CONFRONTING THE JET MODEL OF Sgr A* WITH THE FARADAY ROTATION MEASURE OBSERVATIONS

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ABSTRACT

Sgr A* is probably the supermassive black hole being investigated most extensively due to its proximity to Earth. Several theoretical models for its steady state emission have been proposed in the past two decades. Both the radiative-inefficient accretion flow and the jet model have been shown to well explain the observed spectral energy distribution. The Faraday rotation measure (RM) has been unambiguously measured at the submillimeter wavelength, but it has only been tested against the accretion flow model. Here we first calculate the RM based on the jet model and find that the predicted value is two orders of magnitude lower than the measured value. We then include an additional contribution from the accretion flow in front of the jet and show that the measured RM may be reconciled with the model under some tight constraints. The main constraint is that the inclination angle should be greater than ~73°. However, this requirement is not consistent with an existing observational estimate of the inclination angle.

Key words: accretion, accretion disks – black hole physics – Galaxy: center – ISM: jets and outflows

1. INTRODUCTION

Because of its proximity, Sgr A* at the center of our Galaxy presents us a unique laboratory to study the low-luminosity accretion process of supermassive black holes (SMBHs; see Genzel et al. 2010; Falcke & Markoff 2013; Yuan & Narayan 2014 for the most recent reviews focusing on different aspects of Sgr A*). With a mass of 4 × 10⁶ M☉ (Schödel et al. 2002; Ghez et al. 2008; Gillessen et al. 2009; Meyer et al. 2012), Sgr A* has a bolometric luminosity of only 10⁶ erg s⁻¹ ≈ 3 × 10⁻⁹ L_Edd, the bulk of which is emitted in the submillimeter bump. High spatial resolution Chandra observations have resolved the Bondi radius, R_Bondi ≃ 4R_Ś (≃ 4 × 10⁷ R_S, where R_S ≡ 2GMBH/c² is the Schwarzschild radius of Sgr A*) given that the temperature of the ambient plasma is 1 keV (Baganoff et al. 2003, Wang et al. 2013). In combination with the inferred gas density at the Bondi radius as 10⁷ cm⁻³ (Baganoff et al. 2003), the Bondi accretion rate is estimated to be Čini ≃ 10⁻⁵ M☉ yr⁻¹, which is in good agreement with the three-dimensional numerical simulation for the accretion of stellar winds onto Sgr A* by Cuadra et al. (2006). The low luminosity combined with the Bondi accretion rate indicates that the radiative efficiency of Sgr A* is extremely low, η ≃ 10⁻⁶.

In addition to the continuum spectrum, a high level of linear polarization (2% ~ 10%) at frequencies higher than ~150 GHz has been detected (Aitken et al. 2000; Bower et al. 2005; Macquart et al. 2006). This detection provides us with a tool to measure the magnetized plasma through the Faraday rotation of the polarized light. The rotation of the polarization angle is expressed as χ = x₀ + RMλ² (where x₀ is the intrinsic polarization angle and λ is the observed wavelength). The observed rotation measure (RM) of Sgr A* can thus serve as a probe of the electron density weighted by the line-of-sight (LOS) components of the magnetic field toward these central engines.4

4 The first RM toward the extragalactic radio source was made by Cooper & Price (1962). Since then many VLBI observations (e.g., Udomprasert et al. 1997; Taylor 1998, 2000; Asada et al. 2002; Zavala & Taylor 2002, 2003; Gabuzda et al. 2004) have been carried out to reveal the parsec-scale (i.e., jet RM properties for quasars, radio galaxies, and BL Lac objects. The time variabilities and distributions of the observed RMs suggest that they are primarily intrinsic to active galactic nuclei.

Obviously, any acceptable theoretical models must satisfy both the continuum spectrum and polarization observations.

Marrone et al. (2007) made the first reliable determination of the RM for Sgr A* with simultaneous observations at multiple frequencies using the Submillimeter Array polarimeter; the mean RM is −5.6 ± 0.7 × 10⁵ rad m⁻² while a conservative 3σ upper limit to the variation of the RM is 2 × 10⁵ rad m⁻² (Marrone et al. 2007). This unambiguous detection of the RM limits the accretion rate close to the black hole to be in the range of (2 × 10⁻⁷–2 × 10⁻⁹)M☉ yr⁻¹, depending on the configuration of the magnetic field.

Accompanied by the observational progresses, numerous theoretical efforts on modeling the quiescent state emission of Sgr A* have been made, including the development of the radiatively inefficient accretion flow (RIAF) model (Yuan at al. 2003; see Yuan & Narayan 2014 for the most recent review on RIAF theory and its applications), jet model (e.g., Falcke & Markoff 2000, see also for the updated jet model by Markoff et al. 2007 and Moscibrodzka & Falcke 2013), jet-advection dominated accretion flow (ADAF) model (Yuan et al. 2002), and spherical accretion model (e.g., Melia 1992, Melia et al. 2000).

In particular, both the jet and RIAF models have successfully explained the spectrum (Falcke & Markoff 2000; Yuan at al. 2003) and the size of Sgr A* (Falcke & Markoff 2000; Yuan et al. 2006; Huang et al. 2007; Markoff et al. 2007, see Doeleman et al. 2008 for the current inferred size from 1.3 mm VLBI observations). The two models are difficult to distinguish in this sense. The RIAF model has also explained the polarization and RM. The “old” version of the RIAF model (i.e., the classical ADAF without outflow, see Narayan et al. 1995; Manmoto et al. 1997; Narayan et al. 1998) assumes that the accretion rate is independent of radius. This leads to a large electron number density in the inner region of the accretion flow and thus a large RM, which significantly depolarizes the polarized emission. Interestingly, before the detection of the radio polarization in Sgr A*, theoretical works had begun to show that very little mass available at large radii could actually accrete into the innermost region around the SMBH (e.g., Stone et al. 1999; Hawley & Balbus 2002; Igumenshchev et al. 2003; see Yuan et al. 2012b
for a review). This development could then solve the polarization problem, as explained in the updated RIAF model presented in Yuan et al. (2003). The inward decrease of mass accretion rate was explained either due to outflow (ADIOS; e.g., Blandford & Begelman 1999; Begelman 2012) or to convection (e.g., Narayan et al. 2000; Quataert & Gruzinov 2000a). Yuan et al. (2012a; see also Narayan et al. 2012; Li et al. 2013) has shown that outflow rather than convection is responsible for the inward decrease of the accretion rate. Such a theoretical prediction has been confirmed by the 3M second Chandra observations of Sgr A* (Wang et al. 2013).

In this work, we calculate the RM for the jet model. Our calculations give RM far below the observed value mentioned above (Marrone et al. 2007). Along the LOS toward the jet “nozzle,” the accretion flow should also contribute to the observed RM. This contribution depends on the viewing path through the structure of the accretion flow. We can thus either rule out the jet model or set a tight constraint on the viewing geometry.

In the rest of the paper, we present our RM calculations based on the jet model in Section 2 and calculate the RM contribution from the accretion flow in Section 3. Discussions of the implications of the results are given in Section 4. We summarize our results and conclusions in Section 5. Throughout this work, we assume the SMBH mass is $4 \times 10^6 M_\odot$ for Sgr A* and its distance to be 8 kpc.

2. JET MODEL AND ITS ROTATION MEASURE

We follow the jet model presented in Falcke & Markoff (2000, hereafter FM00, namely, the “old” jet model). In this model, the submillimeter emission of Sgr A* comes from the acceleration region of the jet close to the black hole, called “nozzle.” The sharp spectral cutoff on the infrared (IR) side of the submillimeter bump requires a narrow electron energy distribution in the nozzle. Thus two cases are considered, namely (1) a power-law electron energy distribution with the index $q = 2$ and with a steep cutoff at $5\gamma_{e,0}$ and (2) a relativistic Maxwellian distribution with $\gamma_{e,0} \approx kT/m_e c^2$. The “free” parameters in the nozzle component, such as the magnetic field $B_0$, the electron Lorentz factor $\gamma_{e,0}$, the total electron density $n_0$, and the nozzle length scale $z_0$ (sonic point), are constrained by the submillimeter spectrum. Beyond the jet nozzle, the magnetized, relativistic plasma is ejected from the nozzle to form the extended jet, where the plasma is accelerated along the jet axis through the pressure gradient and expands sideways with its initial sound speed in units of the speed of light, $\beta_{s,0} = \sqrt{\Gamma(\Gamma - 1)/(\Gamma + 1)}$ (where $\Gamma = 4/3$ is the adiabatic index). The velocity field $\beta_j$ in the extended jet with the bulk Lorentz factor $\gamma_j$ follows the modified, relativistic Euler equation. Algebraic transformations then lead to

$$\frac{\partial \gamma_j \beta_j}{\partial z} = \frac{(G^+ \gamma_j \beta_j)^2 - \Gamma}{\gamma_j \beta_j^3} = \frac{2}{z} \tag{1}$$

with $\xi = (\gamma_j \beta_j/(\Gamma(\Gamma - 1)/(\Gamma + 1)))^{1-\Gamma}$.

The equation can be solved with the critical point condition $\beta_j = \beta_{s,0}$ at $z = z_0$. Taking adiabatic cooling due to the longitudinal pressure gradient and lateral expansion (FM00) into account, one can also determine the evolution profiles of the electron number density $n(z)$, magnetic field $B(z)$, and electron Lorentz factor $\gamma_e(z)$ along the $z$ axis in a cylindrical coordinate system. These are shown in Figure 1. The geometric relation between the jet and the accretion flow is schematically shown in Figure 2.

The total jet synchrotron emission can be obtained by integrating along the $z$ axis. As we only care about the submillimeter emission, the SSC process that only contributes to the high-energy band (here X-ray) is neglected in the following calculation. The modification due to general relativistic effects on the spectrum is not included. Due to the Doppler boosting effect, we only consider the emission from the approaching jet. The fitting spectrum with the nozzle parameters is shown in Figure 3. The parameters we adopt to fit the spectrum are quite similar to those in FM00 (see also Markoff et al. 2007), with only slight adjustments due to the different mass and distance of the SMBH adopted here. Specifically, the inclination angle $\theta_i$ is determined in the spectral modeling via the Doppler boosting factor. Note that the difference of $\gamma_e,0$ for the Maxwellian

![Figure 1](http://example.com/figure1.png)

**Figure 1.** Jet dynamical profile of $\gamma_j \beta_j$, Lorentz factor $\gamma_e$, magnetic field $B$, and electron density $n_e$ along the $z$ axis. The solid (dashed) line is for the case of the power-law (Maxwellian) distribution of electrons.

![Figure 2](http://example.com/figure2.png)

**Figure 2.** Cross section structure of the jet and accretion flow (including the corona) of Sgr A* in the $r-\theta$ plane (refer to Figure 4 in Yuan & Narayan 2014 for the more precise MHD numerical simulation result). The black, thick solid line denotes one representative sight line through the plane. The dashed line presents the radial geometry of the magnetic field.
electron energy distribution with FM00 is only because of the different definition of $\gamma_{e,0}$.

We then calculate the RM in the nozzle region along our LOS as

$$\text{RM} = 8.1 \times 10^5 \int \log \frac{\gamma_e(z)}{2\gamma_e^2(z)} n_e(z) B \cdot dl \text{ rad m}^{-2}$$

(2)

for the electron density $n_e$ in units of cm$^{-3}$, the path length $dl$ in units of parsecs, and the magnetic field $B$ in units of Gaussian. The factor $\log \gamma_e(z)/2\gamma_e^2(z)$ is due to the relativistic correction (Quataert & Gruzinov 2000b). In the thermal case, the electron temperature $T$ is related to the Lorentz factor $\gamma_e$ by $\gamma_e = kT/m_e c^2$. The above equation should be applied to the external Faraday rotation, which means that the emitting region and Faraday rotator exist separately. For the case of internal Faraday rotation considered here, namely, both the emission and Faraday rotator are contributed by the jet, there is an additional correction factor of $\sim$ one half to Equation (2) (Burn 1966; Homan 2012). Following the GRMHD numerical simulations of the accretion flow and jet formation (see review by Yuan & Narayan 2014 and Figure 4 of that paper), we find that the magnetic field in the jet is mainly radial and contains no reversals along our LOS. The ordered magnetic field we adopt presents an upper limit of the RM considered here.

In the case of thermal electrons, the integration of Equation (2) for the thermal electrons in the nozzle region gives

$$\text{RM} \approx 7.7 \times 10^3 \text{ rad m}^{-2},$$

(3)

which is two orders of magnitude less than the observed value (Marrone et al. 2007). In the case of power-law electrons, the result, $\text{RM} \approx 1.2 \times 10^3 \text{ rad m}^{-2}$, is similar. The point of the integration begins from the far side of the jet surface at the 4–5 $R_s$ from the black hole (see Figure 2) to the near side of the jet. This integration all the way down to the innermost region of the jet nozzle neglects the optical depth effect on its RM. If the emitting plasma is optically thick, this calculation should be regarded as an upper limit, which means that the corresponding RM will be far below the observed value. We feel that there is little room to adjust the model parameters to increase the RM value to match the observed one. Compared to the RIAF model of Yuan et al. (2003), the strength of the magnetic field is similar, and the small value of the RM is mainly because of the electrons’ density in the nozzle being much lower than that in the accretion flow. The dramatic discrepancy between the jet and the observation for the RM thus puts a challenge to the jet model.

3. ACCRETION FLOW CONTRIBUTION TO THE RM

A possible contribution to the observed RM, in addition to the jet itself, may come from the accretion flow around Sgr A* (see the illustration shown in Figure 2). The RM contribution from the accretion flow depends on the distributions of the electron density and magnetic field in the $r-\theta$ plane of the accretion flow. We obtain such information from the multidimensional MHD numerical simulations (De Villiers et al. 2005; Yuan et al. 2012b).

Based on a numerical simulation with the radial dynamical range as large as four orders of magnitude, Yuan et al. (2012b, see also references therein) show that the radial density profile of the accretion flow can be well described by a power-law form, namely $n_e \propto r^{-\beta}$, with the index $\beta$ in the range of 0.5–1.0. The temperature profile is described by $T_e \propto r^{-1}$. The strength of the magnetic field is tied to the density roughly by a parameter $\beta = q_p/gas/(g_{ps} + p_{mag})$, where $p_{gas}$ and $p_{mag}$ are the gas and magnetic pressures. The value of $\beta$ is typically $\sim 0.5$ (see review by Yuan & Narayan 2014). However, for the “magnetically arrested disk” (Narayan et al. 2003; Tchekhovskoy et al. 2011; Tchekhovskoy & McKinney 2012; Narayan et al. 2012; McKinney et al. 2012), the value of $\beta$ can be smaller, i.e., the magnetic field is stronger. Even in this case, current MHD simulations indicate that the field energy can at most be in equipartition with the thermal energy, i.e., $\beta \gtrsim 0.5$. We therefore consider $0.5 \lesssim \beta \lesssim 0.9$. The configuration of the magnetic field is less well determined. The MHD numerical simulation, however, can give us some information, which is that the field configuration somewhat depends on the initial condition of the simulation. Without losing generality, we can simply assume a radial configuration. In reality, this should be multiplied by a factor of $\cos(\alpha)$ to account for the effect of the inclination angle $\alpha$ of the magnetic field relative to our LOS. This would greatly reduce the RM contribution from the accretion flow. So our calculation for the case of a pure radial magnetic field gives an upper limit to the RM contributed by the accretion flow, which we will see will not change our conclusion presented below. Furthermore, based on fully relativistic three-dimensional numerical simulations of accretion flows under the Kerr metric, De Villiers et al. (2005) find that the density and gas pressure decrease exponentially with polar angle (see Figure 3 of that paper).

With the corresponding distributions normalized to the values at the Bondi radius as inferred from Chandra data (Baganoff et al. 2003; Wang et al. 2013), we obtain the density, temperature, and magnetic field at each point in the $r-\theta$ plane of the accretion flow. The integration of Equation (2) along the LOS then gives
values of however, we can conclude that the above-mentioned “required” et al. 2013). Given the model and measurement uncertainties, constraint will be on the inclination angle. The required large angle means that our LOS should intersect with the accretion disk close to its equatorial plane.

Figure 4. RM contribution from the accretion flow as a function of the viewing angle for four different model parameter sets ($p, \beta$). Only the red solid and blue dotted lines, which correspond to $p = 1.0$ and $\beta = 0.5$–0.9, can reach the magnitude of the observed RM, $\sim$10$^5$ rad m$^{-2}$.

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the corresponding RM as a function of the viewing angle for different parameters $p$ and $\beta$. The jet inclination angle ($\theta_i$) is also considered as a free parameter, although it has a preferred value (see later discussion). Figure 4 shows that a smaller $\beta$ (i.e., stronger magnetic field) and/or a larger $p$ (i.e., weaker wind) can produce a larger RM. This is easy to understand. Only for the red solid and blue dotted lines, which correspond to $p = 1.0$ and $\beta = 0.5$–0.9, plus an inclination angle $\theta_i \gtrsim 73^\circ$, or equivalently the angle between our LOS and the equatorial plane of the accretion flow $\lesssim 17^\circ$, can we obtain the magnitude of the observed RM, $\sim$10$^5$ rad m$^{-2}$.

Are the above values of $p$ and $\beta$ reasonable? As stated above, the MHD numerical simulations of the hot accretion flow have shown that $\beta = 0.5$–0.9 is reasonable. The value of $p = 1$. Is close to its upper limit obtained from numerical simulations and the modeling of Sgr A* (Yuan et al. 2003), although it is larger than that obtained from fitting the iron lines, $p \sim 0.5$ (Wang et al. 2013). Given the model and measurement uncertainties, however, we can conclude that the above-mentioned “required” values of $p$ and $\beta$ are roughly consistent with the current theoretical and observational constraints. In this case, the main constraint will be on the inclination angle. The required large angle means that our LOS should intersect with the accretion disk close to its equatorial plane.

4. DISCUSSION

Is this inclination angle requirement consistent with reality? First, there are a few model constraints on the orientation of the black hole spin. However, all these constraints are based on the assumption that the observed submillimeter radiation of Sgr A* comes from the hot accretion flow rather than the jet, in either the analytical RIAF model (Yuan et al. 2003; see also Huang et al. 2007; Broderick et al. 2011) or the MHD numerical simulations (e.g., Sharma et al. 2007; Mościbrodzka et al. 2009; Dexter et al. 2010; Shcherbakov et al. 2012). Thus such constraints do not apply here.

Second, it is widely accepted that accretion materials onto Sgr A* are mainly supplied by winds from circumnuclear massive stars (e.g., Cuadra et al. 2008). These stars are primarily in a disk, which has an inclination of $\theta_i \sim 53^\circ$, and a line-of-nodes position angle of $\sim$100$^\circ$ (east from north; Paumard et al. 2006). One may expect that the angular momentum of this stellar disk and its inclination are reflected in the accretion flow morphology projected in the sky. Indeed, this expectation has been confirmed by both the X-ray observations of the quiescent X-ray emission from Sgr A* (Wang et al. 2013) and the recent Event Horizon Telescope observations at 1.3 mm (Psaltis et al. 2014). The elongation direction is also consistent with the well-constrained value, $\sim$90–100$^\circ$, inferred from the recent millimeter-VLBA observations (Bower et al. 2014a). While the X-ray emission traces the accretion flow in outer regions, the millimeter emission in innermost ones. Therefore, we may consider that the inclination angle of the accretion flow is well determined by that of the stellar disk. Adopting the value of $53^\circ$ gives a RM less than 10$^4$ rad m$^{-2}$, much smaller than the observed value.

Finally, the jet model itself has a constraint on the inclination angle, which is $\theta_i \approx 55^\circ$ or $60^\circ$ (for the “old” jet model, but see below for the updated one) for the power law or the thermal plasma within the jet and the accretion flow considered above? The jet model fails to explain the observed RM. However, with the further consideration of the 7 mm VLBA data in the spectral energy distribution analysis, the updated jet model (Markoff et al. 2007) constrains the inclination angle as $\theta_i \gtrsim 75^\circ$ and a position angle in the sky as 105$^\circ$. With this large angle, we find that the updated jet model could have a RM chiefly in the foreground accretion flow comparable to the observed one. In this case, the direction of the jet is completely inconsistent with that of the stellar disk.

Are there any other contributions to the RM in addition to the plasma within the jet and the accretion flow considered above? One possibility is from the ISM (interstellar medium). However, several studies have concluded that the ISM contribution to the RM is much less than $\sim$10$^4$ rad m$^{-2}$ due to the weaker magnetic field ($\lesssim 1$ mG; e.g., Han et al. 1999; Baganoff et al. 2003; Marrone et al. 2007). The recently discovered magnetar PSR J1745–2900, close to Sgr A* with a projected offset of $\sim 0.12$ pc, shows a RM of $(-6.69 \pm 0.005) \times 10^3$ rad m$^{-2}$ (Eatough et al. 2013). The recent VLBA observations further demonstrate that PSR J1745–2900 shares the same scattering medium with Sgr A* (Bower et al. 2014a). Therefore, one may conclude that the ISM contribution to the RM is far below the value observed toward Sgr A* itself (Marrone et al. 2007).

Therefore, the “old” jet model may be ruled out, whereas the new one requires that the jet direction deviates significantly from being perpendicular to the accretion flow due to unknown reasons.

5. SUMMARY

We have calculated the expected RM from the jet model of Sgr A*. We find that the contribution to the RM from the jet is estimated to be less than $7.7 \times 10^3$ rad m$^{-2}$, while the observed RM is $5.6 \pm 0.7 \times 10^3$ rad m$^{-2}$ (the minus sign ignored). We have then further considered the RM contribution from the sight line passage through the foreground accretion flow and find that its angle relative to our LOS needs to be larger than $\theta_i \gtrsim 73^\circ$, assuming that the jet is perpendicular to the accretion flow. However, this requirement of the inclination angle is inconsistent with either, $\theta_i \approx 55^\circ$–$60^\circ$, set by the “old” jet model itself (Falcke & Markoff 2000) or $\sim 53^\circ$, set by the stellar disk inclination. Therefore, the “old” jet model can firmly
be rejected. The updated jet model with a highly inclined LOS, however, cannot be ruled out by the current RM observation alone. The jet direction predicted by the model appears to be inconsistent with the axis of the accretion flow. The future high precision imaging data lending more stringent constraints on the putative jet and/or the inclination and size of the accretion flow could finally break the degeneracy of the theoretical models.

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