The Snake - a Reconnecting Coil in a Twisted Magnetic Flux Tube

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ABSTRACT

We propose that the curious Galactic Center filament known as “The Snake” is a twisted giant magnetic flux tube, anchored in rotating molecular clouds. The MHD kink instability generates coils in the tube and subsequent magnetic reconnection injects relativistic electrons. Electrons diffuse away from a coil at an energy-dependent rate producing a flat spectral index at large distances from it. Our fit to the data of Gray et al. (1995) shows that the magnetic field ~ 0.4mG is large compared to the ambient $\sim 7\mu$G field, indicating that the flux tube is force-free. If the *relative* level of turbulence in the Snake and the general interstellar medium are similar, then electrons have been diffusing in the Snake for about 3×10^5 yr, comparable to the timescale at which magnetic energy is annihilated in the major kink. Estimates of the magnetic field in the G359.19-0.05 molecular complex are similar to our estimate of the magnetic field in the Snake suggesting a strong connection between the physics of the anchoring molecular regions and the Snake. We suggest that the physical processes considered here may be relevant to many of the radio filaments near the Galactic Center. We also suggest further observations of the Snake and other filaments that would be useful for obtaining further insights into the physics of these objects.

Subject headings: Galaxy: center, ISM: kinematics and dynamics, ISM: magnetic fields, magnetohydrodynamics, radio continuum: ISM, stars: formation

1. Introduction

The fundamental nature of the numerous radio filaments observed near the Galactic Center (see LaRosa et al. (2000) for an overview) is unclear. In particular: How are they formed? What are the sources of the relativistic electrons? Why do they have such large magnetic field strengths? What is the reason for the unusually flat spectral indices in some of them? The discovery of the Snake (Gray et al. 1991), a 60 pc by 0.4 pc filament, approximately 150 pc to the West of Sgr A, resulted in the additional feature that the characteristics of the radio emission are strongly related to a morphological "kink". Further observations (Gray et al. 1995), revealed a major and a minor kink, with the radio intensity and spectral index systematically varying away from the major kink. Various models have been proposed to explain the spectacular elongated structure of the Snake (see Gray et al. (1995)). However, none of them have been able to successfully explain its major features. In our view, the Snake is in many respects one of the least complicated of the filamentary features close to the Galactic Center and a good physical model may hold the key to understanding the numerous arcs and filaments in the Galactic Center region.

We propose that the Snake is a magnetic flux tube with both ends anchored in dense rotating material (molecular clouds and/or associated HII regions). Differential rotation of the tube at either or both ends produces a monotonically increasing toroidal magnetic field and when this reaches a critical value "coils" or "loops" are formed through localized kink instabilities. Release of the magnetic energy stored in a coil, through magnetic reconnection (and possibly shocks), is the source of the relativistic electron energy. Energetic electrons diffuse away from each coil at an energy-dependent rate causing a flattening spectral index.

2. Details of the model

Let us take R to be the radius of the tube, $L_{\rm tube}$ its length and B_ϕ and B_z the toroidal and axial components of the magnetic flux density, with magnitude B, in a cylindrical (r, ϕ, z) coordinate system coincident with the central axis of the unperturbed tube. As the end(s) of the tube is(are) rotated, the toroidal field increases and when $B_\phi/B_z \sim 1$, the kink instability produces a coil of magnetic flux with magnetic energy $\Delta E_m \approx 4^{-1}\pi R^3 B^2$ (Alfvén (1950), p117). We identify the observed major kink with such a coil; the minor kink may be another coil at a different stage of development. Numerical simulations, in a solar physics context (Bazdenkov & Sato 1998; Amo et al. 1995), have shown that the coil's magnetic energy is annihilated on a time scale of order a few transit Alfvén crossing times, $L_{\rm tube}/v_A$, where v_A is the Alfvén speed. Magnetic reconnection and possibly associated shocks in the coil can provide a source of energy for the acceleration of electrons to relativistic radio-emitting energies [2]. Once accelerated, the electrons diffuse and we model the diffusion of particles away from the acceleration region by a one-dimensional diffusion equation, assuming a uniform cross-section for the tube. Taking $f(p)$ to be the electron phase-space density, x the spatial distance along the flux tube away from the major kink, $K(p)$ the momentum-dependent diffusion coefficient, and $C(p)$ the rate per unit volume of momentum space at which electrons are injected into the coil by the acceleration process, we adopt the diffusion equation:

$$\frac{\partial f(p,x,t)}{\partial t} - \frac{\partial}{\partial x}\left(K(p)\frac{\partial f(p,x,t)}{\partial x}\right) = C(p)\delta(x) \tag{1}$$

The delta function indicates that we are treating the coil, located at $x = 0$, as an infinitesimally small volume with respect to the rest of the tube. We also assume that the timescale for dissipation of energy in the coil is greater than the time over which the electrons diffuse. We discuss this assumption further below. We adopt a power-law for $K(p)$, i.e. $K(p) = K_0(p/p_0)^\beta$, where K_0 is the diffusion coefficient at an electron momentum, p_0 of a GeV/c. We also assume that $C(p) = C_0(p/p_0)^{-s}$. Integrating equation (1) from $x = 0^-$ to $x = 0^+$ gives the boundary condition at $x = 0$, namely,

$$\left.\frac{\partial f(p,x,t)}{\partial x}\right|_{x=0} = -\frac{1}{2}\frac{C(p)}{K(p)} \tag{2}$$

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[2]The presence of shocks cannot be inferred from the Bazdenkov et al. simulations since they assumed an incompressible fluid.

We normalize the diffusion equation and the boundary condition by introducing the distance $L = 15$ pc between the major and minor kinks as a fiducial length together with the normalized variables $\tau = K(p)t/L^2 = (K_0 t/L^2)\,(p/p_0)^{\beta}$, $\xi = x/L$ and $g(\xi,\tau) = 2K_0 C_0^{-1} L^{-1}\,(p/p_0)^{s+\beta}\; f(p,x,t)$. In these variables, the diffusion equation and the boundary condition become

$$\frac{\partial g}{\partial \tau} = \frac{\partial^2 g}{\partial \xi^2} \qquad \text{with} \qquad \left.\frac{\partial g}{\partial \xi}\right|_{\xi=0} = -1 \tag{3}$$

for which the solution is

$$g(\xi,\tau) = \left(\frac{4\tau}{\pi}\right)^{1/2} e^{-\xi^2/4\tau} - \xi\left[1 - \mathrm{erf}\left(\frac{\xi}{\sqrt{4\tau}}\right)\right] \tag{4}$$

The number density of particles per unit Lorentz factor, γ, is

$$N(\gamma,\xi,\tau) = N_0\,\gamma^{-a}\,g(\xi,\tau), \tag{5}$$

where $N_0 = 2\pi(m_e c)^3 (C_0 L/K_0)\gamma_0^{2+a}$, $\gamma_0 = (m_e c)^{-1} p_0$ and $a = s + \beta - 2$. We use $N(\gamma)$ to evaluate the angle-averaged synchrotron emissivity, $< j_\nu >$, as a function of frequency, ν, from

$$< j_\nu(\xi) >= (\sqrt{3}e^2/4c)\,N_0\,\nu_B\,\left(2\nu/3\nu_B\right)^{(1-a)/2} \int_{y_1}^{y_2} y^{(a-3)/2} g(\xi,\tau)\bar{F}(y)\,dy \tag{6}$$

Here, $\nu_B = eB/(2\pi m_e c)$ and the angle-averaged single electron emissivity $\bar{F}(y) = y\int_y^\infty \sqrt{1 - y^2/u^2}\,K_{5/3}(u)\,du$. Because of the γ dependence in $g(\xi,\tau)$, the spectral index near the kink is not simply $(a-1)/2$ but $(s + \beta/2 - 3)/2 = (a-1)/2 - \beta/4$.

For a uniform flux tube, of radius R and angular diameter Φ, imaged with a circular Gaussian beam with standard deviation, σ, the angle-averaged flux density per beam is $F_\nu = 4(2\pi/3)^{1/2}\,(\sigma\Phi)\,[I_0(\Phi^2/12\sigma^2) + I_1(\Phi^2/12\sigma^2)]\,(< j_\nu > R)$ where I_0 and I_1 are modified Bessel functions. Using this expression and the expression for the emissivity, we have performed a least squares fit to the observed flux densities (Gray et al. 1995) at 1446 and

4790 MHz, for which, $\sigma = 4.90''$, $R = 0.22\,\mathrm{pc}$ and $\Phi = 9.4''$ are appropriate. We restrict the fit to the region of the Snake between galactic latitudes of $-3'$ and $-17'$ that is clearly related to the major kink; the radio images and the spectral index plot (Gray et al. (1995), Figure 12) indicate that the minor kink influences the flux density south of $b = -17'$. The parameters of the fit (see Figure 1) are $N_0 = 3.5 \times 10^{-5}\mathrm{cm}^{-3}$, $B = 0.37\,\mathrm{mG}$, $a = 2.14$, $\beta = 0.57$ and $\tau_0 = K_0 t/L^2 = 0.46$. The deviations of the fit from the model are most likely the result of systematic effects, such as variation in the field strength and width of the tube, rather than the statistical uncertainty in the data. The magnetic field can be estimated from the data, since it is related to the frequency index, which varies significantly along the tube. However, experimentation with the fit shows that the precision of the estimate of B is not much better than a factor of a few although the result that the magnetic field is much greater than the ambient interstellar value $\approx 7\,\mu\mathrm{G}$ (Gray et al. 1995), is robust. Therefore, the flux tube is force-free.

If we assume that the injected electron spectrum extends between momenta, p_1 and p_2, the total electron energy in the flux tube can be estimated as follows. Let A be the tube's cross-sectional area, then the rate, P_e of relativistic electron energy injection into the tube, is $P_\mathrm{e} = 4\pi A c \int_{p_1}^{p_2} p^3 C(p)\, dp = 4\pi A C_0 c p_0^4\, (4-s)^{-1}\, \left[(p_2/p_0)^{4-s} - (p_1/p_0)^{4-s}\right]$ The total relativistic electron energy in the flux tube is therefore,

$$\begin{aligned} E_{\mathrm{e,tot}} = P_\mathrm{e} t &= 2\pi R^2 m_e c^2\, \gamma_0^{2-a} \left(\frac{K_0 t}{L^2}\right) \left(\frac{N_0 L}{4-s}\right) \left[(p_2/p_0)^{4-s} - (p_1/p_0)^{4-s}\right] \\ &\approx 6.3 \times 10^{44}\ (p_2/p_0)^{0.43}\ \mathrm{ergs} \end{aligned} \tag{7}$$

using the expression for N_0 (following equation (5)) and the derived parameters. Time enters through the dimensionless model parameter, $\tau_0 = K_0 t/L^2$. For an upper cutoff of 10 GeV, $E_{\mathrm{e,tot}} \approx 3.9 \times 10^{45}$ ergs and for 100 GeV, $E_{\mathrm{tot}} \approx 1.1 \times 10^{46}$ ergs. The available magnetic energy stored in the coil, $E_B \approx 3.5 \times 10^{46}$ ergs, exceeds the total energy in electrons, as required for consistency of the model, but not necessarily by a large factor, depending upon the maximum energy to which electrons are accelerated. This is a consequence of the high value of the derived magnetic field. These comparisons also suggest that the diffusion of electrons has been taking place for a time comparable to the total time available to annihilate the coil, consistent with our not observing the process at a special epoch and consistent with the assumption of continuous injection.

The energy density of electrons, $\epsilon_{\rm e}$, can be derived simply from equation (5) for $N(\gamma)$. Near the coil ($\xi = 0$),

$$\epsilon_{\rm e} = \frac{N_1\, m_{\rm e} c^2}{-a + \beta/2 + 2} \left[(p_2/p_0)^{-a+\beta/2+2} - (p_1/p_0)^{-a+\beta/2+2} \right] \tag{8}$$

where $N_1 = 2\pi^{-1/2} N_0 \tau_0^{1/2} \gamma_0^{-\beta/2}$. The energy density is insensitive to the upper cutoff, and for $p_2 = 10$ GeV/c, $\epsilon_{\rm e} \approx 6 \times 10^{-11}$ ergs cm^{-3}, an order of magnitude larger than the energy density of the ISM.

3. The spectrum of hydromagnetic turbulence

It is usually assumed that relativistic electrons resonantly scatter off a pre-existing level of hydromagnetic turbulence since resonant Alfvén waves are damped rapidly in the warm interstellar medium by ion-neutral collisions, although this constraint is more important at higher then GeV energies (e.g. Melrose (1982)). Let the energy density per unit wave number, k, of resonant Alfvén waves (either pre-existing or self-excited) be $W(k) = W_0\,(k/k_0)^{-\eta}$, where $k_0 = eB/cp_0$ corresponds to waves resonating with 1 GeV electrons. Then, the spatial diffusion coefficient for relativistic electrons is $K(p) = 4\eta(\eta+2)/9\pi\,(c^2/e)\,B^{-1} p\,[W_{\rm m}/k_R W(k_R)]$ where $W_{\rm m} = B^2/8\pi$ and $k_R = eB/cp$ is the resonant wave number (Melrose 1982). Numerically, $K(p) = 1.4 \times 10^{19} \eta(\eta+2)\ (B/{\rm mG})^{-1}\ (W_{\rm m}/k_0 W_0)\ (p/p_0)^{2-\eta}$ cm^2 s^{-1}. Hence, $\beta = 2 - \eta$ and $\eta \approx 1.43$ for the parameters of our model. Our value of $\beta \approx 0.57$ is close to the Ormes &

Protheroe (1983) value of 0.7 derived from a cosmic ray propagation model. However, more recent models adopt a Kolmogorov value, $\beta = 1/3$, combined with the effects of "minimal reacceleration" (e.g. Ptuskin et al. (1999)). We have yet to take account of this possible effect. In order to constrain β more effectively, one needs to take into account, not only minimal reacceleration, but the other physical parameters in the problem such as the width and strength of the flux tube and time variability in the injection process.

The time since the coil started to inject electrons along the flux tube is of interest for comparison with other timescales. This is $t = L^2/K_0\,\tau_0 \approx 3.1 \times 10^5\, K_{0,26}^{-1}\,(\tau_0/0.46)$ yr. For cosmic rays, Ptuskin et al. (1999) take $K_0 \sim 10^{28}\,\mathrm{cm^2\,s^{-1}}$, implying that $k_0 W_0/W_\mathrm{m} \sim 10^{-6}$. If the same *relative* level of turbulence exists in the Snake, then $K_0 \sim 10^{26}\,\mathrm{cm^2\,s^{-1}}$ since $K_0 \propto B^{-1}$ and $t \sim 3 \times 10^5$ yr. According to the numerical simulations of comparatively short wound flux tubes (Bazdenkov & Sato 1998), a coil disappears "explosively" in $1-3$ Alfvén-crossing times, L_tube/v_A. For the Snake, this is $\approx 1.5 - 4.5 \times 10^5\,(n/10\,\mathrm{cm^{-3}})^{1/2}$ yr based on $L_\mathrm{tube} \approx 60$ pc and a number density $n \sim 10\,\mathrm{cm^{-3}}$ for the ambient interstellar medium (Gray et al. 1995). Explosive bursts recur approximately every 5 Alfvén times, i.e. approximately every $7.5 \times 10^5\,(n/10\,\mathrm{cm^{-3}})^{1/2}$ yr. Thus, for $K_0 \sim 10^{26}\,\mathrm{cm^2\,s^{-1}}$, the time over which the electrons have been diffusing is of order the timescales of the energy releasing process and, as above, we are not required to invoke a special epoch of observation. This also again justifies our assumption of continuous injection over the diffusion timescale.

4. The origin of the magnetic field

We suggest that a twisted magnetic flux tube with the properties required by our model would arise in the following way: The magnetic flux tube is initially anchored at both ends in molecular clouds before they undergo contraction and initiate star formation. Since molecular clouds condense from the warm interstellar medium, the cloud magnetic field at the pre-contraction phase exceeds the general ISM value. Hence such a flux tube emerging into the ISM from a molecular cloud would expand. As one or both of the clouds contract and rotate, a significant toroidal field is produced and the resulting magnetic curvature force draws in the flux tube, thereby increasing the poloidal flux density in the entire flux tube to the molecular cloud value and eventually leading to a force free state which is also unstable. (Both a force-free configuration and instability require B_ϕ at the boundary of the flux tube to be of order B_z.)

There is reasonably good evidence for the anchoring of the Snake in molecular clouds or associated HII regions. Observations by Uchida et al. (1996) reveal that the northern end of the Snake intersects an HII region in a CO "hole" in the molecular cloud and HII region complex, G359.19-0.05. The supernova remnant observed in projection against the southern end (Gray et al. 1995) provides at least circumstantial evidence for molecular material in that region. Another possibility is that the Snake could be part of a giant loop, the other end of which is anchored in another region of the Galactic Center. The generation of toroidal field is inextricably linked to the evolution of magnetic field and angular velocity in contracting molecular clouds. Here we discuss some of the physics involved. However, it will be evident that a complete analysis involves substantial issues in the physics of contracting molecular clouds that are beyond the scope of this letter.

The generation of toroidal fields by contracting clouds is related to the radiation of torsional Alfvén waves by the rotating field anchored in the cloud (see Mestel (1999), p 453). Let ρ_0 be the mass density of the background ISM and let B_z be the (uniform) poloidal flux density of the cloud and ISM. The angular velocity, Ω and toroidal component, B_ϕ of the field in the tube are governed by:

$$\rho_0 r \frac{\partial \Omega}{\partial t} = \frac{B_z}{4\pi} \frac{\partial B_\phi}{\partial z} \qquad \frac{\partial B_\phi}{\partial t} = r B_z \frac{\partial \Omega}{\partial z} \tag{9}$$

The angular velocity in the background medium in which the Alfvén speed is v_A, satisfies

$$\frac{\partial^2 \Omega}{\partial t^2} = v_A^2 \frac{\partial^2 \Omega}{\partial z^2} \tag{10}$$

As a consequence of these equations, the toroidal field in a tube which is anchored only in the cloud is $B_\phi \approx -r(4\pi\rho_0)^{1/2}\Omega_0 \approx -1.5 \times 10^{-6}(n/10\,\mathrm{cm}^{-3})^{1/2}(\Omega_0/\mathrm{km\,s^{-1}\,pc^{-1}})$ G, where Ω_0 is the angular velocity of the cloud (Mestel 1999). In order to generate $B_\phi \sim 4 \times 10^{-4}$ G, one requires an extraordinarily large value of $\Omega \sim 270\,\mathrm{km\,s^{-1}\,pc^{-1}}$.

Consider now a tube anchored, as well, in another molecular cloud. The boundary conditions on Ω are now, $\Omega = \Omega_0$ at $z = 0$ and $\Omega = 0$ at $z = L_{\rm tube}$. On a timescale long compared to the Alfvén time, the relevant solution of equation (10) is $\Omega = \Omega_0(1 - z/L_{\rm tube})$, implying from the second of equations (9), that

$$\frac{\partial B_\phi}{\partial t} = -B_0 \frac{r\Omega_0}{L_{\rm tube}} \tag{11}$$

Further, if Ω_0 is constant for a time t, then, after the flux tube has been twisted through an angle $\Delta\phi = \Omega_0 t$ we have $B_\phi = -r\Delta\phi\, B_z/L_{\rm tube}$. This expression can be derived simply from flux freezing in a twisted flux tube, neglecting the propagation time of Alfvén waves and is used by Alfvén (1950), for example, in the theory of the instability of twisted flux tubes referred to above. The purpose of the derivation here is to make a clear connection with the torsional Alfvén waves involved in the standard treatment of magnetic braking. On the basis of this model, $B_\phi \sim B_z$ would be attained for the Snake if $\Omega t \sim L_{\rm tube}/R \approx 300(R/0.2\,\mathrm{pc})^{-1}$ radians. This would be the case, for example, for a cloud rotating at an angular velocity of $30\,\mathrm{km\,s^{-1}\,pc^{-1}}$for a period of 10^7 yr.

However, the above estimates of the toroidal field are somewhat contrived in that they assume that the flux tube has a constant radius which is clearly not the case in a contracting cloud. Moreover, the poloidal field changes under the opposing effects of compression and ambipolar diffusion and the evolution of the field in the external ISM (see above) is also important. However, the main point is that the anchoring of the magnetic field at *both* ends substantially affects the generation of toroidal field and the requirements on the angular velocity.

A related issue involves that of subcritical or supercritical contraction of the anchoring cloud(s). In *subcritical* contraction, the initial magnetic field supports the cloud and contraction occurs as a result of ambipolar diffusion of the magnetic flux together with magnetic braking. The latter prevents the cloud from approaching centrifugal equilibrium (e.g. Basu & Mouschovias (1995) and references therein) and the angular velocity remains low, except for the latest, rapid stages of contraction when the core becomes critical. On the other hand, in the supercritical case, the magnetic field cannot halt contraction, and if the cloud has an initial angular velocity, angular momentum conservation causes it to spin up, until it reaches centrifugal equilibrium. Further contraction is then the result of magnetic braking (Mestel & Paris 1984). Therefore, supercritical contraction may offer the best prospect for twisting of the flux tube. However, this is a complex issue and investigation is deferred for future work. Note also, that Basu & Mouschovias (1995) began their simulations with slowly rotating clouds.

An independent estimate of the poloidal magnetic field is of interest since this is one of the key parameters in our model and also determines whether the molecular cloud contraction associated with the Snake is sub- or supercritical. We use parameters derived by Uchida et al. (1996) who estimate that the clouds adjacent to the CO hole have masses $\sim 5 \times 10^3 M_\odot$ with radii, $R \sim 2\,\mathrm{pc}$. If we assume that these clouds have formed through compression of spheroidal regions (with semi-axes R_0 and KR_0) of the warm interstellar medium of density $n_0 \sim 10\,\mathrm{cm}^{-3}$ and with an ambient magnetic field of $B_0 \sim 7 \times 10^{-6}\,\mathrm{G}$ (Gray et al. 1995), then flux conservation implies that

$$B_z \approx \frac{B_0 R_0^2}{R^2} = \frac{B_0}{R^2}\left[\frac{3}{4\pi K}\frac{M}{\mu n_0 m_p}\right]^{2/3}$$

$$\approx\ 7\times10^{-4}\left(\frac{B_0}{7\times10^{-6}\mathrm{G}}\right)\left(\frac{R}{2\,\mathrm{pc}}\right)^{-2}K^{-2/3}\left(\frac{M}{5\times10^{3}M_{\odot}}\right)^{2/3}\left(\frac{n_0}{10\,\mathrm{cm}^{-3}}\right)^{-2/3}\mathrm{G} \tag{12}$$

Using expressions derived in Mestel (1999) (pp. 429 *et seq.*), the critical magnetic field

$$B_{\mathrm{crit}}\approx 6\times10^{-5}-1\times10^{-4}\left(\frac{M}{5\times10^{3}M_{\odot}}\right)\left(\frac{R}{2\,\mathrm{pc}}\right)^{-2}\ \mathrm{G} \tag{13}$$

with the lowest (highest) value for a spherical (flattened) cloud. These estimates of B_z and B_{crit} raise the prospect that the clouds in the G359.19-0.05 complex are subcritical unless the original ISM region is highly prolate ($K >> 1$). However, our main point is that these indicative estimates of both the actual and critical fields are similar to our estimate of 4×10^{-4} G from our model for the Snake. It is therefore possible that the flux density in the associated contracting molecular cloud is not greatly enhanced over its initial value, as a result of ambipolar diffusion. Many of the molecular clouds in the vicinity may have fields of this magnitude, but it is not until they are twisted and "lit up" by reconnection induced by an instability that they become observable. Interestingly the Basu & Mouschovias (1995) simulations show that the magnetic field outside the supercritical core is indeed time independent.

5. Discussion

High resolution images of the Snake near the major kink (Gray et al. (1995), Figures 10 and 11) show that the Snake appears to be split in two, similar to flux tubes in the late stages of the Bazdenkov & Sato (1998) simulations. This provides additional support for our proposal. As well as being directly applicable to the Snake, our model may open up a number of appealing possibilities for the dynamics of other magnetic filaments in the interstellar medium near the Galactic Center. It is feasible, in an environment with such a large density of molecular clouds, that rotation of magnetic flux tubes threading their cores would lead to kink instabilities and reconnection. The flattening spectral index of the Snake depends upon the differential diffusion of energetic particles and this is such a well known phenomenon in the regular ISM that its role in this model is unremarkable. The index of the momentum dependence of the diffusion parameter that we have inferred for the Snake is in the range of values used in models of cosmic ray propagation. More detailed models raise the prospect of a better determination of this index as well as the other parameters in this model. In particular, a more precise value of the index of the momentum dependence of the particle creation rate, which our current estimates place near the value associated with strong shocks, would be of interest. The type of data that is essential for more detailed modeling include (1) High resolution images showing more clearly the structure of the flux tube over its entire length. (2) Flux densities at different frequencies, enabling one to better constrain the energy dependence of the diffusion parameter and the magnetic field.

It remains to be shown that flux tubes in the Galactic Center can be wound up to such an extent that they produce a significant toroidal field. If an anchoring cloud acquires an angular velocity which persists for long enough that it rotates through 300 radians (~ 50 revolutions), that would be sufficient. Another possibility is that the required winding could be produced in a contracting cloud, although this idea requires further investigation. In our independent estimates of the magnetic field in the Snake and in the related issue of subcritical or supercritical contraction we have concentrated exclusively on the molecular complex at the northern end of the Snake. Currently, however, there is little known about the southern end and the masses and rotation rates of molecular clouds in that region will certainly be of interest.

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Figure Caption

Figure 1: The model fit to the 1446 MHz (filled squares) and 4790 MHz (open circles) flux densities (Gray et al. 1995) for the Snake. The model fit only applies to the region associated with the major kink.

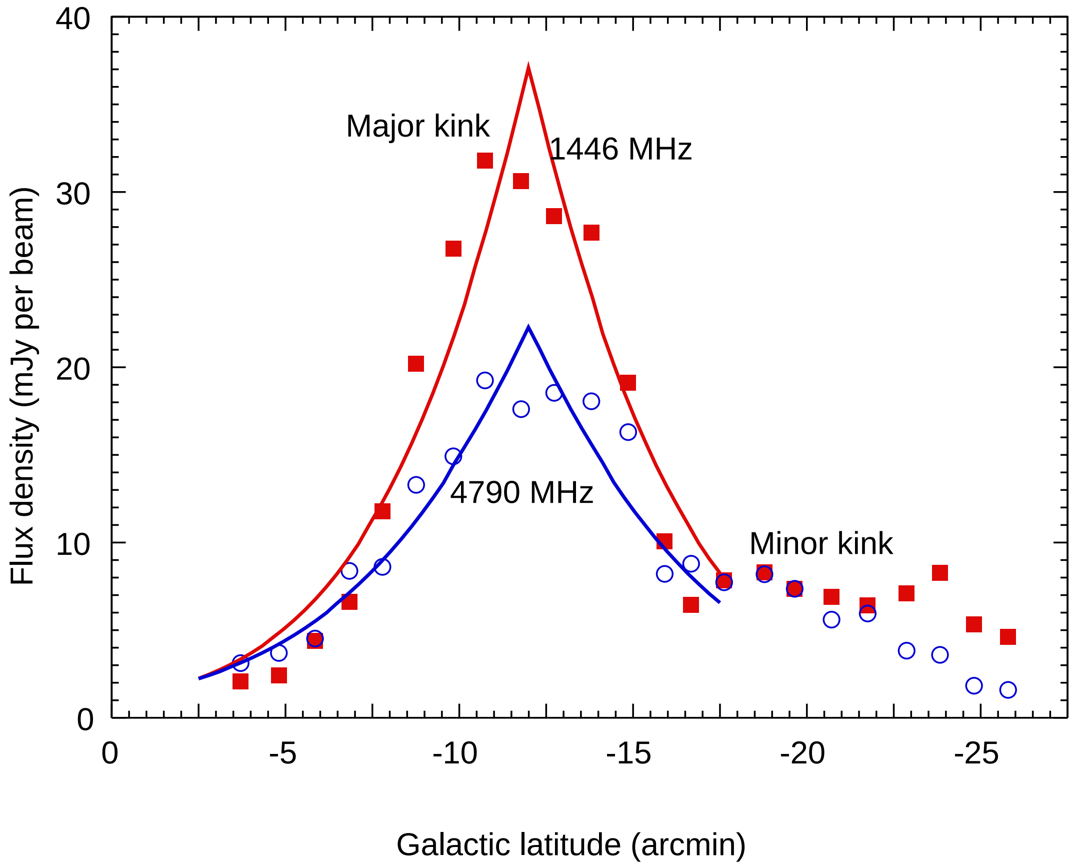
Flux density (mJy per beam)
Galactic latitude (arcmin)
Major kink
1446 MHz
4790 MHz
Minor kink
0
10
20
30
40
0
-5
-10
-15
-20
-25

Fig. 1.—