ELECTRODYNAMICS AT 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 $\vec{v} \times \vec{B}$ 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 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 timescales. Such electrodynamic deceleration of clouds can powerfully increase accretion toward galactic centers and enhance their luminosities.

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.

Probably a hypothetical black hole cannot account for the observed IR luminosity ~ 10^{40} erg/s, since the maximum power of a jet driven by a hot accretion disk is ~ 10^{33} erg/s. (Camenzind, 1986). While such a jet could account for the synchrotron filaments if conversion of jet energy to emission is very efficient (> 10%), there seems no reason why dissipation should occur ~ 30 pc. from the hole when turbulent conditions occur much closer. Expulsion of magnetic loops from the hole disk seems a very "lossy" way to convey energy over such distances, and demands magnetic stability during hundred-fold expansion as well (Heyvaerts, Norman and Pudritz, 1988). Thus we shall consider a mechanism invoking local electrodynamics and dissipation.

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Three different luminous filaments appear within 30 pc. of galactic center. All are very near large molecular clouds which move contrary to galactic rotation. This suggests that such clouds are the dynamo driving separate circuits. Here we focus upon the Arc, since it is most prominent.

A giant molecular cloud moving opposite to the galactic rotation can induce powerful electric fields by $\vec{v} \times \vec{B}$ motion throughout the partially ionized cloud. The plasma component of the cloud can push the poloidal field $\vec{B}$ ($\sim 10^{-3}$ G) 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 through the polarized lobes at the ends of the filaments and thence back toward galactic center, where they connect to the Arch. The ultimate cause of the circuit is the strong milliGauss ordered magnetic field filling the ~ 100 p.c. central volume and arranging systematic current flows. (ordinary molecular clouds should experience little electrodynamic effect because they have lower velocity, weak ionization and encounter weak fields.)

The circuit equation for electrodynamically connected regions is

$$V = IR + \frac{d}{dt}(IL_i),$$

$$V = \int \left(\frac{\vec{v} \times \vec{B}}{c}\right) \cdot \vec{d\ell}, \quad IR = \int \eta \vec{J} \cdot \vec{d\ell}$$

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

$$R = \frac{4\pi L\nu}{A\omega_p^2} \; ; \; L_i = L\mu \, \ell n\left(\frac{8L}{a}\right) \; ; \; C = NL^*\epsilon$$

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* (< L) in parallel, separated by a distance comparable with the radius of the current path. Locally the collision frequency ν governs resistance.

There will be a steady electron drift in the mean field, $v_D = eE/m\nu$, with the appropriate collision frequency ν set by the level of electrostatic turbulence, E_e, described by $W \equiv \langle E_e^2 \rangle / 4\pi n T_e$. We shall take a form suggested by extensive simulation and theory,

$\nu \tilde{=} \omega_p W$, where W includes only $E_e(\omega/k < v_D)$. For steady turbulence, $W \approx 10^{-2}$ to 10^{-5} seems plausible from laboratory experiments. The resistance R of a pinch of length L and radius a is

$$R = \frac{\beta^2_{-4} W\ (L/100\ \text{lt yr})}{n^{1/2}\left(\frac{a}{a_P}\right)^2 T} B^2_{-3}\ 10^9\ \text{ohms}$$

where a_P is the Bennett pinch equilibrium radius for a plasma with temperature T (in eV),

$$a_P = 7 \times 10^8 \text{cm}\ \left(\frac{W_{-2}\ T^{1/2}}{n\beta_{-4} B_{-3}}\right)$$

This is a very small pinch and thus R is very large for such a constricted channel. With many such pinch paths available, the voltage will doubtless flow through a large number N of small pinches in parallel, with

$$V = 3\beta_{-4} B_{-3}\ \left(\frac{L}{100\ \text{lt. yr.}}\right)\ \sin\psi\ 10^{16}\ \text{Volt}$$

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

$$I_t = \frac{V}{R_t} = \frac{N\sqrt{n}}{\beta_{-4}\ B_{-3}}\ \frac{1}{W_{-2}}\ \left(\frac{a}{ap}\right)^2\ T\ \sin\psi\ 3 \times 10^9\ \text{Amp}$$

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

$$B_e = \frac{I_t}{Na_P} \tilde{=} 10^{-4}\text{G.}\ \left(\frac{v_2\ (nT)^{1/2}}{B_{-3}\ \beta^2_{-4}}\ \left(\frac{a}{a_P}\right)^2\ \cos\psi\right)$$

where v_2 is the cloud velocity in units of 10^2 km/s. This confirms a qualitative expectation that B_e should be a good deal less than B if pinches are stable. As B increases B_e decreases, suggesting that B can dominate polarization maps of even a pinched region.

So far we have no idea how many small pinches comprise the ordered regions of illuminated strands. The net energy dissipated in the total circuit is

$$\epsilon = \frac{V^2}{R_T} \tilde{=} \left(\sin\psi\ a/a_P\right)^2 \left(\frac{L}{100\ \text{lt. yr.}}\right)\ \frac{Nn^{1/2}}{W_{-2}}\ 10^{33}\ \text{erg/s}$$

The total observed thermal infrared luminosity ~ 5×10^{40} erg/s comes principally from a large molecular cloud in which the inferred plasma density is 10^3 - 10^4 cm^{-3}. To account for this wholly as Ohmic dissipation requires

$$n^{1/2} \left(\frac{L}{100\ \mathrm{lt.\ yr}}\right) (a/a_p)^2 (\sin\psi)^2 \frac{N}{W_{-2}} \sim 5 \times 10^7.$$

Nonthermal (synchrotron) observed emission is about 4×10^{33} erg/s, easily explained by a few perfectly efficient pinches. Efficiency is probably small, possibly ~ 10^{-5}, by analogy with emission from current systems in our magnetosphere N is probably very large for all observed filaments. Detailed calculation of inductive energy release suggests that if current interruptions occur, flaring times of years should result. Ohmic losses should occur where currents choose the highest available conductivity, which scales with $n^{1/2}$. If Ohmic processes do account for the luminosity in the large molecular clouds, then we should expect that luminosity to follow the visible density ridges. Data of Yusef-Zadeh, et al, (1984) seem to bear this out.

Stability of a host of spaghetti-like pinches is a difficult problem. Reasoning from laboratory experience, the strong external field can stabilize such configurations for long times, with helical twisting being the probable sign of onset.

Our principal inferences from the model, are:

(a) luminosity from Ohmic heating should follow current paths, which in molecular clouds should be regions of higher density;

(b) straight synchrotron filaments may twist slightly about each other from current coupling, and locally may form typical helical force-free geometries;

(c) flares due to changes in resistivity can last years among the intense, straight filaments;

(d) magnetic fields should be polarized along filaments, though some helical confining fields may be observable in the outer regions of a pinch.

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 $\vec{v} \times \vec{B}$ 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. 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.

Active Galactic Nuclei may experience similar process, aiding accretion within the outer 10-100 pc. through such an electrodynamic "catcher's mitt." This would greatly enhance coupling of gravitational energy into IR or synchrotron luminosity, and hasten mass inflow toward the central object.

References

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