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MAGNETIC FLUX ACCUMULATION AT THE GALACTIC CENTER AND ITS IMPLICATIONS FOR THE STRENGTH OF THE PREGALACTIC MAGNETIC FIELD

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ABSTRACT

We study the inflow of disk gas toward the Galactic center during the lifetime of the Galaxy and its effect on magnetic field lines frozen-in to the interstellar plasma. While compression leads to a large amplification of the "vertical" magnetic field (pointing perpendicular to the disk), ambipolar diffusion efficiently removes from the disk magnetic flux components oriented parallel to the Galactic plane. Turbulent interchange motions of nearly parallel vertical field lines at the Galactic center enhance the efficiency of magnetic reconnection of neighboring regions of oppositely directed vertical field. This suggests that the sign of the present-day vertical field at the Galactic center is uniform. If the Galactic-center field originates in the entrainment of a pregalactic field B_0 in radially inflowing interstellar plasma, then observations of the vertical flux through the central 200 pc of our Galaxy yield a measure of the pregalactic field that depends on the total mass accreted into the central 200 pc during the Galaxy's lifetime. If this mass is $3 \times 10^9\ M_\odot$ and if the surface density of disk gas is roughly constant over the lifetime of the Galaxy, then $B_0 \gtrsim 2 \times 10^{-7}$ G, regardless of the angle of the pregalactic field with respect to the Galactic plane. The abundance of mechanisms for radial accretion of disk gas suggests that strong magnetic fields should be a generic feature of the centers of spiral galaxies. We also note that cosmic-ray confinement in the strong vertical field at the Galactic center is expected to be poor.

Subject headings: diffusion — Galaxy: center — Galaxy: evolution — MHD — ISM: magnetic fields — turbulence

1. INTRODUCTION

The region within 200 pc of the Galactic center, the central molecular zone (CMZ), is characterized by a large concentration of molecular material coexisting with extremely hot plasma and an intense magnetic field. Roughly $5 \times 10^7\ M_\odot$ of molecular gas at densities $\gtrsim 10^4$ cm^{-3} fills more than 10% of the volume of the CMZ (Morris & Serabyn 1996, hereafter MS96). This concentration of interstellar matter is suggestive of an inflow of gas from the Galactic disk. The plasma that presumably fills most of the volume of the CMZ is at temperatures characteristic of the intergalactic plasma in galaxy clusters. Estimates for the plasma temperature range from 1 to 3 keV (Markevitch et al. 1993) to 10–15 keV (Koyama et al. 1989; Yamauchi et al. 1990; Nottingham et al. 1993). Strikingly, magnetic fields of several milligauss (roughly 1000 times as strong as the fields in the disk) are also observed within the CMZ (Yusef-Zadeh & Morris 1987a, 1987b, 1988; Morris 1994). Outside of molecular clouds, this field is almost completely vertical (perpendicular to the Galactic plane). Because of its enormous strength, the central Galactic field plays an important role in the dynamics of the gas within the CMZ. The field lines, being tied to a large volume of gas in the halo, provide a sink for the angular momentum of the molecular matter and can thus speed the inflow of matter to the Galactic nucleus. The formation of clouds and stars is also mediated by the intense field.

In the Galactic disk (outside the CMZ), the polarization of starlight, Faraday rotation of pulsar emission, and Galactic synchrotron radiation indicate that the "uniform" component $\boldsymbol{B}_u$ (which varies on scales of several kpc) of the Galactic magnetic field is roughly 2 μG in strength (Zweibel & Heiles 1997). The "fluctuating" component (which varies on scales ranging from <1 pc to 1 kpc) of the Galactic field has an energy between 2 and 10 times the energy of $\boldsymbol{B}_u$ (Zweibel & Heiles 1997). The direction of $\boldsymbol{B}_u$ is largely parallel to the Galactic plane (horizontal), and thus the mean vertical field in the disk is less than 1 μG. On the other hand, the total vertical magnetic flux through the CMZ is comparable to the flux from a 0.2 μG vertical field throughout the disk. Thus, while the CMZ comprises a small part of the Galactic volume, it contains a significant fraction of the total vertical flux. A complete theory of the Galactic field must explain the milligauss field in the CMZ, since it is an important part of the global field structure. Indeed, this requirement may provide one of the few ways in which to decide whether the Galaxy's magnetic field originated primarily in a dynamo operating during the Galaxy's lifetime or in some process occurring prior to or during Galaxy formation. The present work takes a first step toward interpreting the CMZ magnetic field in this light.

In this paper, we present a very simple model of the Galactic magnetic-field evolution that may explain the origin and geometry of the Galactic-center field. The field is taken to be "frozen-in" to the plasma flow. This model is an extension of the model of Howard & Kulsrud (1997) and differs from the model of Sofue & Fujimoto (1987) in its treatment of interstellar turbulence and ambipolar diffusion. We prescribe the neutral gas flow to be an axisymmetric azimuthal flow v_θ given by the Galactic rotation curve plus a radial inflow v_r. Observations are used to determine the approximate dependence of v_r on distance r from the Galactic center. The plasma and field are collisionally coupled to the neutral flow, but magnetic forces cause the plasma and field lines to rise buoyantly through the neutrals (ambipolar diffusion). In the disk the field is amplified by differential rotation, but horizontal magnetic flux is lost from the disk through vertical ambipolar diffusion (Howard & Kulsrud 1997). The field is enhanced near the Galactic center by radial compression. Since the vertical ambipolar diffusion velocity is proportional to B^2, ambipolar diffusion is highly effective at small r and causes the field lines to become nearly vertical in the CMZ.

Given our model, we can estimate the average vertical Galactic field at the time of Galaxy formation from magnetic-flux conservation. Observations suggest that 0.3–0.6 $M_\odot$ yr^{-1} are consumed by star formation within the inner 180 pc of the Galaxy (Güsten 1989), that 0.03–0.1 $M_\odot$ yr^{-1} may be blown out of the central region in a thermally driven Galactic wind, and that roughly 0.03–0.05 $M_\odot$ yr^{-1} reach the Galactic nucleus (MS96). If one assumes that mass accretion into the CMZ has occurred at an average rate of 0.3 $M_\odot$ yr^{-1} throughout the $\sim 10^{10}$ yr lifetime of the Galaxy, and if one assumes that the present surface density profile of disk gas (Dame 1992) is typical of Galactic history, then all of the plasma that was initially in the Galactic disk out to a Galactocentric radius of $r_i \sim 13$ kpc has fallen to within a radius $r_f \sim 200$ pc (i.e., $v_r \sim 1$ km s^{-1}). Because of flux conservation, the magnetic field at the Galactic center can be amplified from the average pregalactic vertical field by a factor of roughly $(r_i/r_f)^2 \sim 4000$ during the lifetime of the Galaxy. Thus, given a CMZ field of 1 mG, we deduce a field of 0.25 μG at the time of disk formation. The large pregalactic field predicted by our model may be evidence for the protogalactic dynamo theory of Kulsrud et al. (1997a, 1997b).

Our simple model is open to a number of criticisms arising from the presence of turbulence in the interstellar medium (ISM). For example, turbulence excited by supernova explosions and stellar winds tangles magnetic field lines, possibly causing the magnetic field to gain structure on such small scales that ohmic resistivity can destroy significant amounts of magnetic energy and thereby invalidate the frozen-in assumption (Parker 1979; Zeldovich, Ruzmaikin, & Sokoloff 1983, 43–44). We call this conveyance in wavenumber space of magnetic energy from large scales to small scales a "cascade process." If this type of cascade process in the interstellar medium is sufficiently effective, then our use of the frozen-in assumption is poor. Interstellar turbulence can also convect field lines out of the Galactic disk, just as turbulent convection in a star can lead to a random walk of fluid elements that convects heat away from a star's core (Parker 1979; Zeldovich et al. 1983, 43–44). We call this type of random walk of fluid elements over large distances a "displacement process." If this displacement process is sufficiently effective, then we should not neglect convective losses of magnetic flux from the Galactic disk.

These particular cascade and displacement processes are components of turbulent resistivity, and the effectiveness of turbulent resistivity is a matter of some controversy. In § 2.3, we offer arguments that suggest limits to the effectiveness of these cascade and displacement processes in the ISM outside of the CMZ. (The special field-line geometry of the CMZ is discussed below.) Using theories of interstellar turbulence and observations of solar-wind turbulence, we argue that the cascade of magnetic energy to small scales is terminated at a sufficiently large scale in the warm and hot phases of the ISM that the amount of magnetic energy destroyed by resistivity during the lifetime of the Galaxy is much smaller than the amount of magnetic energy presently contained in the Galaxy. This suggests that the frozen-in assumption, which is based on the neglect of resistivity, is reasonably accurate in the ISM. There are many related issues that we do not discuss, such as the extent to which resistive destruction of small-scale fields changes the topology of the large-scale field and the role of magnetic reconnection. The arguments that we give are not intended to settle the question of the frozen-in law; they have the less ambitious goal of providing some motivation for our model. In regard to the displacement process, we cite the numerical results of Cattaneo (1994) and Vainshtein, Sagdeev, & Rosner (1997), which suggest that turbulent convection of field lines out of the Galactic disk is suppressed by Lorentz forces. We also argue that the turbulent removal of field lines from the disk is suppressed by gravity.

It has been known for some time, however, that in the special case that magnetic field lines are parallel but oppositely directed, turbulent resistivity can be highly effective (Parker 1979, 476; Cattaneo 1994; Vainshtein et al. 1997). This special case proves to have an important consequence for the Galactic-center field. In the CMZ, the field is observed to be straight and perpendicular to the Galactic plane, but we cannot tell from observations which way the field is pointing along different field lines. For example, the observations cannot rule out the possibility that the field points toward Galactic north in some regions and toward Galactic south in others. However, stirring of the field by infalling molecular clouds, supernovae, and differential rotation will cause "interchange" motions parallel to the Galactic plane that are nearly constant along field lines and do not involve large net displacements. Such motions lead to little field-line bending and are therefore not inhibited by Lorentz forces. If the sign of the vertical field is different in two neighboring areas in the Galactic midplane within the CMZ, then interchange turbulence can cause the boundary between these two areas to gain extremely fine-scale structure, bringing regions of oppositely directed vertical field into close proximity with one another and enabling rapid reconnection of oppositely directed magnetic flux. It should also be noted that if the vertical magnetic field lines at the Galactic center penetrate molecular material, then the ambipolar-diffusion–assisted reconnection of Brandenburg & Zweibel (1995) may also remove fluctuations in the direction of the vertical field. These arguments suggest that there are no reversals in the present-day vertical field within the CMZ.

In § 2 we discuss observations relevant to the radial inflow of gas in the disk, the effectiveness of turbulent resistivity in the disk, and the ambipolar diffusion of field lines through clouds. In § 3 we describe our model in detail. The implications for a pregalactic field are discussed in § 4. We consider briefly the reduction of cosmic-ray confinement in the CMZ in § 5. Our conclusions are given in § 6.

2. GAS FLOW IN THE INTERSTELLAR MEDIUM

We take the gas flow in the ISM to consist of several components that are reviewed in this section.

2.1. *Differential Rotation*

For convenience, we ignore the pronounced noncircular motions induced by the bar potential and model the dominant gas flow as circular rotation in the plane of the Galactic disk around an axis passing through the Galactic center. The circular velocity is roughly a constant ($\sim$220 km s^{-1}) over a large part of the disk, implying that the angular velocity decreases as one moves away from the Galactic center (Honma & Sofue 1997). This differential rotation leads to the production of azimuthal magnetic field, since field lines that span a range in Galactocentric radius get stretched.

2.2. *Radial Inflow*

The second component of the interstellar gas flow in our model is an inward radial velocity that arises when parcels of gas lose angular momentum. Such angular momentum loss can be provided by the shocks on the edges of the spiral arms (Lacey & Fall 1985), gravitational interactions with the Magellanic Clouds, bar-induced torques, and dynamical friction (Stark et al. 1991). In this paper we model the radial inflow at Galactocentric radii r between 2 and 13 kpc by assuming a constant rate $\dot{M}$ of mass accretion into the CMZ,

$$\dot{M} = 0.3\ M_{\odot}\ \mathrm{yr}^{-1}\ . \quad (1)$$

This order of magnitude for $\dot{M}$ seems probable but is not well established. (The fate of the accreted mass is discussed in the introduction.) The assumption of a constant accretion rate is certainly an oversimplification, ignoring, for example, the effects of mergers on mass accretion in the early Galaxy. Nevertheless, it is a reasonable starting point for investigations into the origin of the Galactic-center field. We also assume a steady-state, cylindrically symmetric, radial surface density profile. Data for the surface density profiles of atomic and molecular hydrogen [$\Sigma_{\mathrm{H\,I}}(r)$ and $\Sigma_{\mathrm{H_2}}(r)$, respectively] are taken from Dame (1992). The radial velocity for 2 kpc $< r <$ 13 kpc is then calculated from the equation of continuity:

$$\dot{M} = 2\pi r[\Sigma_{\mathrm{H\,I}}(r) + \Sigma_{\mathrm{H_2}}(r)]\,|\,v_r(r)\,|\ . \quad (2)$$

The radial velocity resulting from equation (2) is plotted in Figure 1. The typical value of v_r is $\sim$1 km s^{-1}, and the time required for a fluid element to move a radial distance of order 10 kpc is roughly 10^{10} yr.

Near the CMZ at r = 200 pc, the strong magnetic field causes the plasma to flow in a manner different from the neutrals. In particular, significant accretion of neutral matter can occur even if radial inflow of plasma is suppressed by magnetic pressure. Equation (2) is thus not a good model for the radial plasma velocity near the CMZ. At radii less than 2 kpc, we will merely attempt to illustrate the qualitative behavior of the magnetic field during its final stage of radial compression by specifying somewhat arbitrarily a functional form for the radial plasma velocity and demanding continuity in the velocity at r = 2 kpc.

We should emphasize, however, that throughout most of the Galactic disk the relative velocity between plasma and neutrals in the radial direction is much smaller than the radial velocity plotted in Figure 1. (A numerical estimate for this relative velocity is given in the two paragraphs following eq. [12] in § 2.4.) It is thus reasonable for us to neglect ambipolar diffusion at Galactocentric radii greater than 2 kpc when we estimate the radial velocity of both neutrals and plasma using equation (2).

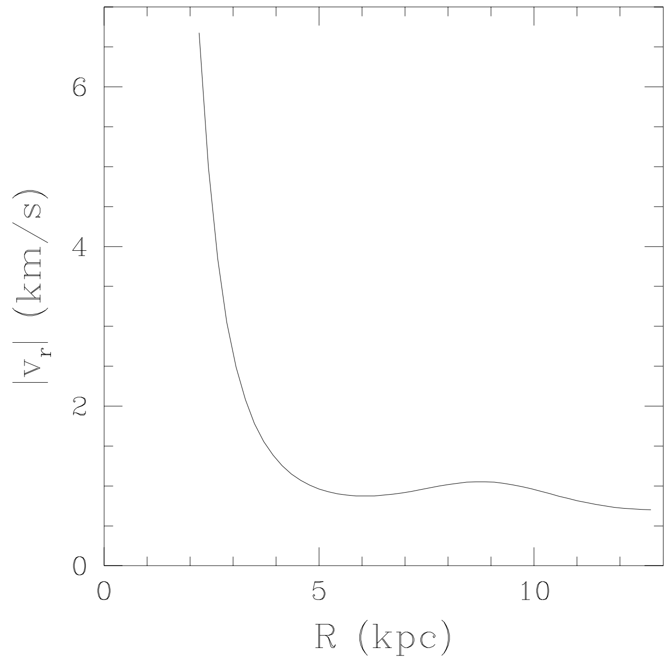

FIG. 1.—Radial velocity of plasma and neutrals at large Galactocentric radii as given by eq. (2).

2.3. *Turbulent Resistivity and the Frozen-in Law*

The ISM is characterized by turbulent motions on many length scales (Larson 1979). At the 10 kpc scale, for example, Larson (1979) estimates a 19 km s^{-1} three-dimensional velocity dispersion σ arising in part from warps in the Galactic disk and the asymmetry between the northern and southern Galactic hemispheres. An example of flow at the 1 kpc scale can be found in gas motions within the Gould Belt, for which Larson estimates σ = 13 km s^{-1}. At the 100–300 pc scale are the random motions of both molecular and diffuse clouds, with $\sigma \sim$ 5–11 km s^{-1}. Velocity dispersions of 3 km s^{-1} are found for CO clouds at the 10 pc scale. Velocity dispersions of 3 km s^{-1} also characterize the internal motions of H I clouds with diameters of $\sim$10 pc. Heiles (1974) estimates $\sigma \sim$ 1 km s^{-1} for dark clouds with diameters of $\sim$1.4 pc. The energy for these random motions comes from a variety of sources, including stellar and protostellar winds, supernovae, and gas streaming in from the halo.

It has been argued that turbulent resistivity leads to considerable loss of magnetic flux from the Galactic disk (Sofue & Fujimoto 1987) and invalidates the frozen-in assumption for Galactic fields (Zeldovich et al. 1983, 43–44). As discussed in the introduction, turbulent resistivity involves both a cascade process, the conveyance of magnetic energy in wavenumber space from large scales to small scales, and a displacement process, the turbulent convection over large distances in physical space of magnetic field lines. In this section we offer arguments that suggest limits on the effectiveness of these particular cascade and displacement processes in the ISM.

In the two leading paradigms of magnetohydrodynamic (MHD) turbulence (the isotropic theory of Kraichnan 1965 on the one hand, and the anisotropic theory of Goldreich &

Sridhar 1995 and Montgomery & Turner 1981 on the other), nonlinear interactions transfer magnetic energy from large scales to scales sufficiently small that some mechanism can dissipate the magnetic fluctuations and terminate the energy cascade. (For completeness, we note that Galactic rotation adds helicity [an average alignment of the velocity and vorticity] to Galactic turbulence, which may lead to an inverse cascade of magnetic energy from small scales to large scales; Pouquet Frisch, & Léorat 1976.) An approximate steady state is possible since energy is fed into the magnetic field at large scales from the turbulent motions generated by supernovae and stellar winds. In the warm neutral medium of the ISM (McKee 1995) ion-neutral damping truncates the magnetic-energy cascade at a scale large enough that resistive damping is negligible (Goldreich & Sridhar 1995, Cesarsky 1980). In the warm ionized medium (Reynolds 1995), the hydrogen is ionized, but approximately half of the helium atoms are neutral R. Reynolds 1999, private communication). The ion-neutral damping arising from the neutral helium again truncates the magnetic-energy cascade at a scale large enough that resistive damping is negligible. In the hot phase of the ISM ($T \sim 10^6$ K, $B \sim 1\ \mu$G), the virtual absence of viscous and collisionless damping of shear Alfvén waves at scales larger than the proton gyroradius $r_{\rm ion} \sim 10^9$ cm allows the energy cascade to proceed to scales as small as $r_{\rm ion}$ (Goldreich & Sridhar 1995). At scales smaller than $r_{\rm ion}$, waves undergo collisionless damping and the cascade is truncated (Quataert 1998; Gruzinov 1998). Observations of the solar wind, for example, show an abrupt steepening of the magnetic power spectrum at a radial wavenumber (in a heliocentric coordinate system) comparable to $r_{\rm ion}^{-1}$ (Tu & Marsch 1995).

To determine whether significant resistive destruction of magnetic energy can occur in the hot phase of the ISM, we assume the following simplified form for the magnetic energy per unit wavenumber $M(k)$ in fully ionized interstellar regions: a power-law inertial range extending from a large scale of $L \sim 100$ pc to a small scale of $r_{\rm ion} \sim 10^9$ cm and a dissipation range at smaller scales in which $M(k)$ decreases much more rapidly with increasing k than in the inertial range. For $T = 10^6$ K, the resistivity η is 1.6×10^4 cm^2 s^{-1} (where the Coulomb logarithm has been taken to be 31, corresponding to a plasma density of 10^{-2} cm^{-3}). In Kraichnan's theory, the rms size of magnetic fluctuations at scale l is $B_l \sim B_0(l/L)^{1/4}$, where B_0 is the total rms field fluctuation. Most of the resistive destruction of magnetic energy occurs close to the scale of the proton gyroradius. The rate of resistive destruction of magnetic energy per unit volume P is thus $\sim(1/8\pi)B_l^2\,\eta/l^2$, with $l \sim r_{\rm ion}$, yielding $E_M/P \sim 10^{12}$ yr, where $E_M \sim B_0^2/8\pi$ is the magnetic energy density. In Goldreich & Sridhar's theory, small-scale fluctuations tend to vary sharply perpendicular to the large-scale field and more smoothly along the large-scale field. Observations of the solar wind that find such anisotropy (e.g., Bieber et al. 1994) suggest that Goldreich & Sridhar's theory may be more appropriate than Kraichnan's for describing small-scale turbulence in highly ionized regions. The rms fluctuation at a perpendicular length scale $l_\perp$ in Goldreich & Sridhar's theory is $B_{l_\perp} \sim B_0(l_\perp/L)^{1/3}$, giving $E_M/P \sim 10^{14}$ yr. For the power-law scalings in both the Kraichnan and the Goldreich-Sridhar theories, the amount of magnetic energy destroyed by resistivity over the $\sim 10^{10}$ yr lifetime of the Galaxy is small compared to E_M, which suggests that the frozen-in law may be a good approximation for Galactic plasma.

One might argue that the dissipation that cuts the magnetic spectrum off at the scale of the proton gyroradius counts toward violating the frozen-in law since magnetic fluctuations on scales $\lesssim r_{\rm ion}$ are not frozen to the ions. However, such fluctuations are frozen to the electrons provided the fluctuation scale is larger than the electron gyroradius r_e. If the power spectrum decays sufficiently rapidly below the scale $r_{\rm ion}$ that there is negligible magnetic energy on scales smaller than r_e, then the magnetic field is effectively frozen to the electrons. Since the difference between the electron velocity and the ion velocity is insignificant on large scales, these considerations suggest that the frozen-in law is valid for the large-scale Galactic field.

With regard to the displacement-process component of turbulent resistivity, the turbulent convection of magnetic flux out of the Galactic disk is sometimes modeled as a random walk, with parcels of fluid taking random steps of length Δr (the size of the dominant turbulent cells) in a time Δt (the time for the dominant turbulent cells to turn over, $\Delta t \sim \Delta r/v$, where v is the rms velocity of the cells; Sofue & Fujimoto 1987). In this approximation, flux diffuses out of the Galactic disk with a diffusion coefficient $D = v\,\Delta r$. A shortcoming of this approximation is that the force of gravity in the vicinity of the disk, which acts to pull clouds and plasma back toward the Galactic plane, increases with distance from the Galactic plane. As a result, successive steps taken by turbulent interstellar clouds and plasma in their random walk are not statistically independent. If a cloud or parcel of plasma takes a step out of the disk in the direction of Galactic north, gravity makes it more likely that the next step will be in the direction of Galactic south. Magnetic tension has the same effect. Clouds and plasma that wander away from the Galactic plane will remain connected by magnetic field lines to matter that is still in the disk. These field lines will act to pull the wandering clouds and plasma back into the disk (Zweibel 1987; Elmegreen 1981). These effects reduce the diffusion of plasma and field lines out of the disk. In a different context, that of homogeneous turbulence, the reduction of the turbulent diffusion coefficient by magnetic forces was illustrated in two dimensions by the direct numerical simulations of Cattaneo (1994), in three dimensions by the Lagrangian simulations of Vainshtein et al. (1997), and in two-dimensional weakly ionized gases by the numerical simulations and analytic calculations of Kim (1997). It is true that both matter and field lines are transported out of the Galactic disk, but it is too simplistic to describe such transport by the above random walk arguments; the actual transport timescale is substantially longer than such arguments would imply. Indeed, if parcels of gas in the interstellar medium were truly undergoing an uncorrelated random walk, then the gas in the disk would be lost to the Galactic halo on the same short timescale as the magnetic field.

2.4. *Ambipolar Diffusion*

Ambipolar diffusion is the process in which magnetic forces drive a relative velocity between ions and neutrals. The magnetic pressure force (the $\nabla B^2/8\pi$ term in the ion momentum equation), for example, will in general have a component pointing away from the Galactic plane and toward the halo. This force will tend to drive plasma away from the disk into the halo, and the plasma will drag the frozen-in field lines with it. Howard & Kulsrud (1997) described this process by assuming that most of the mass in the ISM is in diffuse clouds that fill a fraction f of the interstellar volume. Because we follow Howard & Kulsrud's treatment in the calculations of § 3, we will review their discussion in this section.

Over spatial scales parallel to the Galactic plane that are large compared to the ~ 100 pc separations of randomly moving interstellar clouds and timescales that are long compared to the $\sim 10^7$ yr correlation time of cloud motions (this correlation time is estimated as L/V, where $V \sim 10$ km s^{-1} is the velocity dispersion of randomly moving clouds and $L \sim 100$ pc is their separation), the force per unit volume F on the ions in the direction perpendicular to the Galactic plane (along the z-axis) is dominated by magnetic and cosmic-ray pressure:

$$F = -\left(1 + \frac{\alpha}{\beta}\right) \frac{\partial B^2/8\pi}{\partial z} , \qquad (3)$$

where (β/α) is the ratio of cosmic-ray pressure to magnetic pressure. This ratio is assumed constant in space and time. Collisional friction between ions and neutrals within the clouds exerts a force per unit volume on the ions within clouds in the z-direction given by

$$F_{\rm cloud} = -n_i m^* \nu v_D , \qquad (4)$$

where n_i is the ion number density, m^* is the mean ion mass, and v_D is the relative drift velocity between ions and neutrals in the z-direction. The ion-neutral collision rate ν is given by

$$\nu \approx n_c \langle \sigma v \rangle \frac{m_{\rm H}}{m^* + m_{\rm H}} , \qquad (5)$$

where n_c is the density of hydrogen within the cloud, $m_{\rm H}$ is the mass of hydrogen, and σ is the collision cross section. The mass factor arises because it is assumed that all the neutrals are hydrogen and momentum transfer becomes less efficient with increasing ion mass. It follows that

$$F_{\rm cloud} = -n_i n_c \langle \sigma v \rangle v_D \frac{m_{\rm H} m^*}{m_{\rm H} + m^*} . \qquad (6)$$

Close to steady state, the volume integral of F over the entire interstellar medium is balanced by the integral of $F_{\rm cloud}$ over the volume of the clouds, so

$$F_{\rm cloud} = -\frac{F}{f} = (1 + \beta/\alpha) \frac{1}{f} \frac{\partial B^2/8\pi}{\partial z} . \qquad (7)$$

The ambipolar diffusion velocity v_D within the clouds is thus given by

$$v_D = -\frac{(1 + \beta/\alpha)\partial B^2/\partial z}{8\pi f n_i n_c m^*_{\rm eff} \langle \sigma v \rangle} , \qquad (8)$$

where $m^*_{\rm eff} = \langle m^* m_{\rm H}/(m^* + m_{\rm H}) \rangle$ is the effective mass averaged over the different species of ions.

This ambipolar diffusion velocity is the velocity of ions and field lines within clouds. Howard & Kulsrud (1997) pointed out that because clouds are destroyed and reformed on a timescale that is short compared to H/v_D, the quantity that is most relevant to the transport of magnetic flux out of the disk is the amount of neutral mass that a magnetic field line passes through per unit time. Once a flux tube of length L and diameter d has passed through an amount of neutral matter equal to $\rho H L d$, where ρ is the mass density of neutrals averaged over the whole ISM ($= n_c m_{\rm H} f$), the flux tube has escaped from the disk.

If the clouds are taken as spheres of radius a, the number density of cloud centers is $3f/4\pi a^3$. At any given time, a narrow flux tube of diameter $d \ll a$ and length L intersects a number of clouds equal to the number of cloud centers within a volume $\pi a^2 L$, or $3fL/4a$. Assuming that there is negligible neutral matter between clouds, the amount of neutral mass that a flux tube of length L passes through because of ambipolar diffusion during one cloud lifetime t_c is

$$m \approx (3fL/4a)\rho_c v_D t_c \langle l \rangle d , \qquad (9)$$

where ρ_c is the mass density in a cloud and $\langle l \rangle \sim a$ is the average length of the $3fL/4a$ segments of the flux tube lying within clouds. Because of the assumption that most of the mass is in clouds, there can only be a short time between the destruction of a cloud and the formation of a new cloud from the old cloud's remains. Thus, during a time t the flux tube passes through an amount of mass equal to

$$\Delta M = (t/t_c) m \approx f \rho_c v_D t L d . \qquad (10)$$

Since $f\rho_c$ is the average mass density ρ of the interstellar medium, the effective distance Δx traveled by the flux tube is then defined by the relation

$$\rho \, \Delta x \, L d \equiv \Delta M , \qquad (11)$$

which gives

$$\frac{\Delta x}{t} = v_D \qquad (12)$$

as the effective ambipolar drift velocity of the flux tubes through the inhomogeneous ISM.

In the model, it is assumed that $\beta/\alpha = 2$, that $f = 0.1$, that the cloud ions are all carbon (giving $m^*_{\rm eff} \approx m_{\rm H}$), that roughly 80% of the carbon is in dust grains (following Spitzer 1978), that the remaining carbon is ionized, that the total abundance of carbon has its cosmic value of 3×10^{-4}, that $n_c = 10$ cm^{-3}, and that $\langle \sigma v \rangle = 2 \times 10^{-9}$ s^{-1}. Given a scale height of $H = 100$ pc and a field of 4 μG typical of the magnetic field in the Galactic disk, the time required for flux to diffuse out of the disk is roughly $H/v_D = 2 \times 10^9$ yr. Toward the center of the Galaxy where the field gets stronger and the scale height smaller, the time to diffuse one vertical scale height becomes smaller. The value of v_D is roughly 0.05 km s^{-1}.

So far, we have been discussing the component of the ambipolar drift velocity that is perpendicular to the Galactic plane. There is also a component in the radial direction, $v_D^{\rm radial}$, but to a good approximation this component can be neglected everywhere except near the CMZ. The radial ambipolar velocity consists of two parts, a smooth part and a fluctuating part. The smooth part is driven by the azimuthal average of the radial pressure force, $(1/8\pi)\partial B^2/\partial r$. Throughout most of the disk, this averaged force is $\sim B^2/8\pi R$ (R is the radius of the disk), which is much less than the vertical pressure force ($\sim B^2/8\pi H$). As a result, the smooth radial ambipolar velocity throughout most of the disk is much less than the vertical ambipolar velocity of ~ 0.05 km s^{-1}, which is itself much smaller than the roughly 1 km s^{-1} radial velocity given by equation (2). The fluctuating part of $v_D^{\rm radial}$ is driven by the radial force associated with random variations in the magnetic field. The magnitude of this force is comparable to $B^2/8\pi H$, since the dominant length scale of the random variations of the field is comparable to H. The magnitude of the fluctuating part is thus similar to the value of v_D given in equation (8), or 0.05 km s^{-1}.

Although $v_D^{\rm radial}$ can be neglected to a good approximation throughout most of the disk, it cannot be neglected near the CMZ, where the radial magnetic pressure force $(1/8\pi)\partial B^2/\partial r$ becomes very large. This intense pressure force most likely reduces the radial plasma velocity far below the radial neutral velocity. As a result, we cannot obtain the plasma velocity near the CMZ by adding a small correction to the neutral velocity, which is obtained from equation (2). Instead, when we treat the field evolution near the CMZ in § 3, we will assume a radial plasma velocity profile that drops to zero at the Galactic center but matches the radial velocity at a radius of 2 kpc obtained from equation (2). Our purpose in specifying this somewhat arbitrary velocity profile will be to illustrate the different behaviors of the different field components as field lines are dragged toward the CMZ.

Although we follow the Howard & Kulsrud (1997) analysis when we model the evolution of the magnetic field, certain important physical processes are not taken into account in this treatment. Figure 2 depicts a field line passing through several clouds in the Galactic disk and then turning sharply upward as it enters the rarefied Galactic halo, where there is little mass to hold the field line down. When the last cloud on the field line (*bold circle* in Fig. 2) is destroyed, some fraction of the evaporated gas probably flows along the field into the halo. If there is a sufficient drop in the mass that weighs down the field lines threading the remains of the evaporated cloud, then these field lines can be pulled upward into the halo by magnetic tension, which is enhanced by the sharp bend in the field lines. This reduces the length of the magnetic field line in the Galactic disk, thereby reducing the magnetic flux parallel to the Galactic plane.

This process can be treated approximately by assuming that the length of the magnetic field line in the disk L is reduced at the rate

$$\frac{dL}{dt} = -\frac{L_{\rm intercloud}}{\tau_{\rm cloud}} , \tag{13}$$

where $L_{\rm intercloud}$ is the intercloud spacing and $\tau_{\rm cloud}$ is the cloud lifetime. To the extent that the Galactic field can be considered smooth and ordered, we can write

$$\frac{B_\theta}{B_z} \sim \frac{L}{H} , \tag{14}$$

where $H \sim 200$ pc is the approximate thickness of neutral material in the Galactic disk, and B_θ and B_z are field components in a cylindrical coordinate system (r, θ, z) with the z-axis passing through the Galactic center perpendicular to the Galactic plane. In writing equation (14) we have assumed that $B_\theta \gg B_r$. Let us assume that far from the Galactic center B_z varies slowly in time compared to B_θ. Then equation (14) implies that

$$\frac{1}{B_\theta}\frac{dB_\theta}{dt} = -\frac{B_z}{B_\theta}\frac{L_{\rm intercloud}}{H}\frac{1}{\tau_{\rm cloud}} . \tag{15}$$

If we take $B_z/B_\theta = 0.1$, $H/L_{\rm intercloud} = 2$, and $\tau = 10^7$ yr, then the timescale for loss of azimuthal flux is 2×10^8 yr, significantly shorter than the timescale associated with ambipolar diffusion. However, the arguments leading to equation (15) must be regarded as conjectural since they depend critically on the unknown fraction of the evaporated cloud that flows along the field and into the halo.

Although flux loss due to last-cloud–evaporation could in theory play an important role in determining the magnetic field in the Galactic disk, it has little effect on the magnetic field at the Galactic center. As our calculations in § 3 show, even the slower rate of flux loss by ambipolar diffusion that follows from equation (8) is sufficient to align the magnetic field perpendicular to the Galactic plane as field lines are accreted into the CMZ.

3. ANALYTIC SOLUTION TO MODEL EQUATIONS

In this section we present a simple analytic model that illustrates the different behaviors of the different field components as plasma is accreted toward the CMZ. The basic equation for field line evolution is Ohm's law:

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{v}_{\rm plasma} \times \boldsymbol{B}) , \tag{16}$$

where $\boldsymbol{v}_{\rm plasma}$ is the plasma velocity and the resistivity has been set to zero since resistivity is negligible in the interstellar medium for the evolution of large-scale fields. Equation (16) is solved in cylindrical coordinates (r, θ, z) with the z-axis passing through the Galactic center perpendicular to the plane of the Galactic disk. To simplify the solution, we follow the analysis of Howard & Kulsrud (1997) in assuming that the magnetic field strengths satisfy a time-independent profile in the z-direction. In particular,

$$B_r(r, \theta, z) = B_r(r, \theta, 0) \exp\,[-z^2/h(r)^2] , \tag{17}$$

$$B_\theta(r, \theta, z) = B_\theta(r, \theta, 0) \exp\,[-z^2/h(r)^2] , \tag{18}$$

$$B_z(r, \theta, z) = B_z(r, \theta, 0) , \tag{19}$$

where $h(r)$ is a scale height for the magnetic field. [$h(r)$ will be set equal to 100 pc in the numerical example of § 3.2.] Because of this assumed profile, it is only necessary to solve for the fields at the Galactic midplane, which leads to a considerable simplification of the analysis.

We attempt to solve equation (16) for the smooth, long-time behavior of the magnetic field by including in $\boldsymbol{v}_{\rm plasma}$ only Galactic rotation, vertical ambipolar diffusion, and the radial inflow of matter to the Galactic center:

$$\boldsymbol{v}_{\rm plasma} = r\Omega(r)\hat{\theta} + v_r\hat{r} + v_D(r, \theta, z)\hat{z} . \tag{20}$$

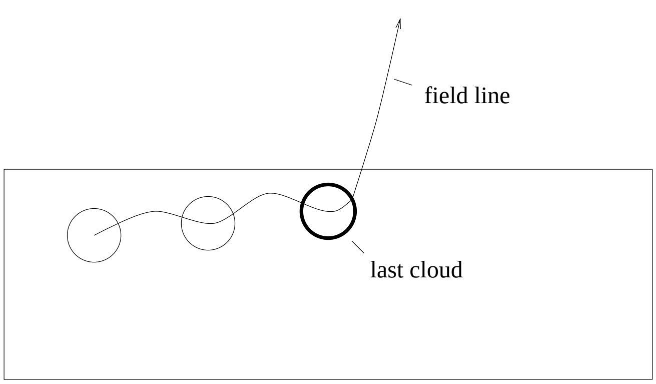

FIG. 2.—Edge-on view of clouds in the Galactic disk and a magnetic field line that passes through the clouds and into the Galactic halo.

We assume that neither the Galactic rotation curve nor v_r changes in time. From equation (8) we find that $v_D = 0$ at the Galactic midplane, while

$$\frac{\partial v_D}{\partial z}(r, \theta, 0) = a(r)(B_\theta^2 + B_r^2) , \tag{21}$$

where

$$a(r) \equiv \frac{1 + \beta/\alpha}{4\pi h(r)^2 f n_c n_i m^*_{\rm eff}\langle \sigma v \rangle} . \tag{22}$$

Equations (16), (20), and (21) yield a nonlinear partial differential equation for $\boldsymbol{B}$. To solve, we first define the path of a fluid element in the r-θ plane by the equations

$$\frac{dr}{dt} = v_r(r) \tag{23}$$

and

$$\frac{d\theta}{dt} = \Omega(r) . \tag{24}$$

Integrating, one obtains $r = r(r_0, t)$, and $\theta = \theta_0 + \Delta\theta(r_0, t)$, where r_0 and θ_0 are the initial radius and angle. Alternatively, one can view the initial conditions as functions of the final position, i.e., $r_0 = r_0(r, t)$ and $\theta_0 = \theta + \Delta\theta_0(r, t)$. The time derivative of $\boldsymbol{B}$ moving with the fluid (i.e., holding r_0 and θ_0 constant) is

$$\frac{d\boldsymbol{B}}{dt} = \frac{\partial \boldsymbol{B}}{\partial t} + v_r \frac{\partial \boldsymbol{B}}{\partial r} + r\Omega(r)\frac{\partial \boldsymbol{B}}{\partial \theta} . \tag{25}$$

In this "Lagrangian" frame, equation (16) becomes the coupled ordinary differential equations

$$\frac{dB_r}{dt} = -B_r \frac{d}{dt}\ln r - a(r)(B_\theta^2 + B_r^2)B_r , \tag{26}$$

$$\frac{dB_\theta}{dt} = -B_\theta \frac{d}{dt}\ln v_r(r) - a(r)(B_\theta^2 + B_r^2)B_\theta + r\frac{\partial \Omega}{\partial r} B_r , \tag{27}$$

$$\frac{dB_z}{dt} = -B_z \frac{d}{dt}\ln(rv_r) . \tag{28}$$

We integrate these equations with $B_r(r, \theta, t = 0) = B_{r0}(r, \theta)$, $B_\theta(r, \theta, t = 0) = B_{\theta 0}(r, \theta)$, and $B_z(r, \theta, t = 0) = B_{z0}(r, \theta)$ specified. The ambipolar drift term in equations (26) and (27) can be eliminated by dividing equation (26) by B_r and equation (27) by B_θ and subtracting. We obtain

$$\frac{d}{dt}\left(\frac{B_\theta v_r}{B_r r}\right) = v_r \frac{d\Omega}{dr} . \tag{29}$$

Equation (29) expresses the conversion of radial flux to azimuthal flux by differential rotation. Integrating equation (29) we obtain (using $dt = dr/v_r$)

$$B_\theta = B_r F(r, r_0, \theta_0) , \tag{30}$$

where

$$F(r, r_0, \theta_0) \equiv \frac{r}{v_r}\left[\frac{B_{\theta 0}(r_0, \theta_0)v_r(r_0)}{B_{r0}(r_0, \theta_0)r_0} + \Omega(r) - \Omega(r_0)\right] . \tag{31}$$

Substituting equation (30) into equation (26), we obtain

$$B_r = \frac{B_{r0}(r_0, \theta_0)r_0}{\sqrt{r^2 + 2B_{r0}^2 r_0^2 r^2 \int_{r_0}^{r} dr'\, a(r')(1 + F^2)/r'^2 v_r(r')}} . \tag{32}$$

From direct integration of equation (28) one finds

$$B_z = B_{z0}(r_0, \theta_0)\frac{r_0 v_r(r_0)}{r v_r(r)} . \tag{33}$$

Equations (30), (32), and (33) solve equation (16). Note that B_r, B_θ, and B_z can be viewed as functions of either (r, r_0, θ_0) or (r, θ, t), since we have assumed that we know $r_0 = r_0(r, t)$ and $\theta_0 = \theta + \triangle\theta_0(r, t)$.

Equation (33) is a direct consequence of flux conservation. Consider a narrow annulus in the $z = 0$ plane of width δr and radius r. As the radius r decreases according to $dr/dt = v_r$, the width of the annulus satisfies the equation

$$\frac{d\,\delta r}{dt} = \delta r \frac{dv_r}{dr} . \tag{34}$$

Since we assume a steady-state radial velocity profile, the operator d/dt can be rewritten as $v_r\, d/dr$, and equation (34) can be rewritten

$$\frac{1}{\delta r}\frac{d\,\delta r}{dr} = \frac{1}{v_r}\frac{dv_r}{dr} , \tag{35}$$

which implies that

$$v_r/\delta r = \text{constant} . \tag{36}$$

The area of the annulus is proportional to $r\,\delta r$, which is proportional to rv_r. Flux conservation then implies that $B_z r v_r =$ constant, which also follows from equation (33). From this and our model for the radial velocity (eq. [2]), it follows that for 2 kpc $< r <$ 13 kpc,

$$\frac{B_z(r)}{\Sigma(r)} = \text{constant} , \tag{37}$$

where $B_z(r)$ refers to the field in a frame moving with the fluid and $\Sigma(r)$ is the mass surface density of the disk.

3.1. *Long-Time Solution for $v_r \sim r^n$ and $\Omega(r) \sim r^{-\beta}$*

To see the qualitative behavior of field line evolution implied by equations (30)–(33), it is helpful to consider the special case in which $\Omega(r) = \Omega_0(r/r_0)^{-\beta}$ ($\beta > 0$ since the inner part of the disk rotates more rapidly than the outer part) and $v_r = v_{r0}(r/r_0)^n$. For $n < 1$, the solution is singular since the ISM collapses to the z-axis in a finite amount of time. For $n > 1$, it can be shown that in the limit that $t \gg r_0/\langle(n-1)v_r(r_0)\rangle$ $B_\theta \gg B_r$, and B_θ approaches that value that gives

$$\frac{\partial v_D}{\partial z} \sim \frac{\partial v_r}{\partial r} . \tag{38}$$

In other words, B_θ approaches a strength at which the timescale for ambipolar diffusion out of the disk is the same as the timescale for amplification by compressive radial inflow. This asymptotic solution is an approximate balance between the first and second terms on the right-hand side of equation (27). In this long-time limit, it can be shown that

$$B_\theta \sim t^{-1/2} . \tag{39}$$

Thus, B_θ decays in time, with B_r decaying as well in such a way that it remains negligible in comparison to B_θ. It should be noted that equation (39) is the solution for B_θ following an inward-moving point, not the solution at a fixed radius. On the other hand, the value of the vertical

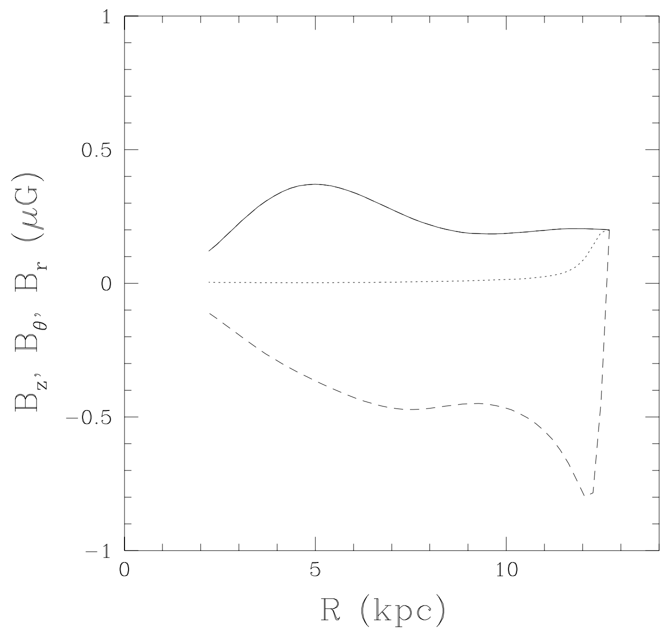

FIG. 3.—The evolution of B_r (*dotted line*), B_θ (*dashed line*), and B_z (*solid line*) at the Galactic midplane as functions of the Galactocentric radius r of an inflowing field line when $r > 2$ kpc. Each field component is assumed to be 2×10^{-7} G at a radius of 12.7 kpc.

field increases with time. Equation (33) implies that

$$B_z \sim t^{(n+1)/(n-1)} . \tag{40}$$

Thus, B_z/B_θ increases with time, implying that field lines become increasingly vertical as they fall toward the Galactic center.

3.2. *Numerical Results*

In this section we present the results of our numerical integration of equation (33). First, we follow a field line as it moves from an initial radius of roughly 13 kpc to a radius of 2 kpc. For this range of radii, we get v_r from equation (2). We obtain $\Omega(r)$ from a polynomial fit to the data of Honma & Sofue (1997) and determine $a(r)$ in equation (22) from the parameters given after equation (12). The initial radius of ~ 13 kpc is chosen because there are $3 \times 10^9\ M_\odot$ of interstellar gas inside this radius given our model of Σ, and we estimate that $\sim 3 \times 10^9\ M_\odot$ of gas are accreted into the CMZ during the lifetime of the Galaxy. The initial value of each field component is taken to be 2×10^{-7} G. The change in $\boldsymbol{B}$ is not very dramatic in this radial interval, as can be seen in Figure 3. As noted in the discussion of equation (37), flux conservation and equation (2) imply that $B_z \propto \Sigma$ (for radii in the range 2–13 kpc in which eq. [2] applies). Because Σ is at a relatively low value at $r = 2$ kpc, the value of the vertical field is actually lower at $r = 2$ kpc than at $r = 13$ kpc. The reason that B_θ becomes negative is that it is dominated by the differential rotation of the radial field.

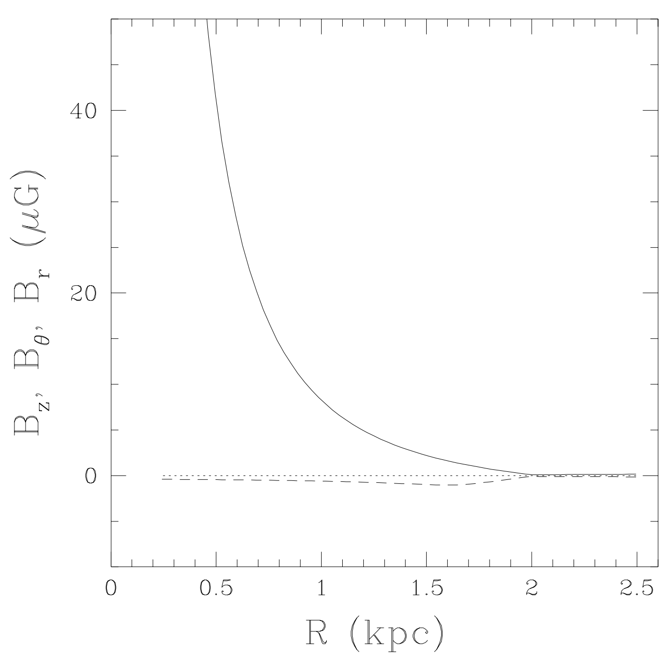

FIG. 4.—Same as Fig. 3, but for $r < 2.5$ kpc

Close to the CMZ, magnetic forces cause the plasma to behave in a markedly different way from the neutrals. In particular, the radial component of the magnetic pressure $[-(1/8\pi)\partial B^2/\partial r]$ inhibits the radial inflow of plasma, leading to a situation in which neutrals are accreted more efficiently than plasma. As a result, it is not a good approximation to get the radial velocity of field lines and plasma from the equation $r|v_r|\Sigma = \dot{M}$. To illustrate the different behaviors of the different field components near the CMZ, we take a simple model for the plasma radial velocity in the region 200 pc $< r <$ 2 kpc:

$$v_r = \frac{1}{c_1 r + c_2 r^{-1}} , \tag{41}$$

where c_1 and c_2 are constants chosen so that v_r is continuous at 2 kpc and so that the magnetic field grows rapidly at small radii. Because this model for the radial velocity is artificial, the numerical integration of equation (32), plotted in Figure 4, is not evidence in favor of the primordial origin of the Galactic center field. Rather, Figure 4 serves to illustrate how the magnetic field lines become increasingly vertical at small radii when there is significant radial compression of the plasma. The magnitude of B_θ cannot increase beyond a modest value, or else damping of B_θ due to ambipolar diffusion becomes rapid; roughly speaking, the time for ambipolar diffusion of flux out of the disk must remain greater than the time for amplification by radial compression or differential rotation. On the other hand, B_z grows dramatically as plasma gets concentrated at small radii. Magnetic pressure and radial ambipolar diffusion should set some limit on the maximum possible field within the CMZ. Our theory does not predict this limit, but observations of the present-day CMZ field suggest that this limit is on the order of 1 mG. The radial field is small in comparison to B_θ because it is not amplified by differential rotation, while B_θ is.

4. IMPLICATIONS FOR THE STRENGTH OF THE PREGALACTIC FIELD

In this section we consider several issues concerning the relationship between the present flux through the CMZ and the flux through the Galactic disk just after Galaxy formation.

4.1. *Efficiency of Magnetic Reconnection Near the Galactic Center*

Because of the high conductivity of interstellar plasma, magnetic reconnection can annihilate oppositely directed flux in the CMZ over interesting timescales only if the sign of the vertical field B_z changes over very short length scales. In this section we describe three different mechanisms for generating such short length scales: differential rotation, interchange motions, and ambipolar diffusion within the molecular material of the CMZ (Brandenburg & Zweibel 1995). We find that these mechanisms make the length scales of any sign reversals in B_z sufficiently short that magnetic reconnection is capable of rapidly annihilating oppositely directed flux. Because of this, the vertical flux currently observed through the Galactic center should be of uniform sign.

To determine the effects of differential rotation, let us suppose that neighboring patches of the Galactic plane of dimensions $\delta r_0 \times \delta r_0$ have oppositely directed vertical fields at some early time. As these patches move from a Galactocentric radius of r_i to r_f, they are stretched out in azimuthal extent as illustrated in Figure 5. Note that the side of the parallelogram parallel to the $\hat{\theta}$ direction (the azimuthal direction in the Galactic disk) does not change in length because of the assumed cylindrical symmetry of the gas flow. On the other hand, the radial extent of the parallelogram δr satisfies the relation

$$\frac{\delta r}{v_r(r)} = \frac{\delta r_0}{v_r(r_0)} , \tag{42}$$

as discussed prior to equation (36). For this last equation, we have assumed that $\delta r_0 \ll R$ and $\delta r \ll R$, where $R \sim \{\text{Galactocentric radius}\}$ is the common scale length of both the radial velocity and the Galactic rotation rate. It follows from equation (42) that the azimuthal dimension L of the parallelogram illustrated in Figure 5 is given by $L = r_f \, \Delta\theta$, where $\Delta\theta$ is the difference in the total angle traversed by the two different sides of the parallelogram parallel to the $\hat{\theta}$ direction in Figure 5:

$$\Delta\theta = \int_{t_0}^{t} dt \, \delta r \frac{d\Omega}{dr} = \int_{r_0}^{r_f} dr \frac{\delta r}{v_r(r)} \frac{d\Omega}{dr} = \frac{\delta r_0}{v_r(r_0)} [\Omega(r_0) - \Omega(r_f)] . \tag{43}$$

Here we have made use of the constancy of $\delta r / v_r(r)$. The slope of the slanted lines in the parallelogram in Figure 5 is thus

$$m \equiv \frac{\delta r}{L} = \frac{v_r(r_f)}{r_f[\Omega(r_i) - \Omega(r_f)]} . \tag{44}$$

If we take $r_i = 10$ kpc and $r_f = 500$ pc and estimate v_r and Ω using equation (2) and polynomial fits to data from Dame (1992) and Honma & Sofue (1997), then we find that $m \sim -1/4600$. At smaller Galactocentric radii, it becomes increasingly difficult to estimate m because the radial velocity of the plasma and field structures is reduced relative to the radial velocity of the neutrals estimated from the mass accretion rate because of the buildup of the field. Let us assume, however, that for $r_f = 200$ pc, $m = 10^{-4}$.

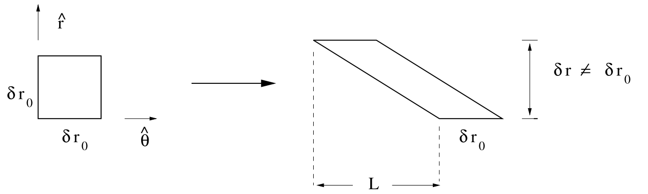

FIG. 5.—Schematic depiction of the deformation of a square patch of plasma in the Galactic plane as it moves to the center of the Galaxy in the presence of differential rotation.

Because the initial squares are stretched into long and thin parallelograms of width $\sim m \, \delta r_0$, the length scale l of the variation in the vertical field is reduced by a factor of approximately m as plasma flows to the Galactic center. If we take the initial patch to be a square 100 pc^2, then the length scale of field variations at a radius of 200 pc will be roughly $l = 3 \times 10^{16}$ cm. The time required for such a patch of vertical field to reconnect depends on the rate of reconnection in the CMZ. If reconnection proceeds at the Petschek rate of $\sim (\ln R_m)^{-1} v_A / l$ (where $v_A \sim 4 \times 10^8$ cm s^{-1} is the Alfvén speed in the hot plasma overlying the CMZ and $R_m = l v_A / \eta = 3 \times 10^{24}$, where $\eta = 4$ cm^2 s^{-1} is the resistivity of the 5×10^7 K plasma overlying the CMZ), then the oppositely directed vertical fields will reconnect on a timescale of $\sim 10^2$ yr in the hot plasma at the Galactic center. Alternatively, if reconnection proceeds at the Sweet-Parker rate of $\sim R_m^{-1/2} v_A / l$, the oppositely directed vertical fields will only reconnect in $\sim 10^{12}$ yr. Since there is considerable uncertainty as to the actual rate at which reconnection proceeds, it is not clear that stretching by differential rotation alone is sufficient to make reconnection rapid.

However, as discussed in the introduction, even if differential rotation is not sufficient to make reconnection rapid, turbulence within the CMZ is probably very effective at enhancing the rate of reconnection because of the special geometry of the CMZ magnetic field. As argued by Parker (1979), Cattaneo (1994), and Vainshtein et al. (1997), turbulent interchange motions of nearly parallel field lines, such as those found within the hot CMZ plasma, bring regions of oppositely directed field, if they exist, into close proximity. The scale length for field reversals thus becomes extremely small, and magnetic reconnection can occur rapidly. This strongly suggests that the vertical field that has survived to this day within the CMZ all penetrates the Galactic midplane in the same direction. Although Lorentz forces may in general inhibit turbulent diffusion (Cattaneo 1994; Vainshtein et al. 1997), they are ineffective at inhibiting interchange motions since such motions require negligible field-line bending.

Another mechanism for increasing the efficiency of reconnection has been proposed by Brandenburg & Zweibel (1995). They argued that ambipolar diffusion can cause the formation of current sheets that enhance the rate of reconnection in gas with low fractional ionization. Vishniac & Lazarian (1999) found that ambipolar diffusion can increase the reconnection speed to roughly 10^{-3} times the Alfvén speed for Sweet-Parker reconnection geometries in molecular clouds. If the CMZ can be thought of as a ring of molecular clouds at the Galactic midplane about 50 pc thick threaded by a vertical field that alternates in sign, then reconnection within the partially ionized gas would connect a field line approaching the midplane from Galactic north to a field line returning to Galactic north (Fig. 6). Magnetic tension would then remove the reconnected loop from the central region. It should be noted, however, that the polarization of thermal dust emission shows that the fields within clouds are most often oriented parallel to the Galactic plane (Morris & Serabyn 1996). This may be evidence that the field lines within clouds are not in general connected to the

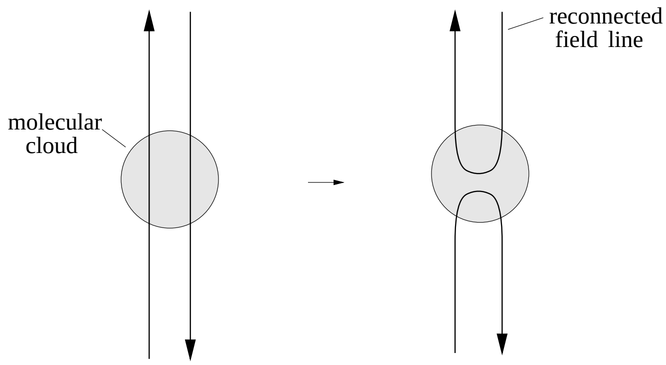

FIG. 6.—Reconnection of oppositely directed flux within the molecular material in the CMZ. Once the lines are reconnected, magnetic tension forces remove the lines from the neighborhood of the Galactic plane.

vertical field lines outside clouds. For vertical field lines that do not thread the molecular material, the scenario depicted in Figure 6 is not applicable.

4.2. *Numerical Estimate of the Galactic Field at the Time of Galaxy Formation*

Let us imagine that all the interstellar matter within the Galactic disk out to a Galactocentric radius r_i has been accreted to within the CMZ (at radius $r_f \sim 200$ pc) during the lifetime of the Galaxy. Because of the arguments of § 4.1, the sign of the vertical field in the CMZ is probably uniform, and the vertical magnetic flux through the CMZ can be simply estimated as $\pi r_f^2 B_f$, where B_f is the present-day strength of the vertical field in the CMZ. Writing the initial vertical flux through the Galactic plane out to radius r_i as $\pi r_i^2 \overline{B}_i$, flux conservation implies that

$$\overline{B}_i = B_f \frac{r_f^2}{r_i^2} . \tag{45}$$

If we define M to be the total amount of disk mass accreted into the CMZ during the lifetime of the Galaxy, then r_i can be estimated by assuming that the surface density profile $\Sigma(r)$ of the disk has remained constant throughout the lifetime of the Galaxy:

$$M = \int_{r_f}^{r_i} 2\pi r \Sigma(r)\, dr . \tag{46}$$

If we take $M \sim 3 \times 10^9\ M_\odot$ and use a polynomial fit to the data of Dame (1992) on the mass surface density, then equation (46) can be inverted to yield

$$r_i \approx 13 \text{ kpc} . \tag{47}$$

The polynomial fit to Dame's data (which cover radii greater than 2 kpc) does a poor job of representing the CMZ, where Σ can reach several hundred $M_\odot$ pc^{-2} (MS96), but the resulting error in r_i is not so significant since the central 2 kpc account for only a small fraction of the $3 \times 10^9\ M_\odot$. Given equation (47), equation (45) can be written

$$\overline{B}_i = 2.4 \times 10^{-7} \text{ G} \left(\frac{B_f}{1 \text{ mG}}\right)\left(\frac{r_f}{200 \text{ pc}}\right)^2 . \tag{48}$$

The radius of the CMZ (~ 200 pc) may be an underestimate of the value of r_f if the strong vertical field is not well confined to the CMZ but is instead spread out over a significantly larger radius. On the other hand, there is some observational evidence that the CMZ fields have a milligauss value only within 100 pc of the Galactic center and that the field grows weaker between 100 pc and 200 pc. Equation (48) gives the average of the pregalactic vertical field over the disk of the Galaxy. If the direction of the pregalactic vertical field varies in space on length scales smaller than r_i, then the average strength of the pregalactic field is larger than implied by equation (48). Although equation (48) involves only the vertical field, it should be emphasized that it does not imply that the pregalactic field is primarily vertical. Moreover, the collapse of protogalactic plasma occupying a sphere of radius ~ 10 kpc down to a disk of half-thickness ~ 100 pc would amplify field components parallel to the disk by a factor of ~ 100. As pointed out by Kulsrud et al. (1997a), this suggests that the magnetic field may affect the formation of the Galactic disk.

5. COSMIC-RAY CONFINEMENT AT THE GALACTIC CENTER

Observations fail to detect any excess gamma-ray emission from cosmic-ray interactions with gas in the central 200 pc of the Galaxy (Blitz et al. 1985). Given the abundance of violent activity and interstellar matter in the central region, this suggests very poor cosmic-ray confinement, which the strong vertical field in the CMZ could help explain in two ways. First, the vertical field lines in the CMZ provide a short path straight out of the Galaxy along which cosmic rays can escape, whereas in the Galactic disk the field lines are predominantly parallel to the Galactic plane. Second, it is widely believed that cosmic-ray propagation in the interstellar medium is diffusive (Berezinskii et al. 1990), with frequent scatterings of cosmic rays by turbulent fluctuations with scale lengths equal to the radii of cosmic-ray gyrations about the magnetic field. For a GeV cosmic-ray proton in a milligauss field, this radius is $\sim 3 \times 10^9$ cm. One possible source for this small-scale turbulence is the cosmic rays themselves. When cosmic rays stream along the magnetic field faster than the Alfvén speed, they excite instabilities. These instabilities in turn scatter the cosmic rays. Under the right conditions (Cesarsky 1980), the turbulence can limit the cosmic-ray streaming velocity to roughly the Alfvén speed. In the coronal plasma of the CMZ, where $B \sim 10^{-3}$ G and the number density of ions is ~ 0.1 cm^{-3}, the Alfvén speed v_A is $\sim 7 \times 10^8$ cm s^{-1}. The time required for cosmic rays to diffuse 100 pc along the uniformly vertical field at the Alfvén speed is thus roughly 10^4 yr, which compares to a cosmic-ray residence time of several times 10^6 yr in the Galactic disk.

6. CONCLUSION

In this paper we describe a scenario that may explain both the geometry and the strength of the magnetic field at the Galactic center, and we describe the implications of this scenario for the strength of the pregalactic magnetic field. By assuming a constant mass accretion rate into the CMZ of $3 \times 10^{-1}\ M_\odot$ yr^{-1}, we estimate that all the disk gas within ~ 13 kpc of the Galactic center at the time of Galaxy formation has been accreted to within the CMZ. By equating the present-day vertical magnetic flux through the CMZ with the vertical magnetic flux through the Galactic disk out to 13 kpc at the time of Galaxy formation, we find that the area average of the pregalactic vertical field was roughly

2×10^{-7} G. If the pregalactic field changed direction on spatial scales small compared to 13 kpc, then the local strength of the magnetic field at the time of Galaxy formation would have been larger than the area average. On the other hand, the radial accretion rate may have been substantially larger in the earliest phases of the Galaxy's history because of an enhanced importance of mergers and galaxy interactions, both of which can cause interstellar material to lose angular momentum. If so, the radius from which the primordial field has been concentrated is larger than 13 kpc, and the primordial field strength correspondingly smaller. A magnetic field on the order of 10^{-7} G at the time of Galaxy formation may be evidence for the protogalactic dynamo theory of Kulsrud et al. (1997a, 1997b). It should be noted that our estimate of the pregalactic field does not imply that the pregalactic field was predominantly vertical.

The mechanisms that lead to radial accretion of disk gas—torques due to spiral density waves, Galactic bar potentials, and neighboring galaxies—are present quite generally in spiral galaxies. This suggests that intense vertical magnetic fields and their attendant phenomena may be typical of the centers of spiral galaxies. We would predict strong central fields to be most pronounced in barred systems, where the rate of angular momentum loss by gas is presumably largest.

While our simple model is, we believe, a plausible scenario for the origin of the field in the CMZ, other models are certainly possible. Dynamo amplification in the CMZ itself is one possibility, but it seems unlikely since the field has considerably larger energy than the turbulent velocities in this region; this can be deduced from the fact that the field remains straight and undeformed at sites of interaction with molecular clouds. Alternatively, the field could have been amplified in the disk by dynamo action and then accreted into the central region by radial inflow. If this were the case, then reversals in the direction of the vertical field within the CMZ would probably be required. A third possibility is that fields were generated by dynamo action in an accretion disk surrounding a central object and then expelled into the CMZ. A model of this type has been considered by Heyvaerts, Norman, & Pudritz (1988). Further studies to determine which model is correct may provide important clues to the origin of Galactic fields in general.

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