( a \) is the black hole’s angular momentum parameter. This orbit has a radius \( r_{ms}(0) = 3r_S \) for a Schwarzschild black hole, in which \( a = 0 \). However, if the black hole is rotating, the location of the innermost stable orbit (including the effects of frame dragging) is dictated by the relative orientation of the spin angular momentum vector of the accretor and that of the infalling material. For illustrative purposes, we will consider the situation for a maximally rotating object, for which \( a = r_G \equiv GM/c^2 \). In that case, the prograde (+) and retrograde (−) marginally stable orbits have radii, respectively, \( r^{+}_{ms}(r_G) = r_G \) and \( r^{-}_{ms}(r_G) = 9r_G \).
Since for circular equatorial orbits in the Kerr metric, Kepler’s Third Law takes the form
\[ \Omega = \frac{2\pi}{P} = \pm \frac{c r_G^{1/2}}{r^{3/2} \pm a r_G^{1/2}}, \]  
the most rapid fluctuations associated with Sgr A* are expected to have a period somewhere within the following extreme values: \( P_{\text{min}}(a = r_G, +) \approx 2.7 \text{ minutes} \; (M/2.6 \times 10^6 \; M_\odot) \), and \( P_{\text{min}}(a = r_G, -) \approx 36.3 \text{ minutes} \; (M/2.6 \times 10^6 \; M_\odot) \), with \( P_{\text{min}}(a = 0) \approx 19.9 \text{ minutes} \; (M/2.6 \times 10^6 \; M_\odot) \). In other words, depending on its spin, Sgr A* is expected to show variations on a time scale of \( \sim 3 - 30 \text{ minutes} \) at a spectral frequency \( \nu \sim 2 \times 10^{11} \text{ Hz} \).

As such, we should be able to distinguish this from other (known) possible sources of variability, all of which have a considerably longer time scale than this: stellar opacity changes typically occur over months to years (e.g., long-period variables); a wind source fluctuation would occur over 1 day (e.g., for IRS16NW, the Wolf-Rayet star closest to Sgr A*, the time scale would be \( R_{\text{star}}/v_{\text{wind}} \sim 18 \text{ hours} \) using the parameters from Najarro, et al. 1997); stellar rotations, sunspot activity, and binary motion all would last for days; and the gravitational lensing of stars passing behind the black hole would take weeks to years to produce a noticeable variation (e.g., Alexander & Sternberg 1998). In addition, the fluctuations associated with lensing and accretion phenomena should be achromatic, in contrast to the other forms of variability discussed above, and should occur at the position of Sgr A* within the instrument’s spatial resolution.

4. Sample Light Curves and Discussion

To illustrate the possible mm and sub-mm variability in Sgr A*, we here adopt the specific model for the gas accretion near the event horizon described in § 2, which is based on the magnetohydrodynamic dynamo picture developed by Melia, Liu & Coker (2000, 2001). We have chosen a Keplerian structure that runs from an inner boundary near \( r_S \) to \( 5r_S \); the accretion flow is on circular orbits, except within \( r_{\text{ms}}(a) \), where the gas is assumed to be on freefall trajectories origination from just within the marginally stable orbit. The dynamo model then provides temperature, density and magnetic field strength in local reference frames which comove with the
gas. From these we calculate the local synchrotron emissivity (e.g., Pacholczyk 1970).

The accretion flow resides in a strong gravitational field so that relativistic beaming, Doppler shifting and gravitational focusing all modulate the flux measured well away from Sgr A*. Here we use a fully relativistic ray tracing code (Bromley, Chen & Miller 1997) to determine how these effects influence the synchrotron emission as it propagates from a comoving frame to a distant detector, idealized as an array of pixels. We obtain the specific intensity $I$ at observed frequency $\nu$ for each pixel by tracing photon trajectories back to the disk and using the Lorentz invariant $I/\nu^3$. The frequency of the photons and their emission angles in the comoving frame come from projection of the photon 4-momentum onto a tetrad basis tied to the emitter (e.g., Kojima 1991). The observed flux then follows from integration over pixels in the detector array.

Flux variations will presumably result from localized perturbations within the disk. For simplicity, we model such a perturbation by raising the temperature within a wedge-shaped patch of gas on the disk by 30% while leaving all other model parameters unmodified. The wedge rotates as a pattern with angular velocity pegged to the Keplerian value at the innermost stable circular orbit, since most of the emission at the peak frequency is produced within a narrow range of radii there (see above). We obtain the lightcurve from the patch by tracking position along its orbit and the time of flight for photons emitted within the patch.

We consider three black hole spin values, $a = 0$ and $a = \pm 0.9$. For the cases with non-zero angular momentum, the disk is assumed to lie in the equatorial plane of the black hole. The wedge-shaped perturbation is 45° in azimuthal extent, and its inner edge is at or near the marginally stable orbit. The figure caption indicates the exact radial boundaries in each of the three systems. Figure 1 illustrates the lightcurves obtained in this way at $\nu = 3 \times 10^{11}$ Hz for a disk inclined at 60° relative to the plane of the sky. Even the modest perturbations considered here can yield a detectable modulation in the lightcurve (see below). The weakest signal comes from the counterrotating disk, since in this case the perturbation is squeezed into a relatively small area between the outer edge of the disk and the marginally stable orbit. In all cases, the variability increases with frequency in mm and sub mm wavebands.
A key question concerns the feasibility of measuring the effects we have described above. The detection of the predicted flux variability in Sgr A* appears to be well within the capabilities of bolometric systems on existing mm/sub-mm telescopes. For the limiting case where $a = 0$, the predicted flux variation over the minimum predicted period, $P_{\text{min}} = 19.9$ minutes, is $\sim 80$ mJy. On a 10 m class submillimeter telescope, a typical bolometric sensitivity at 0.87 mm is $600$ mJy Hz$^{-1/2}$. (This is the NEFD of the MPIfR 19 channel bolometer array on the Heinrich Hertz Telescope. Note that this value of NEFD includes atmospheric loss and time spent on the reference position.) To determine the period of the flux variability, two independent measurements are needed over $P_{\text{min}}$. Setting the observed integration time to $\tau = P_{\text{min}}/2$, an rms noise level of 25 mJy can be obtained, suggesting the predicted variability can be detected at $\geq 3\sigma$ level in one 20 minute scan. Multiple scans can be co-added to improve the signal to noise ratio. Ultimately, it may be necessary to use a mm/sub-mm interferometer to resolve-out continuum emission not associated with Sgr A*.

This sensitivity represents a fluctuation amplitude of $1 - 2\%$ in Sgr A*'s average mm flux. Previous monitoring of this source has yielded only upper limits to the variability, though well above this level. In their multi-wavelength campaign, Falcke et al. (1998) deduced a variability amplitude in Sgr A* of no larger than 20% over several days at 3 and 2 mm. Earlier, Gwinn et al. (1991) searched for refractive scintillation arising from broadening in the ISM, and inferred an upper limit of $\sim 10\%$ variability at 0.8 and 1.3 mm on time scales of minutes to days. The present capability of bolometric systems on mm/sub-mm telescopes appears to be considerably improved, and new observations should improve these limits by factors of five or better.

In this paper, we have focused primarily on the possibility of measuring Sgr A*'s light curve at mm/sub-mm wavelengths with sufficient precision for us to infer the period associated with the marginally-stable orbit. A power-density spectrum showing power at one or more QPO frequencies could in principle provide additional information on the gas dynamics near the black hole. A detection of a periodic modulation in the light curve of Sgr A*, or of QPOs associated with its mm/sub-mm emission, would add considerably to our data base in a currently unexplored
region of the spectrum. Given that the Chandra-detected X-rays from this source apparently scale strongly with the radio emission, periodic or QPO signals may also be evident in the X-ray component. Very importantly, these measurements would demonstrate convincingly that the radio emission from this source is associated with a nuclear Keplerian flow, whose gravitational confinement is provided by a supermassive compact object. And it may lead to the measurement of this object’s spin with unprecedented accuracy.

Acknowledgments This research was partially supported by NASA under grants NAG5-8239 and NAG5-9205, and has made use of NASA’s Astrophysics Data System Abstract Service. FM is very grateful to the University of Melbourne for its support (through a Miegunyah Fellowship).
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This manuscript was prepared with the AAS Li\TeX macros v4.0.
Fig. 1.— Flux density at $\nu = 3 \times 10^{11}$ Hz plotted as a function of the observational phase for a $2.6 \times 10^6 M_\odot$ black hole accreting at $4 \times 10^{15}$ g s$^{-1}$, with a black hole spin $a = 0$ (middle curve) and $a = 0.9$ (top curve). All curves are for a “hot” wedge ($\Delta\phi = 45^\circ$), within which the temperature is artificially raised by 30% above the value at other azimuthal angles. The assumed inclination angle is $i = 60^\circ$, and the outer disk radius is taken to be $5r_S$, in accordance with the best fit model of Melia, Liu, & Coker (2000). The wedge extends from $r = 3r_S$ to $5r_S$ in the case of $a = 0$, from $r = 1.5r_S$ to $3.5r_S$ for $a = 0.9$, and from $r = 4r_S$ to $5r_S$ when $a = -0.9$. For this particular simulation, the peak to trough variation in flux can be as high as 10% over one complete cycle, though it tends to be smaller for the retrograde orbits. Similar variations may be evident in the X-ray component of Sgr A*’s spectrum if, as suggested by recent Chandra observations, the high-energy photons are produced by self-Comptonization in the radio-emitting region.