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LETTER TO THE EDITOR

A time-dependent jet model for the emission from Sagittarius A*

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ABSTRACT

Context. The source of emission from Sgr A*, the supermassive black hole at the Galactic Center, is still unknown. Flares and data from multiwavelength campaigns provide important clues about the nature of Sgr A* itself.

Aims. Here we attempt to constrain the physical origin of the broadband emission and the radio flares from Sgr A*.

Methods. We developed a time-dependent jet model, which for the first time allows one to compare the model predictions with flare data from Sgr A*. Taking into account relevant cooling mechanisms, we calculate the frequency-dependent time lags and photosphere size expected in the jet model. The predicted lags and sizes are then compared with recent observations.

Results. Both the observed time lags and size-frequency relationships are reproduced well by the model. The combined timing and structural information strongly constrain the speed of the outflow to be mildly relativistic, and the radio flares are likely to be caused by a transient increase in the matter channelled into the jets. The model also predicts light curves and structural information at other wavelengths which could be tested by observations in the near future.

Conclusions. We show that a time-dependent relativistic jet model can successfully reproduce: (1) the quiescent broadband spectral energy distribution of Sgr A*; (2) the observed 22 and 43 GHz light curve morphologies and time lags; and (3) the frequency-size relationship. The results suggest that the observed emission at radio frequencies from Sgr A* is most easily explained by a stratified, optically thick, mildly relativistic jet outflow. Frequency-dependent measurements of time-lags and intrinsic source size provide strong constraints on the bulk motion of the jet plasma.

Key words. black hole physics – Galaxy: center – galaxies: active – galaxies: jets – radiation mechanisms: general – radio continuum: general

1. Introduction

The compact radio source Sagittarius A* (hereafter Sgr A*), at an estimated distance of 8.4 ± 0.6 kpc (Reid et al. 2009) and mass of ~4 × 10⁶ M☉ (Ghez et al. 2008; Gillessen et al. 2009), is our closest supermassive black hole. When compared to other active galactic nuclei (AGN), Sgr A* is extremely under-luminous at all wavelengths, suggesting either that the mass accretion rate (Ṁ) onto the black hole, or the radiative efficiency, is very low. Polarization measurements suggest that Ṁ ≤ 10⁻⁷ M☉/yr (Marrone et al. 2007). Recent multiwavelength campaigns that have monitored Sgr A* simultaneously from radio to X-rays have found that even though the luminosity of Sgr A* is low relative to its AGN counterparts, its emission is quite variable at all wavelengths. Flaring activity at both sub-mm and higher frequencies has been observed on timescales ranging from minutes to hours, suggesting that the emission at these frequencies is produced very close to the supermassive black hole, probably within a few tens of gravitational radii (Rg = GM/c²).

Although flaring appears to be nearly simultaneous at these frequencies (Marrone et al. 2008; Eckart et al. 2008; Dodds-Eden et al. 2009), the flares seem to have an increasingly long time delay at longer wavelengths. For example, Yusef-Zadeh et al. (2008) found that the 43 GHz flares precede the 22 GHz flares by 20 ± 10 min, and that 350 GHz flares precede those of 43 GHz by 30–60 min.

The physical origin of the observed electromagnetic radiation from Sgr A* has been under active debate for more than a decade. Attempts to model the emission from Sgr A* can be broadly classified into two categories: (1) accretion inflow models (Melia 1992; Narayan et al. 1998; Liu & Melia 2002; Yuan et al. 2006); and (2) relativistic outflow/jet models (Falcke & Biermann 1999; Falcke & Markoff 2000; Yuan et al. 2002). The radio, NIR, and X-ray flare light curves were modeled assuming expansion of a spherical plasma blob (see e.g., Yusef-Zadeh et al. 2008; Eckart et al. 2009). Recently Falcke et al. (2009) suggested that the radio time-lag data and measurements of intrinsic size at various frequencies (e.g., Bower et al. 2004; Shen et al. 2005; Doeleman et al. 2008) can be used to resolve the degeneracy between inflow and outflow models. It has long been suspected that radio flares such as those reported by Yusef-Zadeh et al. (2008) could be “smoking gun evidence” of jets in sources such as Sgr A* (Falcke 1999b).

While jets have not been directly imaged in Sgr A*, several observations strongly suggest the presence of jets in this source. The flat/slightly inverted radio spectral energy distribution (SED) (signature of a compact self-absorbed jet in the radio; see e.g., Blandford & Königl 1979) observed from Sgr A* are similar to those of other low-luminosity AGNs. M81 and Sgr A* have very similar spectra and polarization properties in the cm-radio band, and M81 has been found to have weak jets (Nagar et al. 2005). Radio observations of the stellar X-ray
binary system A0620−00 (Gallo et al. 2006) at almost near quiescent luminosity suggest that compact jets are present at bolometric luminosities as low as $\sim 10^{-3} \, L_{\text{Edd}}$. If jet physics and accretion flow scale with the mass of the black hole, then Sgr A* ($L_{\text{bol}} \sim 10^{-2} \, L_{\text{Edd}}$) is also expected to harbor a faint, compact jet. Steady-state jet models have previously been used to model the broadband quiescent spectra of Sgr A* successfully (Falcke & Markoff 2000; Yuan et al. 2002); steady-state models, however, cannot predict the flaring activity.

In this paper we develop a proper treatment of the time-dependent cooling processes of the particle distribution, while keeping the basic hydrodynamic outflow model the same as in Falcke (1996), allowing a semi-analytical treatment of the problem. Once dominant cooling mechanisms are taken into account, the time-dependent jet model naturally accounts for all the observational constraints, namely, (a) the broadband SED; (b) the observed light-curve morphologies and time-lags; and (c) the observed frequency-size relationship.

2. Model

We assume that a fraction of the accretion inflow is channelled into two symmetric, collimated supersonic outflows. The energy distribution of the radiating leptons entering the jet is assumed to be a thermal, relativistic, Maxwell-Juttner distribution. Most of the kinetic energy of the jet is assumed to be carried by cold, non-radiating baryons. The bulk speed at the base of the jet is assumed to be the sound speed, and beyond the base (or the “nozzle”) the jet plasma accelerates longitudinally via pressure-driven supersonic jet.

The observed spectrum from the compact jet is modeled as the sum of emission from cylindrical segments along the jet axis. Within each segment, we consider the following processes influencing the local evolution of the particle distribution:

- **synchrotron cooling**: Losses due to synchrotron emission are given by $\dot{\gamma}_{\text{syn}} = 4c\sigma_T U_B \gamma^2 / (3m_e c^2)$, where $\sigma_T$ is the Thomson cross-section and $U_B = B^2 / 8\pi$ is the magnetic energy density;

- **inverse Compton (IC) cooling**: Losses due to IC scatterings are given by $\dot{\gamma}_{\text{Com}} = 4c(\sigma_T U_{\text{rad}})(\gamma^2 / (3m_e c^2))$, where, following de Kool et al. (1989), we define $(\sigma_{\text{nc}} U_{\text{rad}})(\gamma) = 4\pi c \int \sigma_{\text{nc}}(\gamma, \nu) J_\nu \text{d}\nu$. Here $\sigma_{\text{nc}}(\nu, \gamma)$ is the Klein-Nishina correction to the scattering cross-section and $J_\nu$ is the mean intensity;

- **adiabatic expansion**: Cooling due to adiabatic expansion is given by $\dot{\gamma}_{\text{ad}} = (1 / 3) / \nabla \cdot \mathbf{v}$, where $\nabla \cdot \mathbf{v}$ denotes the divergence of the bulk velocity field (Longair 1992).

For numerical discretization, we assume that the plasma in each segment cools during the time that it requires to cross the segment. We follow the evolution of this “parcel” of jet plasma as it moves from one segment to another, i.e., in a comoving frame, without any particle loss/escape. For simplicity, we assume that this comoving “parcel” of particles cools and radiates independently, i.e., is not influenced by its neighbors. While this is obviously a simplification, given the overall simplicity of the model we feel this is justified. The continuity equation for the time evolution of leptons in this case is given by

$$\frac{\partial N(\gamma, t)}{\partial t} = \frac{\partial}{\partial \gamma} \left[ \dot{\gamma}(\gamma, t) N(\gamma, t) \right] \quad \dot{\gamma}(\gamma, t) = \dot{\gamma}_{\text{syn}} + \dot{\gamma}_{\text{Com}} + \dot{\gamma}_{\text{ad}}$$

Given the low luminosity of Sgr A* ($\sim 10^{-9} \, L_{\text{Edd}}$), the compactness parameter ($\ell \approx L_{\text{bol}} / (R_m c^2)$; see Guilbert et al. 1983) is very small ($\ell \sim 10^{-6}$ for $R = 10 \, R_g$). Therefore, pair processes are not important here. There is also no injection term in Eq. (1) since particle acceleration seems to be very weak or absent in Sgr A* (Markoff 2005). Recasting Eq. (1) as a Fokker-Planck equation, we used the fully implicit Chang-Cooper algorithm (Chang & Cooper 1970; Chiaberge & Ghisellini 1999) to solve it.

Once the time-evolved particle distribution solution had been obtained, we then computed the emitted SED due to angle-averaged synchrotron emission using Eq. (10) of Crusius & Schlickeiser (1986) for relativistic electrons with Lorentz factor $\gtrsim 2$, and using Eq. (8) of Katarzyński et al. (2006) for electrons in the cyclo-synchrotron regime with Lorentz factor $<2$. Following the prescription of Blumenthal & Gould (1970), IC is computed by incorporating the Klein-Nishina correction for scattering beyond Thomson limit. The seed photons for IC are the photons produced locally by synchrotron emission (synchrotron self-Compton; SSC). In the absence of detailed spatial information about the hot stars constituting the central star cluster close to Sgr A* (see e.g., Genzel et al. 2000), we estimated emission from these stars by considering 100 stars each of temperature 10 000 K, situated 0.5 parsecs from Sgr A*. The photon density of locally produced synchrotron+SSC photons in the jet is at least 3 orders of magnitude higher than the total photon density from these stars, suggesting that external inverse Compton losses due to photons from the nearby cluster is not important.

Since the bulk motion of the emitting jet plasma is relativistic, we first compute the Doppler factor $D = [\Gamma (1 - \beta \cos \theta)]^{-1}$, where $\theta$ is the angle between the velocity and the line of sight, $\beta$ is the bulk speed, and $\Gamma = 1 / \sqrt{1 - \beta^2}$ is the bulk Lorentz factor. The observed SED is then calculated by applying the appropriate special relativistic transformations to the emitted frequency and flux (see e.g., Lind & Blandford 1985), and taking into account time-lags due to the spatial extent of the flow.

For any given frequency, when the flux from each jet segment is plotted as a function of distance from the black hole, it roughly resembles a bell-shaped curve (in the self-absorbed part of the jet). The full width at half maximum (FWHM) is an indicator of the size of the photosphere of the jet at this frequency. We used this procedure to calculate the frequency-size relationship.

In our model, the radio flares are caused by a perturbation in $M$ at the jet-base, leading to a transient density enhancement. During a flare of duration $t_f$, this density enhancement is quantified by the parameter $f_0$, so that the number density at the base $(n_0)$ as a function of time is given by

$$n_0(t) = \begin{cases} 1 + f_0 & 0 \leq t \leq t_f \\ n_0 & \text{otherwise} \end{cases}$$

As the overdensity propagates outward along the jet, the additional pressure in the overdense region should cool and expand into the neighboring segments of lower pressure and density. While a full computation of this diffusion (and resultant cooling) would require MHD simulations beyond the scope of
the present paper, the effect can still be captured by assuming an additional velocity-dependent cooling term in the continuity equation for the overdense region. Assuming that the overdense region expands longitudinally into the neighboring segments with some fraction of the sound speed, we write this additional cooling term as a function of distance from the black hole as $\gamma/\gamma = f \beta c/\gamma$. Thus $f \beta c$ can be interpreted as the longitudinal speed with which the overdense region expands.

### 3. Modeling the quiescent broadband emission and the radio flares from Sgr A* on July 17, 2006

We compare the model predictions with the simultaneous observations of Sgr A* in 22 and 43 GHz on 2006 July 17 (Yusef-Zadeh et al. 2008), which has the best simultaneous coverage to date of a flare at both frequencies. Indirect evidence suggests that Sgr A* is observed at a large inclination angle (Markoff et al. 2007; Falcke et al. 2009). For simplicity, we therefore assume that the jets are perpendicular to our line-of-sight, even though the model can accommodate any inclination angle. The free parameters of the model are: temperature ($T_e$) and density ($n_0$) of the thermal leptons at the base, location of the sonic point or the nozzle ($h_0$), radius of the nozzle ($r_0$), and its magnetic field ($B_0$). The flare is parametrized by its start time ($t_0$), duration ($\Delta t$), density enhancement fraction ($f_e$), and expansion speed of the overdense region ($f_o$, which is a fraction of the sound speed). The model is set to match the specific flare under consideration.

The good agreement between the data and the model light curves is shown in Fig. 1. The model parameters are given in Table 1. Note that we only model the flare that peaks around 6.5 h UT in 43 GHz. The increase in flux in both bands during the end of the observations may be the beginning of another flare as suggested by Yusef-Zadeh et al. (2008), but we do not model this due to lack of full coverage. In Fig. 2, we show model-predicted light curves at 0.7, 1.3, 2, 3.6, 6, and 13 cm. From Fig. 1, it is clear that the light curves are asymmetric and even a phenomenological model would require assuming: (a) a rise timescale; (b) a decay timescale; and (c) an amplitude. In our model, three parameters also describe the flare completely, viz. $\Delta t$ (which can be roughly associated with the rise time), $f_o$ (associated with decay time), and $f_e$ (associated with amplitude). It is thus important that a single set of flare parameters fits two rather disparate light curves at two frequencies. Moreover, the decrease in amplitude is consistent with the decrease in average variability with frequency. A compilation of the rms flux variability of Sgr A* averaged over many flares as compiled by Falcke et al. (2009) shows that the rms variability decreases with increasing wavelength. The relative amplitude of this flare at both 43 and 22 GHz is about 0.6 times the long-term rms variability; therefore this flare was not extraordinarily bright or faint, and may be considered to be a fairly typical flare from Sgr A*.

The frequency-size relationship predicted by the model is displayed in Fig. 3, and shows reasonable agreement with the data at low frequencies where the jet becomes optically thick. The discrepancy at shorter wavelengths where the spectrum is optically thin is expected given that our model ignores general relativistic effects, and simplifies the physics of jet formation and launching, both of which must play an important role.
very close to the black hole. For this model, the rate at which
matter is channeled toward both jets is \( M = 2n_{\text{H}} \beta c \gamma \pi r_0^2 \) = 
\( 2.4 \times 10^{-9} M_7 \) yr\(^{-1}\), which is about 2 orders of magnitude lower than the upper limit of \( 10^{-7} M_7 \) yr\(^{-1}\) suggested by linear polar-
ization observations.

### 4. Discussion

We have shown that a time-dependent relativistic jet model can explain most of the observational features of Sgr A*. The main conclusions of this work are:

- the model presented here can describe the quiescent broad-
band SED of Sgr A*, as well as its long-term radio variabil-
ity;
- assuming that the radio flares are caused by a transient den-
sity enhancement at the base of the jet, which then prop-
agates outward, the model can also fit the 22 and 43 GHz
light curve morphology of the flares seen on 2006 July 17 by
Yusef-Zadeh et al. (2008). We predict light-curve morphol-
ogy and delays at longer wavelengths, which can be used to
test the model with future observations;
- the model predicted frequency-size relationship also matches
the observed radio data quite well.

The radio emission in our model originates in the self-absorbed,
optically thick part of the outflow, where adiabatic losses dom-
inate over radiative cooling. Therefore, variability in the ra-
dio light curves largely traces the expansion of the jet plasma.
Assuming that the flares have the same frequency-size rela-
tionship as the quiescent emission, the time-delay measure-
ments combined with frequency-size measurements strongly
constrain the bulk speed of the jet plasma in this model and ex-
clude subrelativistic expansion speeds. An alternate model used by
Yusef-Zadeh et al. (2008) to fit the radio light curves as-
sumes adiabatic, subrelativistic expansion of a spherical blob of
plasma, i.e. the classic van der Laan (1966) model. At the very
least, our modeling shows that the van der Laan model is not
unique, and that the jet model, in contrast to the van der Laan
model, not only correctly predicts the light curves and the over-
all variability amplitudes, but also fits the frequency-size relation
without violating any other observational constraints. It must be
kept in mind that the jet model does not attempt to explain ei-
ther the NIR or X-ray flares. The NIR/X-ray flares trace particle
(re)energization and cooling very close to the black hole, while
only marginally affecting the optically thick radio flux (Markoff
et al. 2001), and no tight correlation between radio and X-ray
flares have so far been found. A full general relativistic MHD
model including radiative cooling (see e.g., Fragile & Meier
2009; Mościbrodzka et al. 2009; Dexter et al. 2009) would be
required to model the jet launching region. However, the simple
model presented here captures the important physics and shows
that the jet model explains the radio flaring properties naturally,
because of the simple adiabatic expansion of overdensities in
the outflow (likely linked to variations in the acceleration rate).
Future coordinated multiwavelength campaigns, especially mea-
surements of time-lags, sizes and positional offset at other wave-
lengths, will enable a clearer understanding of the velocity pro-
file of the jet from Sgr A*.

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### References

Chang, J. S., & Cooper, G. 1907, J. Comp. Phys., 6, 1
Falcke, H. 1999a, in The Central Parsecs of the Galaxy, ed. H. Falcke, A. Cotera,
W. Duschl, F. Melia, & M. J. Rieke, ASP Conf. Ser., 186, 113
Falcke, H. 1999b, in The Central Parsecs of the Galaxy, ed. H. Falcke, A. Cotera,
W. Duschl, F. Melia, & M. J. Rieke, ASP Conf. Ser., 186, 148
van der Laan, W. 1966, Nature, 211, 1311