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AN ELECTRODYNAMIC MODEL OF THE GALACTIC CENTER

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ABSTRACT

Molecular clouds moving at Keplerian velocities can induce strong electric fields in ionized regions near the Galactic center. The $\boldsymbol{v} \times \boldsymbol{B}$ induced field can drive currents over equivalent circuits ~ 100 pc along the highly ordered magnetic fields, $B \sim 10^{-3}$ G. Such current paths drive low-level ion acoustic turbulence, providing a resistance in the circuit. Small magnetic pinches form which are generally kink unstable but which can organize into larger, long-lived structures. Ohmic losses are energetically important in the molecular clouds, where high-density regions should be most luminous. Electrons can accelerate in the induced fields to relativistic energies, yielding the radio luminosity. Electrodynamic flares may occur on year time scales. Such electrodynamic deceleration of clouds can powerfully increase accretion toward galactic centers and enhance their luminosities.

Subject headings: galaxies: nuclei — hydromagnetics — interstellar: molecules

I. INTRODUCTION

Near Galactic center lie several types of ordered, luminous structures visible in the radio bands. Most prominent is the Arc, which has two very different segments: straight nonthermal filaments perpendicular to the Galactic plane, and the Arch—thermally emitting filaments above the Galactic plane which turn back toward Galactic center. These features are weakly echoed at negative Galactic latitude, suggesting an overall structure connecting the ends of the straight filaments toward the Galactic center. This paper attempts an electrodynamic model for these observed bright elements.

Observations of recombination lines and thermal dust emission show that the Arch filaments are thermal emitters. They appear to lie near giant molecular clouds and often overlap the edges. These clouds are denser ($\sim 10^4$ cm^{-3}, by CS and NH_3 emission seen throughout the clouds), warmer (gas temperatures of 50–100 K), and of larger local line width (20–40 km s^{-1}) than their counterparts in the galactic disk a few kiloparsecs from the center (Gusten and Downes 1980; Gusten, Walmsley, and Pauls 1981; Armstrong and Barrett 1985; Balley *et al.* 1987). Distribution of ionized and molecular gas suggests that they are ionized by external sources (Serabyn and Gusten 1986). Low dust temperature and high gas temperatures there further suggest that shock dissipation or some other unusual process does this heating, rather than gas-dust collisions.

Heyvaerts, Norman, and Pudnitz (1988) recently proposed a model of energy transfer from the inner parsec of the Galactic center through expanding magnetic loops. While this model explains some morphological and energetic puzzles close to the center, in order to explain the well-ordered filaments and high luminosity it must invoke a set of shock waves where the loops meet a heavier medium. To observe their shocks as linear filaments requires a special viewing angle. Further, although their loops apparently expand symmetrically from the center and so should strike the dense outer medium on both sides of the center, there is conspicuously less luminosity on the side opposite the Arch. It seems plausible that another agency closer to the filaments might be the cause of so much Arch luminosity.

Two prominent clouds, G0.1 + 0.08 and G0.18 − 0.04, apparently interact with the Arch. A cloud with 40 km s^{-1} velocity seems to protrude into the Arch, judging from contour maps of molecular line emission. Yusef-Zadeh and Morris (1987) estimate a milligauss magnetic field in this region, and perhaps throughout the entire volume. Emission measures give a relativistic electron density of at least 4×10^{-4} cm^{-3}.

Further, these giant clouds move oppositely to the direction of galactic rotation at high velocity, perhaps on highly eccentric orbits (Bally *et al.* 1987). Serabyn and Gusten (1986) propose that tidal disruption forces portions of these clouds inward toward Galactic center.

This unusual configuration suggests a connection with the straight filaments, especially since Yusef-Zadeh and Morris (1987) show that polarization peaks at the overlap between the straight filaments and the Arch, suggesting interaction and particle acceleration there. Their work reveals linear polarization along the straight filaments, which remain coherent and smoothly luminous for 30 pc perpendicular to the Galactic plane. Some depolarization along their length implies intervention of nonthermal matter along our line of sight. The spectral index of nonthermal filamentary emission is flat, implying young, monoenergetic electrons (Yusef, Morris, and Chance 1984). The straight filaments curve slightly concave toward galactic center, along loci of constant angular velocity.

As the straight filaments extend away from the Galactic plane they become diffuse and broad, leading to polarized lobes aligned with the filaments and placed symmetrically (Seiradakis *et al.* 1985; Tsuboi *et al.* 1986). This could arise from a decrease in external gas pressure away from the plane, or an adjustment of possible magnetic confinement of the filaments. Yusef-Zadeh and Morris (1987) detect apparent helical structure winding about the system of linear filaments with constant pitch angle and radius of curvature ~ 9 pc. They see three distinct helical segments crossing in front of the filaments, with a common axis at the mean position of the filaments. They further suggest that some filaments gently twist about each other. They resemble the individual filaments near the plane, which are separated by ~ 1 lt-yr. The regular pattern of the straight filaments suggests some ordering principle, since it is unlikely that we are in a privileged observing position and are witnessing, for example, a family of shocks seen sidewise. This ordering vanishes in the Arch. Further from the Arch and straight filaments, which together comprise the Arc, isolated, thin, nonthermal threads extend over 30 pc with diameters of less than 0.5 pc.

All these observations suggest a model for the entire region invoking electrodynamical coupling and formation of large current paths. The Arc, Arch, threads, and filaments remind one powerfully of plasma discharges in the laboratory which are heated by currents and are shaped by both external and self-generated magnetic fields. Given the evidence for a strong poloidal field within 50 pc of Galactic center (Yusef-Zadeh and Morris 1987), it seems natural to suppose currents run along these ordered fields, illuminating individual paths by synchrotron emission in the filaments and by thermal radiation in the regions nearer the large molecular clouds. For convenience let us term all such structures "strands," implying that they may have deeper, smaller structure, but all are woven by similar effects.

There is further suggestive evidence. The gas temperature inferred from radio recombination lines is ~ 1 eV, but ionization in some regions requires 10–100 eV. This implies a wide range of local temperatures or else some local ionizing agency, such as current flow. Polarization measurements show that all filaments thus far studied are aligned along the field. Along with evidence of helical structure in some southern filaments, these morphologies suggest strong magnetic ordering of the energy release. (Heyvaerts, Norman, and Pudnitz 1988).

The low-energy jet emanating from the Galactic nucleus (Yusef-Zadeh *et al.* 1986) suggests that relativistic particle acceleration and ordered flows are common near Galactic center (Jacobson 1982). The slim "threads" (Morris and Yusef-Zadeh 1985) speak for extremely localized heating which is naturally explained by field lines which carry current but may have been separated from the filament families by the nearby intervening molecular clouds. With these hints, we attempt here a discussion in terms of an overall circuit equation for the region.

II. BASIC CIRCUIT

Consider an electrodynamic plasma region in which currents $\boldsymbol{J}$ flow, electrostatic potentials ϕ and vector potentials A exist, with resistivity η and electron pressure P_e.

The circuit equation for electrodynamically connected regions is

$$-\int \boldsymbol{E}_0 \cdot \boldsymbol{dl} = \int \eta \boldsymbol{J} \cdot \boldsymbol{dl} + \int \nabla\phi \cdot \boldsymbol{dl} + \frac{1}{c}\int \frac{\partial A}{\partial t} \cdot \boldsymbol{dl} , \quad (1)$$

where we neglect electron inertia and write

$$E = -\nabla\phi - \frac{1}{c}\frac{\partial A}{\partial t} ; \quad \boldsymbol{E}_0 = \frac{1}{ne}\nabla P_e - \frac{\boldsymbol{v} \times \boldsymbol{B}}{c} . \quad (2)$$

The integrations here are performed over any path in the plasma. The left side of equation (1) is the applied voltage V, and the terms on the right side are, respectively, the resistive, capacitive, and inductive voltage drops. The quantity E_0 contains both solenoidal and electrostatic terms, but a small displacement of electrons carrying negligible currents will make the capacitive part in equation (1) cancel the electrostatic term, which is proportional to the gradient of electron pressure, ∇P_e. The circuit equation then is

$$V = IR + \frac{d}{dt}(IL_i) , \quad V = \int \left(\frac{\boldsymbol{v} \times \boldsymbol{B}}{c}\right) \cdot \boldsymbol{dl} , \quad (3)$$

$$IR = \int \eta \boldsymbol{J} \cdot \boldsymbol{dl} , \quad \frac{d}{dt}(IL_i) = \frac{1}{c}\int \frac{\partial A}{\partial t} \cdot \boldsymbol{dl} . \quad (4)$$

Local conditions contribute to the integrals, and evolution of the circuit depends also on global aspects of the current. We can write

$$R = \frac{4\pi L \nu}{A\omega_p^2} ; \quad L_i = L\mu \ln\left(\frac{8L}{a}\right) ; \quad C = NL_d^* \epsilon . \quad (5)$$

Here the inductance L_i is that of a loop of length L and cross-sectional area $A = \pi a^2$. The capacitance C is that of N current paths of length L_d ($<L$) in parallel, separated by a distance comparable with the radius of the current path. Locally the collision frequency ν governs resistance. The quality measure of such circuits is $Q = (1/R)(L_i/C)^{1/2}$. Now we turn to the microphysics necessary to estimate circuit quantities, principally R. We shall return to the dynamical implications of L_i and C later. Most of this paper will assume a steady state in which Ohmic losses dominate.

The basic picture appears in Figure 1. A giant molecular cloud moving opposite to the Galactic rotation can induce powerful electric fields by $\boldsymbol{v} \times \boldsymbol{B}$ motion throughout the partially ionized cloud. The plasma component of the cloud can push the poloidal field $\boldsymbol{B}$ out of the way, locally deforming it. Electric fields will drive currents which can become attached to neighboring, straighter field lines, through scattering of the electrons by current-induced turbulence. Once on the ordered field lines, the currents proceed around a large circuit which leads through the Galactic plane. Conditions in the plane are unclear, so we cannot judge whether ionization is sufficient there to return the currents through the plane to field lines lying closer to Galactic center, and thence back up into the Arch. If not, the currents may proceed to negative Galactic latitudes, forming the somewhat weaker filamentary structures there. Presumably the circuit eventually closes by turning near the polarized lobes at the ends of the filaments and moving back toward Galactic center. The circuit probably passes through the Arch. Figure 1 illustrates this last possibility. Along a given current path there may be several molecular clouds which induce electric fields, i.e., several "batteries."

Strong electric fields induced by $\boldsymbol{v} \times \boldsymbol{B}$ motions can explain some of these features. The induced field is

$$\boldsymbol{E} = \frac{\boldsymbol{v}}{c} \times \boldsymbol{B} = 10^{-8}\beta_{-4}B_{-3} \sin\psi \text{ statvolt cm}^{-1} , \quad (6)$$

where β is v/c, v is the velocity of mass motion, $B_{-3} = (B/10^{-3}$ G), and ψ is the mean angle between $\boldsymbol{v}$ and $\boldsymbol{B}$. In a complex plasma-filled environment, laboratory experiments and nonlinear theory can be a useful guide. A plasma moving across a strong magnetic field immediately experiences the induced E produced by the plasma motion. The plasma edges experience charge separation, and small "capacitors" form transverse to the plasma velocity (Peter and Rostoker 1982). Using equation (6), we require that the energy lodged in the electric field across a width h be less than the incident plasma kinetic energy $eEh \approx mv^2/2$. This implies that $h < \rho_i v/2v_i$, with ρ_i the ion cyclotron radius and v_i the ion thermal velocity. Since $v \sim 10v_i$, we expect the cloud to shred into filaments wherein electric

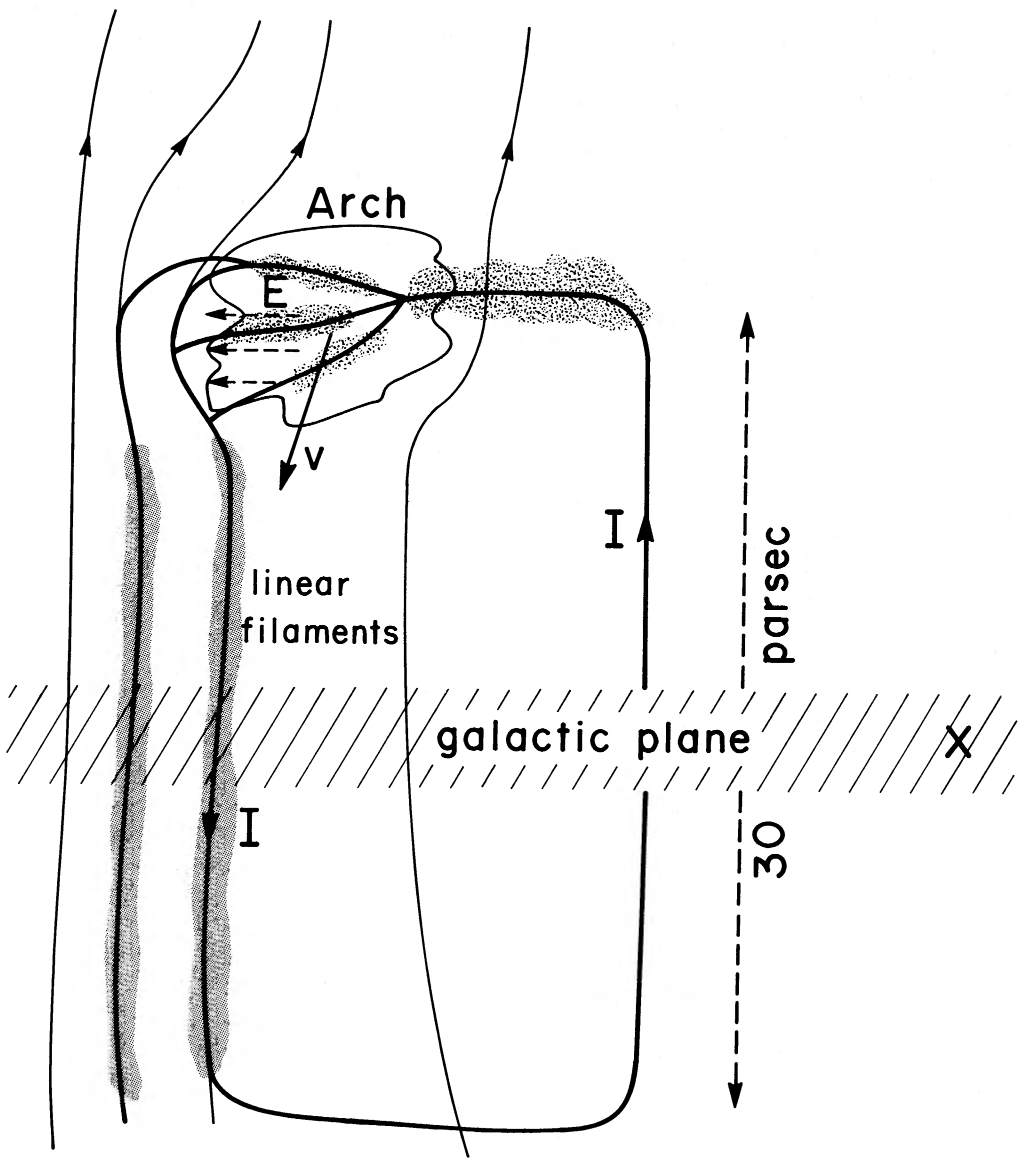

FIG. 1.—Schematic of a circuit with currents driven along ordered magnetic field lines by induction from a partially ionized molecular cloud. Lightly shaded irregular clouds are thermal radio emitters. Synchrotron-emitting linear filaments are ~1 lt-yr wide. A molecular cloud with velocity v drives the circuit current I with inductive field E. Local ordered magnetic field lines are deformed by the cloud. Galactic center is at position X. We presume all features are roughly in the plane of the paper.

fields comparable to equation (6) occur, driving charge separation sheaths (Schmidt 1966). The plasma cloud slows very slightly as it breaks into separate regions of strong E fields. There is some evidence in numerical simulations of structures larger than h (Mitchell *et al.* 1985). In any case, $\rho_i \approx 10^5$ cm is very small compared with other dimensions, so the setting up of the "battery" is microscopic in the larger circuit picture. The circuit forms because nearby plasma will immediately move to compensate the charge separations which form from the induced E. Although the induced E is perpendicular to B, currents will flow along B to neutralize charge. A complex pattern of resulting electric fields on larger scales drives the overall circuit, as is seen in experiment (Wessel and Robertson 1981). Note, though, that $h \lesssim 10\rho_i$ can be comparable with the Bennett pinch radius we discuss shortly. The induced field will occur where the external magnetic field begins to diffuse into the molecular cloud. This process is usually very slow if only classical Coulomb scattering occurs, but there is an added effect from the strong magnetic field. The appropriate conductivity is reduced because of the pinning of electrons to the field lines, and this enhances inward diffusion of the magnetic field. A rough estimate is (Felber *et al.* 1982).

$$\tau_B \approx \left[\left(\frac{x}{\mathrm{pc}}\right)^2\left(\frac{T_i}{T_e^2}\right)^{3/2} n\right] 100 \text{ yr} ,$$

where x is the distance diffused, and the ion temperature T_i and the electron temperature T_e are in eV. This implies that considerable mixing of the ambient field into the cloud can occur during one Keplerian orbit about the Galactic center. The induced electric fields will be strongest at the edges of such clouds, where shredding and magnetic diffusion are going on.

We should therefore expect to see circuits set up preferentially at the margins of molecular clouds which are being heated by their soft "collisions" with the strong, ordered magnetic field. This fits well the observations of long, luminous features near clouds. In particular, the Sgr C linear filament at negative latitudes (Liszt 1985) and two parallel filaments at positive latitudes (Bally and Yusef-Zadeh 1988) appear at cloud edges. The entire "Continuum Arc" complex seems to lie at the edges of a 40 km s^{-1} Sgr A molecular cloud. Cloud heating is also indirect evidence of the strong coupling. The Keplerian velocity at distance r from an enclosed mass M is

$$v_{\rm K} = 50 \text{ km s}^{-1}\left[\left(\frac{M}{10^7\, M_\odot}\right)\left(\frac{r}{40 \text{ pc}}\right)^{-1}\right]^{1/2}, \quad (7)$$

and large molecular clouds with twice this speed appear near some linear filaments. A field of $B_{-3} \approx 1$ would provide rough equilibrium with the ram pressure of thermal gas in the area, which moves at a few tens of km s^{-1} and has density $n \approx 400$ cm^{-3}. Only slight bending of a filament interacting with the "sickle" (Yusef-Zadeh and Morris 1987) by such gas implies $B_{-3} \gtrsim 1$. There will be a steady electron drift in the mean field of equation (6),

$$v_D = \frac{\omega_p^2 E}{4\pi n e \nu}, \quad (8)$$

with the appropriate collision frequency ν set by the level of electrostatic turbulence, E_e, described by $W \equiv \langle E_e^2 \rangle / 4\pi n T_e$. Since v_D will typically be comparable with the ion thermal spedd, v_i, we select the nonlinear scattering rate from fields E_e with phase velocity $\gtrsim v_i$. Since we know so little of conditions at galactic center, we should seek a broadly plausible agency for the enhanced scattering. Extensive experience with laboratory plasma suggests that a low level of ion-acoustic waves will permanently exist wherever a relative drift takes place (Stringer 1964). Electron scattering from these space-charge waves gives rise to momentum-transfer collision frequencies of $\nu \sim 3 \times 10^{-3}$–$2 \times 10^{-2}\omega_p$ (Schrijver 1973) in conditions where $T_e \gg T_i$ and $v_D > 9C_s(T_e/T_i)^{1/2}$, with C_s the ion sound speed. Ion cyclotron modes with $v_D \geq 10 v_i$ can also produce collision frequencies of order $(10^{-5}$–$10^{-4})\omega_p$ (Kindel, Barnes, and Forslund 1981). Although ion heating can shut off this mode momentarily, convective cooling turns it back on again in, for example, solar heating conditions (Benford 1983).

We do not need outright, constant instability to produce a low level of electrostatic turbulence, since in a steady state levels with $W \ll 1$ can persist and still dominate over classical resistivity, which for our conditions would yield $\nu \approx 10^{-8}\omega_p$. We shall take a form suggested by extensive simulation and theory (Boris *et al.* 1970; Schrijver 1973; Papadopoulos 1977)

$$\nu \approx \omega_p W, \quad (9)$$

where W includes only $E_e(\omega/k < v_D)$. For steady turbulence, $W \approx 10^{-2}$–10^{-5} seems plausible from laboratory experiments. Thus

$$v_D = 3 \times 10^4 \frac{\beta_{-4} B_{-3}}{W n^{1/2}} \sin\psi \text{ cm s}^{-1}. \quad (10)$$

Further, we find, with the ion temperature T_i in units of eV,

$$\frac{v_D}{v_{\rm A}} = 1.5 \times 10^{-2} n^{-1/2} \sin\psi\, \beta_{-4} W_{-2} \ll 1,$$

$$\frac{v_D}{v_{ti}} = 3\,\frac{\beta_{-4} B_{-3}}{W\sqrt{nT_i}}. \quad (11)$$

The first condition insures that drifting electrons cannot resonate with the Alfvén velocity, v_A, and suffer severe pitch angle scattering. The second implies that $v_D > v_{ti}$ the ion thermal speed, can excite ion instabilities in regions where T_i (in eV) ~ 1, $n \sim$ cm^{-3}, and the other quantities are of order unity. The condition $v_D > 10 v_i$ for the ion cyclotron instability thus occurs if $W_{-2} \lesssim 0.3$. Low levels of turbulence, $W \sim 10^{-5}$, thus yield high v_D, self-consistently producing the resultant W. How the plasma strikes a steady state, fixing W, depends on macroscopic losses as well. We cannot plausibly include such considerations, given our level of ignorance of conditions at Galactic center, and so leave W an open parameter.

III. ENERGETICS

A self-constricted pinch achieves a balance between inner thermal pressure and the $B_\theta^2/8\pi$ confining pressure. The radius of a cylindrical pinch is then fixed by specifying the net drift speed and the plasma pressure to be confined (Krall and Trivelpiece 1973; Spitzer 1962). This yields

$$a_P = \frac{c}{e v_D}\sqrt{\frac{2(T_e + T_i)}{\pi n(0)}}.$$

Here $n(0)$ is the plasma density on axis, where the current density is $n(0)ev_D$. Using equation (10) for v_D yields

$$a_P = 2 \times 10^9 \left(\frac{W}{\beta_{-4} B_{-3} \sin\psi}\right) T^{1/2} \text{ cm}. \quad (12)$$

This is a very small object for astrophysical conditions, and it suggests immediately that any self-pinched discharges will be discernible only if they congregate, contributing to a larger structure. The narrowness of the pinch means its resistance is large, as equation (5) yields

$$R = \left(\frac{L}{\text{pc}}\right)(T n^{1/2} W)^{-1}\left[\left(\frac{a_P}{a}\right)\beta_{-4} B_{-3} \sin\psi\right]^2 5 \times 10^7 \text{ ohm}. \quad (13)$$

With many such pinch paths available, the voltage derived from equation (1) will doubtless flow through a large number of small pinches in parallel. The driving voltage is

$$V = \beta_{-4} B_{-3}\left(\frac{L}{\text{pc}}\right) \sin\psi\; 10^{18} \text{ volt}. \quad (14)$$

The total resistance of N pinches in parallel is $R_t = R/N$, and total current flowing is

$$I_t \equiv \frac{V}{R_t} = \left(\frac{N\sqrt{n} W T}{\beta_{-4} B_{-3} \sin\psi}\right)\left(\frac{a}{a_p}\right)^2 2 \times 10^{10} \text{ amp}, \quad (15)$$

while the magnetic field seen near any small pinch, B_e, is still small,

$$B_e = \frac{I_t}{N a_P} \approx 6 \times 10^{-4}\sqrt{nT} \text{ G}. \quad (16)$$

Note that $B_e < B \sim 10^{-3}$ G, which is necessary for stable, long-lived pinches, as we shall discuss.

So far we have no idea how many small pinches comprise the ordered regions of illuminated strands. Equation (12) shows that a pinch supported by gas pressure with $T \sim 1$ is very small compared with the 0.3 pc observed width of the linear filaments. This means a filament is a congregation of self-pinched elements which may cooperate to form a larger scale (perhaps nearly force-free) equilibrium. We can confidently predict that higher resolution maps of the filaments will show finer, complex structure. To estimate how many pinches are in given features we can consider the circuit losses. The net energy dissipated in the total circuit is

$$\epsilon = \frac{V^2}{R_T} \approx \left[\left(\frac{a}{a_p}\right)^2 n^{1/2} NTW\left(\frac{L}{\text{pc}}\right)\right] 2 \times 10^{35} \text{ ergs s}^{-1} . \quad (17)$$

The total observed thermal infrared luminosity $\sim 5 \times 10^{40}$ ergs s^{-1} comes principally from a large molecular cloud in which the inferred plasma density is $\sim 500 \text{ cm}^{-3}$ (Morris and Yusef-Zadeh 1988). (This estimate comes from assuming most of the molecular material is locally ionized.) To account for this wholly as ohmic dissipation requires

$$n^{1/2}\left(\frac{L}{\text{pc}}\right)\left(\frac{a}{a_p}\right)^2 WNT \sim 2.5 \times 10^5 . \quad (18)$$

For the thermal emitters we estimate $L = 10$ pc, $n = 100 \text{ cm}^{-3}$, $T = 1$(eV), so with $a \approx a_p$ we need $NW = 1000$. With turbulence levels of $W = 10^{-3}$ this requires about a million current filaments.

Ohmic losses should occur where currents choose the highest available conductivity, which by equation (13) scales with $n^{1/2}$. Luminosity should follow the visible density ridges, within the constraint that voltages occur at cloud edges, so circuits should include the cloud perimeter. Data of Yusef-Zadeh *et al.* (1987) seem to bear this out.

Nonthermal (synchrotron) emission observed in linear filaments is $\sim 4 \times 10^{33}$ ergs s^{-1}, quite easily explained by only a few pinches.

Further, the voltage of equation (14) provides ample opportunity to accelerate electrons to the ~ 20 MeV needed to radiate the 5 GHz synchrotron emission in the 10^{-3} G field. If unscreened over a distance of $\sim 10^8$ cm, this voltage will provide the synchrotron electrons. This length is about a pinch radius when $W = 0.01$. Irregularities of flow on this scale are certainly plausible. The mean free path of a relativistic electron with collision frequency given by equation (9) is $5 \times 10^7/W_{-2} n^{1/2}$ cm, so the scattering will not impede some electrons reaching MeV energies. Irregular conditions may arise naturally, as in double layers, which can produce substantial acceleration in concert with ohmic processes (Borovsky 1986). The few isolated "threads" are current paths, perhaps connected to other moving clouds. They could have been pulled away from the filaments by induction of passing conducting clouds, yet remain electrodynamically coupled to the governing potential.

IV. STABILITY

Thin, luminous strands suggest a self-pinched electrical flow, with the poloidal field B_z providing "backbone" while the flow confines itself with an ordered B_θ. Essentially, our envisioned circuit connects thermal gas regions which are at different potentials, so the linear luminous features are like lightning guided by the strong global fields.

Within a pinched structure, radial pressure P obeys

$$\frac{\partial P}{\partial r} + \frac{B_\theta^2 r}{2\pi a^2} = 0 .$$

Where $B_\theta = 2I/ca$ is the magnetic field at the surface of the flow, $r = a$, assuming j is independent of r for $r < a$ and $I = j\pi a^2$. For $r > a$, the "cocoon" region, external plasma can be held by the B_θ field lines (Benford 1981). The electron gyroradius is

$$r_e \approx 7 \times 10^8 \sqrt{\frac{\nu_G}{B_{-3}^3}} \sin\theta \text{ cm} . \quad (19)$$

Here ν_G is the observed synchrotron frequency (in GHz) of the electron. This corresponds to a radiating electron which has a low pitch angle θ in the combined (B_z, B_θ) helical structure. The structure is liable to sidewise instabilities if B_θ is large, however.

A plasma flow in a helical magnetic field is unstable to pinching modes (sausage) if (Benford 1987)

$$B_\theta > \frac{B_z}{\ln(L/a)} , \quad (20)$$

where L is the structure length along z. It will kink if

$$B_\theta > 2\pi a B_z/L . \quad (21)$$

We envision quite small pinches which have $L \gg a$. Stability requires small B_θ, yet it must be large enough to enhance the luminosity of the core region, so B_θ cannot be very weak compared with B_z. To argue that pinches can survive kink instability for the dynamical time of the region ($t_d \approx 2 \times 10^5$ yr) we must include stabilizing effects. These are as follows:

1. The cocoon dragged by B_θ as it moves during kinking will slow growth to a time (Benford 1981).

$$t \approx 5 \times 10^3 \text{ yr}\left[\sqrt{\frac{M_c}{M_p}} \frac{\sqrt{n}}{B_{-3}} \left(\frac{\lambda}{50 \text{ pc}}\right)\right] , \quad (22)$$

where $M_c(M_p)$ is the mass per unit length of the cocoon (pinched region). Here λ is the wavelength of the kink, which is comparable with the length of filaments. For large $M_c/M_p \sim 1000$, long wavelengths may be suppressed for $t \approx t_d$. This requires a comoving cocoon of radius $R_c \sim 30a$, if densities in the two regions are comparable.

2. To suppress short-wavelength modes requires mirror forces on a relatively nearby surrounding, massive, conducting body at distance b. Then waves are stable with

$$\lambda_z > 2\pi a \ln(b/a) . \quad (23)$$

This calls up our earlier picture of many small pinches, stabilized now by the inertia of surrounding clouds of plasma. These nearby "walls" by definition do not carry a net current (because of varying conditions of $\boldsymbol{v} \times \boldsymbol{B}$) but can inhibit sidewise motions. The gross effect of many such small pinches can comprise a quasi-stable strand configuration of width 1 lt-yr.

However, this total "anthology" filament of pinches will then obey the same conditions as equations (20) and (21), with an effective radius a^* equaling roughly the observed filament radius, ~ 1 lt-yr. Then, without a stabilizing "wall" nearby, equation (21) demands for $L = 100a^*$, $\langle B_\theta \rangle / \langle B_z \rangle < (2\pi a)/L \approx 0.06$, or $\langle B_\theta \rangle \approx 6 \times 10^{-5}$ G for $\langle B_z \rangle = 10^{-3}$ G. We can then estimate the synchrotron luminosity of a filament filled with relativistic electrons, assuming scattering from ion turbulence, equation (9), will keep their pitch angles large. A density of relativistic electrons $n_e = 4 \times 10^{-4}$ can yield the 40 Jy of synchrotron radio emission overall. Clear signs of interaction between the larger, more wispy thermal filaments and the straight ones (Yusef-Zadeh 1986) argues that electrons may undergo large scattering where they leave the molecular cloud region and thereby attach to strong field lines.

Presumably the synchrotron electrons are either brought into the pinches from other acceleration sites or are produced by local processes. The level of plasma turbulence provides easy, nonadiabatic scattering for fresh electrons to enter pinch configurations. The mean free path to scatter a relativistic electron of $v_0/c \equiv \beta_0 \approx 1$ through one gyroradius is (Benford 1986).

$$L_S \approx \frac{\beta_0^4(\tan \psi \sin \theta)}{T^{3/2} N_2^* W_{-2}} 10^{-4} \text{ pc} , \quad (24)$$

where N_2^* is the size of the scattering center in units of 10^2 plasma Debye lengths. This short length means relativistic electrons can enter and illuminate the compressed pinch cores. The average B_θ of these pinches is produced by the spatial average of the $\boldsymbol{v} \times \boldsymbol{B}$ induced locally by passage of conducting clouds through the poloidal field.

The family of small, Bennett-sized pinches can organize into a larger nearly force-free configuration in a time $\sim L/v_A \sim$ 1000 yr. Yusef-Zadeh and Morris (1987) argue for some helical morphology in nonthermal filaments, so perhaps locally this evolution to force-free equilibria occurs. Most of our envisioned current path, though, does not display any obvious evidence of any more complex morphology than linear pinches. The Arch filaments cannot be force-free since they have $nkT > B^2/8\pi$.

Yusef-Zadeh and Morris (1987) observe that two of the straight synchrotron filaments twist slightly about each other. This suggests electromagnetic attraction between currents. Consider two pinches, each carrying current I, a distance d apart, in helices 180° out of phase. With average pitch angle $dz/da \equiv \cot \theta$, force balance is (Achterberg 1987)

$$\frac{2\pi a^2}{d} \left(mnv_D^2 - \frac{B^2}{4\pi} + \frac{B_\theta^2}{16\pi} \right) \sin^2 \theta = \frac{I^2}{c\,d} \cos 2\theta ,$$

neglecting terms of order $(a/d)^2 \ll 1$. Both B_θ and the drift kinetic energy destabilize the force equilibrium, while the axial field B gives the configuration "backbone" against the destabilizing Lorentz force on the right-hand side. Perturbations changing the pitch angle of the helically entwined currents can grow in a time

$$\tau_g \approx \frac{d}{v_D} \approx 10^5 \left(\frac{W_{-2}\, n}{\beta_{-4} B_{-3}} \right) \text{yr} .$$

This mutual twisting could grow within the strand lifetime which is limited by galactic rotation to $\sim 10^6$ yr. Observations of such forms would support our picture.

Networks of current-carrying paths can be unstable to runaway heating. If one path heats and thereby lowers its resistivity, it can draw current from nearby paths. Eventually this path dominates the circuit, eliminating the others. Detailed treatment shows that the collision rate of equation (9) does not lead to this instability, so a net of paths will persist even if they are all connected to the same voltage. Since each filament could arise from a different inductive region, there may be no possibility of such instabilities.

There is no true long-term equilibrium for the magnetic pinches we envision, and changes may occur more rapidly than our instability conditions suggest. Returning to the circuit analogy, note that the capacitance of equation (5) can be written as the product of the free space capacitance of a length y, $C^* = y/4\pi$, and the low-frequency dielectric constant, c^2/v_A^2, so $C = dc^2/4\pi v_A^2$. Also, the inductance L_i can be written in cgs units as $4L/\pi c^2$. This yields a measure of circuit quality,

$$Q = \frac{1}{R} \sqrt{\frac{L_i}{C}} \sim 100 \frac{B_{-3}}{WN} \left(\frac{a_p}{10^9 \text{ cm}} \right) \left(\frac{a_p}{L} \right) \sqrt{\frac{L}{y}} . \quad (25)$$

The small ratio a_p/L forces Q to low values. This means our circuit is very "lossy" and may suppress signals along it.

We have considered the Galactic center circuit as steady state, but the origin of the electric fields in passing molecular clouds, and of resistivity in sustained turbulence, argues for intermittent change. If conditions alter, the circuit as a whole will relax, dissipating energy in a time determined by both global and local characteristics. A sharp rise in resistivity in series with the current, for example, could follow a rise in the effective collision frequency to ν^*—either from increased turbulence, or from intrusion of dense plasma into the circuit. If this occurs the global time constant is approximately

$$t_G = \frac{L_i}{R + (2\,d\nu^*/\omega_p^2 x^2)} ,$$

where x is the distance over which magnetic energy is dissipated locally; typically $x \approx a$. Two regimes emerge: (*a*) $R \ll 2\,d\nu^*/(\omega_p x)^2$, or $\nu L \ll \nu\, d(a_p/x)^2$, in which case in a time

$$\tau_G = 50 \sqrt{n} \left(\frac{L}{gd} \right) \left(\frac{a}{10^9 \text{ cm}} \right)^2 \text{ s} ,$$

the bulk of the circuit energy stored inductively dissipates in the region d. Here we have written $\nu^* = g\omega_p$, and assumed the pinch radius a_p does not change throughout. For $L/d = 100$ and $g = 10^{-3}$, $n = 100 \text{ cm}^{-3}$, τ_G is 20 months. Observation of such rapid changes in the thin filaments would support a circuit interpretation.

Case *b* holds when $\nu L \gg \nu^* d(a_p/x)^2$ and only a small fraction of the globally stored energy dissipates, given by

$$\delta\epsilon \approx \frac{1}{2} L_i I^2 \left(\frac{a_p}{x} \right)^2 \left(\frac{d}{L} \right)^2 .$$

Effective dissipation occurs, as in solar flares, when the local ratio of plasma energy to field energy is low. The well-ordered filaments provide such a site. They should be monitored to study rapid luminosity changes, perhaps correlated (although delayed by light-travel time) with flares or alterations in the inductive processes in the molecular clouds. While field configurations can alter only at speed $v_A = 2 \times 10^9 B_{-3} n^{-1/2}$ cm s^{-1} ohmic dissipation can propagate at nearly light speed.

For comparison, the time to decelerate a molecular cloud electrodynamically by ohmically dissipating its velocity v_c into luminosity L_c is

$$\tau \approx 10^4 \text{ yr} \left(\frac{M_c}{10^5 M_\odot} \right) \left(\frac{v_c}{100 \text{ km s}^{-1}} \right) \left(\frac{L_c}{10^6 L_\odot} \right)^{-1} ,$$

less than the dynamical time of $\sim 10^5$ yr. Thus the entire complex may exist only relatively briefly. Perhaps this is why we see only a few such luminous features near Galactic center, including filaments near Sag C (Liszt 1985).

Why do not all molecular clouds suffer this deceleration? Two conditions are necessary: enough ionization to produce the induction, and a strong, ordered magnetic field which the cloud crosses. Probably neither condition holds for clouds in the Galaxy generally, although a sign of some interaction would be a warming of clouds at their edges. Most ordinary clouds probably encounter external fields that are disordered over scales of a few cloud radii, so the mean time-averaged value of sin ψ in our equations is very small before any significant energy loss can occur. The first condition probably requires unusual levels of heating to make a cloud act at least partially as a plasma. This may be why clouds moving opposite the Galactic rotation seem to cause the luminous filaments; they are first heated by collisions, then ionized somewhat, and finally drive inductive circuits.

V. CONCLUSIONS

The discussion so far conspicuously ignored the possible black hole at dynamical Galactic center (Genzel and Townes 1987). Much effort of the last decade has explored methods of electrodynamically harvesting energy in black holes and accretion disks to fuel Galactic jets. Can we expect that the Galactic center black hole, if it exists, figures strongly in the circuit model presented here?

Probably not. Consider a simple circuit model of a hole and disk (Fig. 2), as in Camenzind (1986). We envision a disk field B_θ which reverses sign as we pass axially through the disk, since presumably twin jets flow from both polar regions. A typical value for $B_\theta^2/8\pi$ will not exceed the thermal pressure of the disk, which should be of order 400 dyne cm^{-2}, following the general scheme proposed by Rees *et al.* (1982) for massive black holes and applied by Rees (1982). This implies $B_\theta \approx 100$ G at a distance of 20 AU from the hole, which corresponds to the size of the observed radio point source (Lo 1986). This radio source emits $\sim 2 \times 10^{34}$ ergs s^{-1}, making it the brightest object of such a size.

To envision the circuit that might operate with such a hot disk as its source, we note that to reverse B_θ in the disk requires that a radial current must flow there of magnitude

$$I_r = \left(\frac{r}{10^{14}\ \text{cm}}\right)\left(\frac{B_\theta}{100\ \text{G}}\right) 3 \times 10^{17}\ \text{A}\ . \qquad (26)$$

This current is presumably the return current of the polar outflow. It flows into the corotation region of the inner magnetosphere and connects with the high latitude region, where in order to maintain corotation a Goldreich-Julian density must exist:

$$n_{\text{GJ}} = \left(\frac{B_z}{100\ \text{G}}\right)\left(\frac{r}{10^{14}\ \text{cm}}\right)^{-1} 10^{-3}\ \text{cm}^{-3}\ .$$

Electric fields will drive this density away from the poles at relativistic speeds, through an area A_j. The outflowing current and luminosity will be

$$I_j \approx \left(\frac{B_z}{100\ \text{G}}\right)\left(\frac{r}{10^{14}\ \text{cm}}\right)\left(\frac{r_j}{2.5 \times 10^9\ \text{cm}}\right)^2 3 \times 10^{17}\ \text{A}\ ,$$

$$\approx n_{\text{GJ}}\, ecA_j$$

$$L_j = \left(\frac{I_r}{310^{17}\ \text{A}}\right)\gamma_j \times 10^{30}\ \text{ergs s}^{-1}\ . \qquad (27)$$

Here a jet radius r_j of order 10^9 cm will carry the needed current. (We assume the axial field $B_z \approx B_\theta$ in the generating region for simplicity.) The Lorentz factor of the jet, γ_j, may be fixed by comparing with the observation of a broad, low-energy jet visible at 160 MHz of luminosity $\sim 10^{33}$ ergs s^{-1} (Yusef-Zadeh *et al.* 1986). If this feature is indeed driven by the black hole accretion disk through electrodynamic processes, we require $\gamma_j \approx 1000$. This is comparable with the Lorentz factor needed to yield the 160 MHz emission in the jet at the estimated 10^{-5} G equipartition magnetic field.

These rough estimates suggest a low-energy jet is compatible with present understanding of simple electrodynamic disk models. If the extended ridge of emission seen by Yusef-Zadeh *et al.* (1986) is such a jet, it would be self-confined by its own magnetic field with radius R_j if $I_j \approx 10^{18}(R_j/10$ pc) A, which compares well with the estimate of equation (27). However, this seeming jet could easily be confined by external gas pressure.

The main point is that these expected luminosities are far below the 10^{40} ergs s^{-1} required to fuel the molecular cloud emission. It seems unlikely that the black hole magnetosphere, some tens of parsecs away, plays a major role in driving the

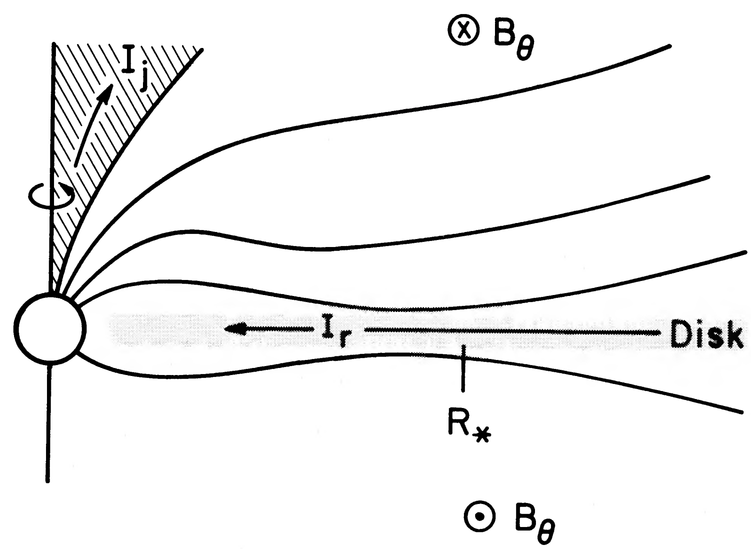

FIG. 2.—Corotating magnetosphere formed by magnetic fields attached to the disk orbiting a rotor. In the disk a radial current I_r must flow to support the change in sign of B_θ which occurs axially at the disk layer. Plasma centrifugally driven out at the polar zone carries a density at least that required by corotation. The jet current I_j returns as I_r through the disk.

circuit flowing through the Arc. Although the weak, one-sided jet may derive electrodynamically, it probably emits most of the available energy in an accretion disk-powered circuit, leaving little to contribute to the more luminous features 100 pc away (Uchida, Shibata, and Sofue 1985).

This paper attempts a qualitative understanding of a circuit model for our Galactic center. Any such picture must finally stand or fall on its inherent plausibility and its predictions.

Our principal inferences from the model, which may be checked by observation, are the following:

1. Luminosity from ohmic heating should follow current paths. Since inductive voltages occur at the edges of molecular clouds, filaments should be most commonly seen there. Within clouds, luminosity should follow high-density ridges.

2. Straight, synchrotron filaments may twist about each other from current coupling, and locally may form typical helical force-free geometries.

3. Flares due to changes in resistivity can last years among the intense, straight filaments.

4. Magnetic fields should be polarized along synchrotron filaments, although some transverse confining fields may be observable in the outer regions of a pinch.

5. "Threads" are current paths which have been pulled away from the more active regions by magnetic tension, driven by the induction of passing molecular clouds. There should be many of them at low luminosity.

6. Strong acceleration occurs where smooth current flow is disrupted, producing capacitor-like regions where the inductive potential of the clouds is unscreened by plasma. This should produce flat-spectrum synchrotron emission. Probably sites between diffuse, thermal emission and ordered, synchrotron radiation are such regions.

The electrodynamic picture can account for the observed total thermal luminosity from regions near molecular clouds with a large number N of small pinches. These can organize into the larger structures observed, perhaps locally forming force-free equilibria. In this view the straight filaments correspond to magnetically ordered pinches, while the Arch is the region where $\boldsymbol{v} \times \boldsymbol{B}$ induced electric fields provide the dynamo of the circuit.

How the circuit closes is not clear, but observed filamentary structure below the Galactic plane suggests that ordered current flow may pass through the plane and return to the molecular clouds through a region nearer the Galactic center. It is possible that the return current for each linear filament flows in a halo around the filament itself, so each is a tight current loop. This could be accomplished inductively, as plasma initially pinches inward, driving an electric field in a surrounding denser plasma. This might account for the characteristic 0.3 pc separation of the filaments. Once started, currents generated along a strong magnetic field will continue until they can be conducted through a (presumably denser) return path. This apparently means that once currents attach to the strong field lines near the molecular clouds of the Arc they run along the ordered fields, through the Galactic disk, and return through some nonluminous path (Fig. 1). Diffuse return currents would be undetectable, however, and their emission depolarized by intervening matter, as is seen along the linear filaments intermittently.

Further observations may be able to detail probable return paths. The energetics we have sketched here should remain valid no matter what the actual geometry of the circuit, though.

The model may also apply to the inner regions of Galactic nuclei. Generally, electrodynamic braking can be a powerful aid to accretion of clouds toward the center, if the disk provides a strong, ordered magnetic field. This aids black hole fueling and also increases luminosity of the region, perhaps contributing to the broad line region in QSOs through ohmic heating. The crucial ingredient is a large, ordered magnetic field which must arise from the disk and could affect the jet-forming processes further in. The origin of this field in our own Galaxy is an outstanding mystery.

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