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Magnetic-Reconnection and Current-Sheet Model for the Radio Arc and Threads in the Galactic Center

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Abstract

We propose a new mechanism to explain the radio arc and threads in the Galactic center by current sheets produced by local magnetic shears due to the interaction of a moving cloud and a vertical field based on three-dimensional magnetohydrodynamical simulations. Magnetic reconnection and acceleration of cosmic-ray electrons in the current sheet would result in a high contrast of the radio emissivity inside and outside the arc and threads.

Key words: Galaxy: center — ISM: clouds — ISM: jets and outflows — ISM: magnetic fields — magnetohydrodynamics: MHD simulation

1. Introduction

The Galactic center is full of spectacular radio features, among which the nonthermal radio arc is the most prominent unusual structure, believed to be a highly ordered magnetic field vertical to the galactic plane. Each magnetic tube is as thin as one pc or less, and as long as a few tens of pc (Yusef-Zadeh et al. 1984; Morris, Yusef-Zadeh 1985; Yusef-Zadeh, Morris 1987). Besides the arc, there are numerous vertical radio filaments, called radio threads, also believed to be of magnetic origin (Anantharamaiah et al. 1991; Lang et al. 1999; LaRosa et al. 2000, 2004).

Magnetic fields, as strong as 0.01–1 mG, have been inferred for the radio arc and threads from their large Faraday rotation measures (Tsuboi et al. 1986; Sofue et al. 1987; Yusef-Zadeh et al. 1997; Lang et al. 1999). Their straight structures indicate that they are composed of highly ordered magnetic fields perpendicular to the galactic plane. Although large-scale vertical magnetic fields appear to be common in the central regions of spiral galaxies (Tsuboi et al. 1986; Sofue et al. 1987; Sofue, Fujimoto 1987b), it has been a mystery why the arc and threads are shining so locally, exhibiting a high contrast of brightness to the ambient regions.

Some models have been proposed for their origin. In a spark model for the radio arc (Sofue, Fujimoto 1987a), the ejection of magnetized gas from Sgr A, observed as thermal filaments, hits the vertical field in galactic rotation, and reconnection of the fields in the arc and thermal filaments results in the acceleration of cosmic-ray electrons to radiate nonthermal radio emission. Benford (1988) proposed an electrodynamic model of the radio arc and filaments. In his model, the electric field induced by the motion of molecular clouds drives currents along the magnetic field, which accelerate cosmic rays to emit synchrotron radiation. On the other hand, a galactic-wind model (Dahlburg et al. 2002) suggests that the interaction of the wind from the nucleus with a gas cloud causes a wake instability, which grows to produce filamentary structures perpendicular to the galactic plane, mimicking the radio threads. This theory may explain the morphology of the threads, but cannot be applied to the arc, and also has difficulty to explain the high contrast of radio brightness in the threads.

In this letter, we expand the basic idea of the spark model and/or the electrodynamic model, and try to explain the arc and threads, including their morphology, by current sheets produced by local magnetic shears due to the interaction of moving clouds and a vertical field. The magnetic reconnection and acceleration of cosmic-ray electrons in the current sheet would result in a high contrast of radio emissivity inside and outside the arc and threads.

2. Three-Dimensional Non-Axisymmetric MHD Simulation of the Cloud-Magnetic Field Interaction

Vertical magnetic fields are often observed in spiral galaxies, including the Milky Way, and will be a common structure in the central regions (Sofue, Fujimoto 1987b). If there exists an accreting gas disk, the vertical field lines would be twisted, and form a large-scale magnetic jet; various simulations have been made using an axisymmetric scheme (Uchida et al. 1985; Uchida, Shibata 1985; Shibata, Uchida 1986, 1987).

On the other hand, the distribution of molecular gas in the Galactic center is far from axisymmetric, but is significantly shifted to positive galactic longitudes, and is very clumpy (Bally et al. 1987; Oka et al. 1998). Longitude–velocity diagrams also show non-axisymmetric kinematics, which is partly induced by the accretion of gas by a bar structure (Sawada et al. 2004). Such non-axisymmetric motions of gas will cause significant local disturbances of the magnetic fields, which may only be treated by three-dimensional MHD calculations.

In order to examine how a locally moving gas cloud disturbs the ordered magnetic field, we performed three-dimensional MHD simulations. The calculations were carried out using the CIP-MOC-CT scheme (Evans, Hawley, 1988; Yabe, Aoki 1991; Yabe et al. 1991; Stone, Norman 1992; Kudoh et al. 1999; Kigure, Shibata 2005). The CIP scheme can accurately follow the contact discontinuity, or the surface of the cloud in the present case. This scheme has been developed into a three-dimensional cylindrical code, and is now applicable to local disturbances of field lines near the origin of the coordinates (Kigure, Shibata 2005). The numbers of meshes were $171 \times 100 \times 480$ in the radius, azimuth, and height (r, ϕ, z) directions.

We assumed that the ambient magnetic field is at rest with respect to the rest coordinate frame, and the filed lines are perpendicular to the galactic plane defined by $(r, \phi, z = 0)$. The gravitational force was added by putting a point mass M at the Galactic center coinciding with the origin of the coordinates, which mimics the central massive core (Takamiya, Sofue 2000) including the black hole (Genzel et al. 2003; Ghez et al. 2005). We put a gaseous corona around the central mass at hydrostatic equilibrium, but neglected its rotation.

The initial field strength was taken to be uniform at $B = B_0$. A gas cloud with a radius r_w was put at an initial position of $(r, \phi, z) = (1, 0, 0)$. The cloud was given of a Keplerian initial velocity of $(v_r, v_\phi, v_z) = (0, 1, 0)$. The gas cloud is assumed to have an initial density distribution represented by

$$\rho = \rho_0 \left[1 + \cos(\pi |x - x_0|/r_\mathrm{w})\right]/2 \qquad (1)$$

if $|x - x_0| < r_\mathrm{w}$ with $x_0 = (r, \phi, z) = (1, 0, 0)$. We took $r_\mathrm{w} = 0.3$. The density distribution of the corona around the center was given by

$$\rho = \rho_\mathrm{c} \exp\left[\alpha \left\{r_0/(r^2 + z^2)^{1/2} - 1\right\}\right], \qquad (2)$$

where r_0 is the unit length. The parameter α is defined as $\alpha = \gamma V_{\mathrm{K}0}^2/s_\mathrm{c}^2$, where s_c is the sound velocity in the corona, $V_{\mathrm{K}0} = (GM/r_0)^{1/2}$ is the Keplerian velocity at radius $r = r_0$. Here, ρ_c is the coronal density at radius r_0, $\alpha = 1.0$ and $\rho_\mathrm{c}/\rho_0 = 10^{-3}$, where ρ_0 is the initial cloud density at the cloud center $(r, \phi, z) = (1, 0, 0)$.

The plasma-β, the ratio of the gas pressure to the magnetic pressure defined by $\beta = 2s^2/\gamma V_\mathrm{A}^2$, was taken to be 0.4 in the cloud center, and was of the order of $\sim 10^{-2}$ in the ambient region, where $\gamma = 5/3$ is the specific heat ratio of the gas. Here, s is the sound velocity at the cloud center. We assumed a free boundary condition. The gravitational and kinetic energy densities in the cloud were much greater than the magnetic field energy density. Hence, the field lines were nearly passive to the motion and distortion of the cloud. Initially, we took $u_\mathrm{m}/u_\mathrm{g} \sim u_\mathrm{m}/u_\mathrm{k} = (V_{\mathrm{A}0}/V_{\mathrm{K}0})^2 = 5 \times 10^{-3}$, where $V_{\mathrm{A}0}$ and $V_{\mathrm{K}0}$ are the Alfvén velocity and the velocity of cloud. Here, $u_\mathrm{g} = GM_0\,\rho/r$, $u_\mathrm{k} = \rho v^2/2$, and $u_\mathrm{m} = B^2/(8\pi)$. On the other hand, we assume that the ratio of magnetic-to-thermal pressures is ~ 5 for the coronal gas, and therefore, the magnetic field is not strongly disturbed by the corona. The gas pressures between the corona and cloud were assumed to be balanced, so that $(s_\mathrm{c}/s)^2 = \rho_0/\rho_\mathrm{c} \sim 10^3$.

Figure 1 shows the result of the three-dimensional MHD simulation. The vertical lines are the magnetic lines of force. The (x, z) plane is indicated by a colored panel, with the brightness being proportional to the gas density. A gas cloud is rotating around the center in Keplerian motion. The top panels show the time evolution of field lines from $t = 0$ to 3, and the bottom-left panel is at $t = 3$. Here, time t is normalized by $P/2\pi$ with P being the rotation period of the cloud around the center. As the cloud moves, the magnetic field lines are wound, and twisted locally due to the cloud motion as well as the gravitational distortion of the cloud shape. Note that the viewing point of figure 1 is rotating with the cloud motion, so that the (x, z) plane is apparently rotating in the figure.

According to the twisting distortion of the field lines, a current sheet is produced, along which magnetic reconnection is supposed to take place. The bottom-left panel of figure 1 shows an equal-current-density surface with $J = 1.5$ at $t = 3$. Here, J is the current density calculated by $J = \mathrm{rot}\,B$, and is normalized by $J_0 = b_0/r_0 = [\rho_0 V_{\mathrm{K}0}^2]^{1/2}/r_0$, where b_0 is the non-dimensionalized initial magnetic strength. We emphasize that the thus-formed local enhancement of current density produces a feature mimicking the radio arc and thread. The bottom-right panel shows the radio arc as reproduced from VLA observations at 21 cm (Yusef-Zadeh, Morris 1987).

3. Magnetic-Reconnection and Current-Sheet Model for Arc and Threads

Based on the simulation, we propose a new model to explain the origin of the radio arc and threads in the Galactic center, which we call the magnetic-reconnection and current-sheet (MRC) model.

Suppose a gas cloud with a different velocity from that of the field lines hits the vertical magnetic lines of force, such as due to an infalling cloud, ejection from the center, or shock waves. The cloud would locally twist the vertical magnetic field. Figure 2 illustrates how a moving cloud would influence the magnetic field lines. The locally twisted field lines would then produce a magnetic shear between the twisted and ambient fields. This magnetic shear produces a current sheet, along which magnetic reconnection would occur. This mechanism is similar to the nano-flare model for solar-coronal heating (Parker 1988). In the present case, the twisted field looks more like a bunch of lines of force than a sheet, and, hence, the current sheet would be more like a "current thread", as figures 1 and 2 show.

The flux density of the released energy per unit volume along the current sheet can be expressed by the Poynting flux,

$$f \sim (B_z B_\phi/4\pi)V, \qquad (3)$$

where B_z, B_ϕ, and V are the magnetic strengths in the vertical and azimuthal directions, and the velocity of gas, respectively.

The vertical component, B_z, is on the order of the initial value, $B_z \sim B_{z0}$. On the other hand, the initial value of B_{ϕ_0} is almost zero, while it is created during the twist to attain a finite value of B_ϕ, which we denote as $B_\phi \sim \xi B_{z0}$. Hence, the flux of the released energy along the current thread is of the order of

$$f \sim \xi(B_{z0}^2/4\pi)V. \qquad (4)$$

In the present numerical calculation, we have $\xi \sim 0.1$. This flux should be compared with the one in the ambient region,

$$f_0 \sim (B_{z0} B_{\phi_0}/4\pi)V_0. \qquad (5)$$

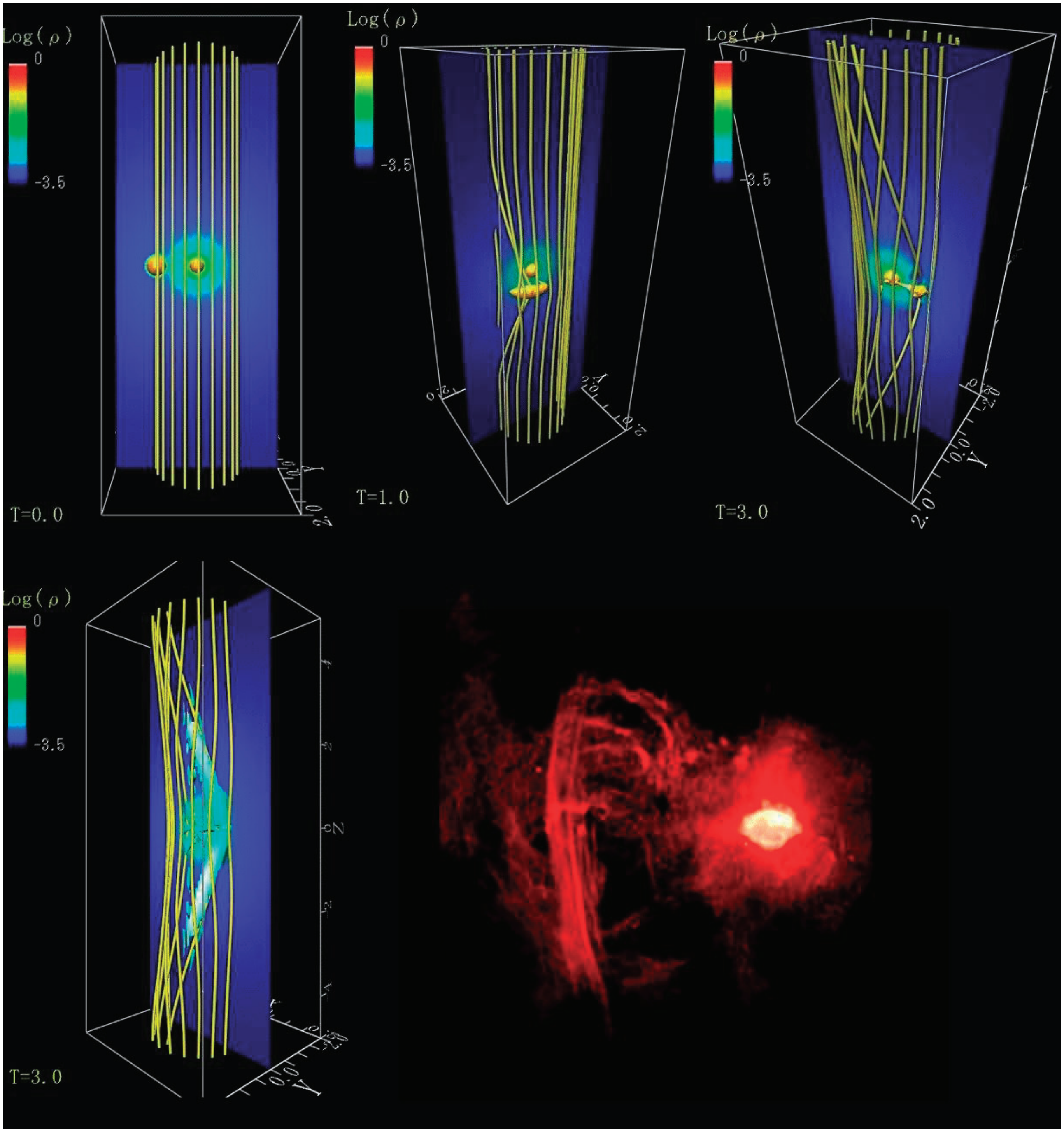

Fig. 1. Three-dimensional, non-axisymmetric MHD simulation of the interaction of a gas cloud with a vertical magnetic field in the Galactic center region. The field is embedded in a hydrostatic gaseous halo around a central mass. The upper panels show the evolution of magnetic lines of force at $t = 0$, 1, and 3. The moving cloud is disturbed by the gravitation, and locally twists the magnetic field. For the units of time and linear scale, see the text. The lower-left panel shows an equal-current-density surface of the current sheet (current thread) at $J = 1.5$ for $t = 3$. The lower-right panel is the radio arc (vertical structures) near the Galactic center (the brightest spot) (Yusef-Zadeh, Morris 1987).

Thus, the ratio of the released fluxes inside and outside the current thread is of the order of

$$\eta \sim f/f_0 \sim \xi[B_{z0}/B_{\phi 0}][V/V_0]. \tag{6}$$

The ratio η would attain an extremely large value, because the ambient region has almost a negligible value of $B_{\phi 0}$, because there exists neither a magnetic twist nor a current sheet.

The energy released in the current sheet will be used to accelerate cosmic-ray electrons, which interact with the magnetic field and radiate synchrotron emission. We emphasize that the radio emissivity in the current sheet (thread) increases significantly even without large amplification of the field strength because of the large η value. Let the fraction, δ, of the Poynting flux, f, be transformed to the synchrotron

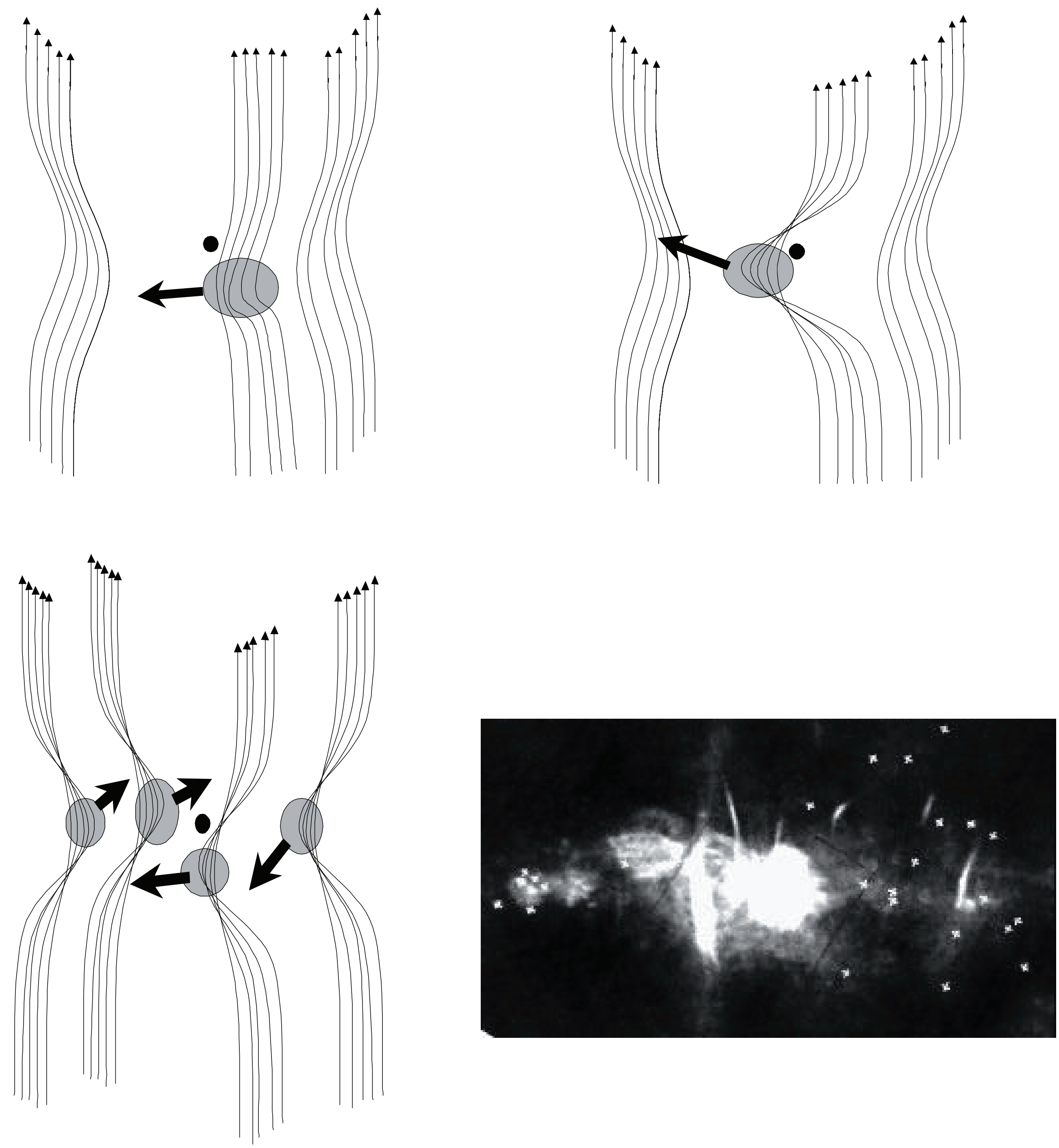

Fig. 2. Schematic illustration of a scenario for the origin of Galactic center radio threads, due to a local twist of the vertical magnetic field lines. Reconnection of the field lines along current sheets (threads) accelerates cosmic-ray electrons to emit synchrotron radiation. Inserted in the bottom-right corner is the observation of 90-cm radio threads (LaRosa et al. 2000).

emission. We then obtain a radio flux of

$$f_{\rm r} \sim \delta\xi (B_{z0}^{\ 2}/4\pi)V. \tag{7}$$

The surface brightness of radio emission at frequency ν is, then, estimated to be on the order of

$$\Sigma = f/\nu \sim \delta\xi B_0^2 V/4\pi\nu. \tag{8}$$

If we take $B_0 \sim 10^2\,\mu$G, $V \sim 100\,{\rm km\,s^{-1}}$, and $\nu \sim 1\,$GHz, we obtain $\Sigma \sim \delta\,\xi\,10^{-11}$ erg s^{-1} cm^{-2} Hz^{-1}, or $\Sigma \sim \delta\,\xi\,10^{-14}\,{\rm W\,m^{-2}\,Hz^{-1}}$. This leads to a brightness temperature at 1 GHz of $T_{\rm b} = \delta\,\xi\,\lambda^2\,\Sigma/2k \sim 10^5\,\delta\,\xi$ K at around $\nu \sim 1\,$GHz, where $\lambda = c/\nu$ is the wavelength and k is the Boltzmann constant.

The radio brightness for the radio arc and threads has been observed to be of the order of $T_\mathrm{b} \sim 0.1\,\mathrm{K}$ at $\sim 1\,\mathrm{GHz}$ (Yusef-Zadeh, Morris 1987; LaRosa et al. 2004). Here, ξ is approximately ~ 0.1 from the simulation. The transformation efficiency δ of the Poynting flux to the radio emission is subject to sophisticated treatments of magnetic reconnection and acceleration of cosmic rays. Instead, we here estimate a possible value of the parameter δ. In order for the formulated radio brightness to agree with the observed brightness, we require only a very small efficiency on the order of $\delta \sim 10^{-5}$.

We have discussed the MRC model for one particular cloud. However, due to barred galactic shocks as well as angular-momentum loss by a large-scale magnetic field twist, a number of clouds are infalling to the Galactic center. Recurrent interactions of gas clouds and clumps would, therefore, result in many "threads" in the Galactic center region, as indeed observed (LaRosa et al. 2000, 2004). Among the many threads, the strongest interaction between a cloud and a magnetic field is presently observed at the radio arc. In fact, the field lines in the arc are interacting with a dense gas cloud (Tsuboi et al. 1997). An interaction with the thermal filament extending from Sgr A with the arc (Sofue, Fujimoto 1987a) may also infer a local twist. Such disturbances would be caused not only by accreting gas clouds, but also by hydrodynamical waves and shocks triggered by various activities in the Galactic center region, such as star formation and gas ejection from the center. Analyses of the shapes, distribution, and frequency of radio threads may give information about the hydrodynamical conditions in the Galactic center region.

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