WHAT ARE THE RADIO FILAMENTS NEAR THE GALACTIC CENTER?

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Abstract. A population of nonthermally-emitting radio filaments tens of parsecs in length has been observed within a projected distance of ~130 pc of the Galactic center. More or less perpendicular to the Galactic plane, they appear to define the flux lines of a milligauss magnetic field. The characteristics of the known filaments are summarized. Three fundamental questions raised by these structures are discussed: 1) Do they represent magnetic flux tubes embedded within an ubiquitous, dipole magnetic field permeating the inner Galaxy, but which have been illuminated by some local source of relativistic particles, or are they instead isolated, self-sustaining current paths with an approximately force-free magnetic configuration in pressure equilibrium with the interstellar medium? 2) What is the source of either the magnetic field or the current? and 3) What is the source of the relativistic particles which provide the illuminating synchrotron radiation? We are nearer an answer to the the last of these questions than to the others, although several interesting models have been proposed.

1. The State of our Knowledge

Filaments of various kinds and having various appelations, including streaks, streamers, strands, strings, striations and fibers, can be found in numerous astrophysical situations, so one must begin by clarifying the particular characteristics of the radio filaments being considered in this paper. These polarized nonthermal radio emission structures are tens of parsecs long, and only a fraction of a parsec wide. They may occur in isolation (in which case they have been called "threads") or in bundles. Morphologically, they are strikingly uniform in brightness and curvature, and therefore are quite dif-

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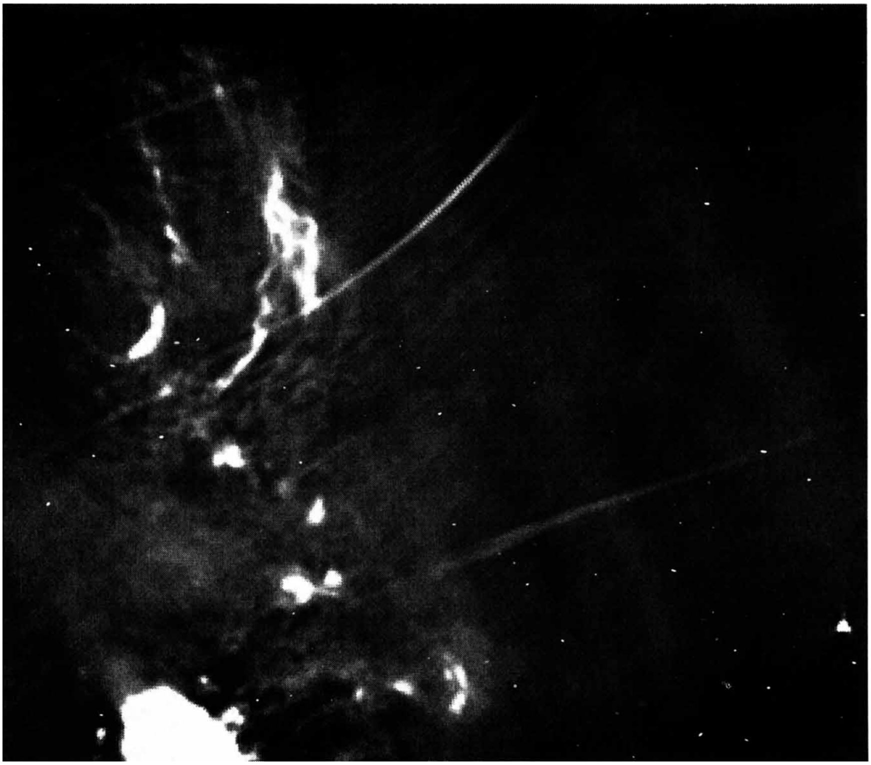

Figure 1. Radiograph at λ20cm of the radio "threads", first identified by Morris & Yusef-Zadeh (1985). Sgr A lies at the bottom left.

ferent from the meandering, contorted filamentary structures one may find in supernova remnants and emission-line nebulae. Examples of filaments are shown in figures 1 through 3.

1.1. A CATALOG OF KNOWN FILAMENTS

A catalog of known, nonthermal filaments is quickly completed*:

1. The "Snake" (G359.1-0.2) (Gray *et al.* 1991)
2. Sgr C (Liszt 1985)
3. G359.54+0.18 (Bally & Yusef-Zadeh 1989)
4. G359.96+0.09, a thread which merges in projection with the halo of Sgr A (Morris & Yusef-Zadeh 1985; Echevarria & Morris 1995)
5. G0.08+0.15, the northernmost thread (Morris & Yusef-Zadeh 1985)

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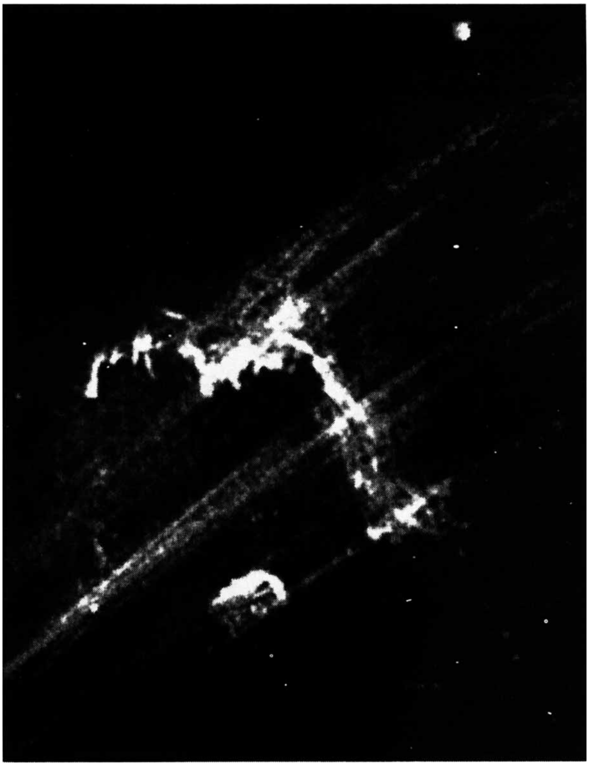

Figure 2. Radiograph at λ6cm of G0.18-0.04, located at the center of the Radio Arc – a prominent bundle of filaments. Numerous nonthermal filaments run diagonally through the figure, and interact with the thermal source, G0.18-0.04

6. The Radio Arc, l = 0.2° (Yusef-Zadeh, Morris & Chance 1984), including:
   - the bundle of ~ a dozen filaments between b = ±0.2° (Yusef-Zadeh & Morris 1987a,b)
   - the few northern filamentary extensions to at least b = ~0.4° (Yusef-Zadeh & Morris 1988)
   - a few southern filamentary extensions of the Arc (Yusef-Zadeh *et al.* 1990)
7. G0.25-0.2 (Yusef-Zadeh *et al.* 1990)
8. G0.29-0.22 (Yusef-Zadeh *et al.* 1990)

*some consider G359.79+0.17 to be a filamentary thread like the others, but it may be a superimposed, partial nonthermal shell source.

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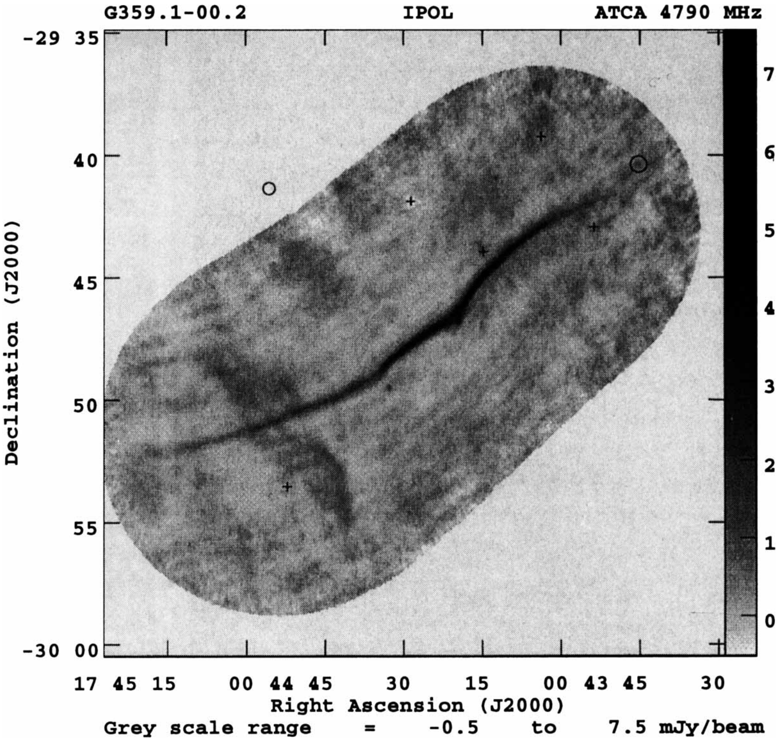

Figure 3. 6.3-cm radiograph of the "Snake" resulting from a four-field mosaic made with the Australia Telescope (from Gray 1994 and personal communication). This is the only filament showing such prominent cusps, or directional discontinuities, and the furthest from the Galactic center.

1.2. THE ARCHED FILAMENTS

Not included in this accounting are the "arched filaments" or "bridge", which define the thermal part of the Radio Arc. They represent a different kind of filament from the ones of primary concern in this paper, but they warrant mentioning because they are intimately linked to the nonthermal portion of the Radio Arc (Yusef-Zadeh & Morris 1988; Morris & Yusef-Zadeh 1989). The appellation "bridge" was originally introduced because, in low-resolution radio maps, the arched filaments appeared to connect the Radio Arc with Sgr A, although VLA maps clearly illustrate that there is no such connection (Morris & Yusef-Zadeh 1989). While the arched filaments are clearly filamentary structures, they are somewhat fleecy and less well-defined than the nonthermal filaments. Their thermal nature is revealed by their radio recombination line emission (Pauls *et al.* 1976; Yusef-Zadeh,

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Morris, & van Gorkom 1987), and by their far-IR fine structure line emission (Erickson *et al.* 1991).

The arched filaments lie at or near the surface of a massive molecular cloud observed in CO (Bally *et al.* 1987), CS (Serabyn & Güsten 1987) and CII (Poglitsch *et al.* 1991). The exceptionally luminous ($\sim 3 \times 10^7$ $L_\odot$) far-IR continuum emission from this cloud is aligned with, but is more broadly distributed than, the arched filaments. A particularly curious, and perhaps important property of this cloud is that it has velocities which are forbidden, in the sense of Galactic rotation, and the molecular and recombination lines show a strong velocity gradient: -20 to -80 $\mathrm{km \cdot s^{-1}}$. The molecular cloud extends well beyond the arched radio filaments; Poglitsch *et al.* (1991) have argued it may be physically linked to the circumnuclear disk within Sgr A. Thus, this cloud may constitute the "bridge". At the northern extreme of the molecular cloud underlying the arched filaments, these thermal filaments and the nonthermal, quasi-linear filaments of the Radio Arc meet in a right-angle junction . Along a very well-defined line constituting the edge of the molecular cloud, the arched filaments end and the brightness of the nonthermal filaments undergoes an abrupt discontinuity (Yusef-Zadeh & Morris 1988). Thus, the geometrical evidence for a real physical interaction is quite strong.

1.3. ARE THE FILAMENTS REALLY AT THE GALACTIC CENTER?

There can be little doubt that the filaments are located at the Galactic center. First, they are known in only that direction. Ten years ago when they were first found, there was a serious question about whether they may be found anywhere in galactic plane, but now, with the passage of time and the acquisition of a great deal of data with the VLA and other telescopes, further examples have only been found in the inner degree of the Galaxy. Second, the molecular clouds found to be interacting with the filaments all have the broad lines (FWHM > 20 $\mathrm{km \cdot s^{-1}}$) characteristic of the Galactic center cloud population, and are quite rare elsewhere. Third, Uchida *et al.* (1992) have used HI absorption line data to place one filament – the Snake – behind high-velocity molecular gas that is part of the Galactic center's dynamical system, so it is likely that this feature arises from within a few hundred parsecs of the center.

1.3.1. *Characteristics of the Filaments*

The properties of the galactic center radio filaments, those which define them more explicitly and differentiate them from other kinds of linear structures, are as follows:

1. All of them are oriented roughly perpendicular to the Galactic plane.

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Their orientation may, in fact, be a function of Galactic latitude, with the perpendicularity being almost exact at b = 0°, and with the orientation deviating from this more and more up to and beyond b= 0.25°. This statement requires some extrapolation of the curvature of those filaments which do not pass through the galactic plane or which do not extend very far in latitude.

2. They generally have a smoothly and slowly-varying curvature, and a surface brightness which varies only slowly along their length. (The Snake is a notable exception to this, inasmuch as it has two apparent directional discontinuities. This unusual characteristic may be related to the fact that the Snake is substantially further from the Galactic center, in projection, than any other filament.)
3. Their radio emission is strongly linearly polarized.
4. The filament defines the magnetic field direction. This is more of a presumption than a demonstrated fact. The intrinsic direction of the magnetic field has only been determined for the filaments of the radio Arc. Tsuboi *et al.* (1986) made rather large corrections of the observed polarization angle for Faraday rotation, and deduced that the intrinsic field lies along the filaments. This was confirmed by Reich (1994), who measured the polarization angle at such a high frequency that the Faraday rotation angle (proportional to λ^2) is small.
5. The spectra of the filaments, where they have been measured, is either falling with frequency ($I_\nu \; \alpha \; \nu^{-0.6}$), or is flat or slowly rising (Anantharamaiah *et al.* 1991). In either case, a nonthermal emission mechanism is indicated, as was already implied by the linear polarization. The filaments with the flat or rising spectra are possibly the ones into which fresh, high-energy electrons are still being accelerated.
6. There are no obvious radio point sources associated with the filaments, such as might be invoked to provide the illuminating relativistic particles.
7. In every sufficiently well-studied case, an interaction with a molecular cloud somewhere along the length of the filament is suspiciously in evidence. In spite of these interactions, the filaments are only sightly bent or distorted at the location of the interaction. The fact that the magnetic pressure must therefore be at least as large as the turbulent pressure in the cloud, or the ram pressure of the interaction, led to an estimate of > a few milligauss for the magnetic field strength in the filaments of the radio Arc (Yusef-Zadeh & Morris 1987a,b; Morris & Yusef-Zadeh 1989); a similar estimate can be derived from all of the filamentary systems where a molecular cloud has entered the picture.

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2. Unsolved Problems

There is little doubt that the filaments represent magnetic structures – flux tubes – in which relativistic electrons are trapped, and along which they are presumably streaming. However, there are really two major problems which need to be solved before we fully understand the nature of the filaments. The first involves the geometry and the origin of the magnetic filaments. Are the apparently strong fields local to the filaments, do they form a cylindrical wall about the Galactic nucleus, or are they ubiquitous throughout the inner 100 parsecs or so? A related question is how the magnetic field structures originated. The answer to this is quite different for the different field geometries.

If the magnetic field is dipolar and ubiquitous, as I have previously argued (Morris 1990, 1994), then the total magnetic energy within a radius of 100 pc is $> 4 \times 10^{54}$ B^2_{mG} ergs, comparable to the energy of the hot coronal gas occupying about the same volume (Koyama, these proceedings). Furthermore, the pressure balance of the interstellar medium near the Galactic center is dominated in this case by the magnetic pressure, $B^2/8\pi \sim 4 \times 10^{-8}$ ergs cm^{-3}. This hypothesis may also help account for the paucity of cosmic rays near the Galactic center (Blitz *et al.* 1993).

The second major, unanswered question is, "What is the source of the relativistic electrons in the filaments?" Are they accelerated *in situ* by some magnetic mechanism, or do they have a discrete source? I think we are closer to solving the second of these two problems than we are to the first.

3. Models

Six models of the filamentary phenomenon have been offered to date, although not all of them address the same unsolved problem. I will describe each of them briefly in turn and comment on its strengths or weaknesses.

3.1. EXPANDING MAGNETIC LOOPS

Heyvaerts, Norman, & Pudritz (1988) propose that the Galactic nucleus contain a generator of magnetic loops, presumably a differentially rotating accretion disk around a central black hole. Once formed, the loops shear off from the central disk and expand away from it, provoking observable phenomena on a variety of scales. On the largest scale (~40 pc), the loops are invoked to account for the filaments of the Radio Arc as a result of a collision with a hypothetical, vertical magnetic wall surrounding the nucleus at this distance. The asymmetry of the Arc about the galactic center and the apparently random distribution of filaments about the center can be explained in terms of the stochastic nature of the loop ejection phenomenon.

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The nonthermal emission from the filaments is attributed to particle acceleration to relativistic energies as a result of magnetic field line reconnection taking place along the colliding interface between the loop and the wall. The difficulty with this hypothesis lies in understanding how loops can survive their trajectory through the busy and tumultuous Galactic center medium without suffering energy loss (other than that owed to expansion) and consequent disruption. Perhaps the interior of the 40-pc-radius magnetic cylinder is relatively empty. Additionally, however, this hypothesis does not incorporate any explanation of the role of the molecular cloud underlying the arched filaments of the Arc, which, according to others, is an essential component of the Radio Arc. The anomalous velocity of this cloud would simply be coincidental.

However, some elements of this hypothesis have appeared in subsequent discussions of the filaments: the possibility of a cylindrical, magnetic wall surrounding the Galactic nucleus, and the notion that field line reconnection may be an important mechanism for accelerating particles.

3.2. INDUCED ELECTRIC FIELDS, CURRENTS, AND MHD-INDUCED IONIZATION

Benford (1988) and Morris & Yusef-Zadeh (1989) describe a model for the Radio Arc which can be generalized to the threads. They note that a molecular cloud moving through a strong, uniform field can induce an electric field at its surface via the $\mathbf{v}\times\mathbf{B}$ interaction. They identify the arched filaments as the resulting current sheets at the surface of the negative velocity cloud. The rarity of this phenomenon can be ascribed to the rarity of massive clouds which have such a large anomalous velocity as the one underlying the arched filaments. Indeed, if the ambient magnetic field lines move with approximately the circular orbital velocity at the location of the Radio Arc, then the arched filament cloud is moving at $\sim 10^2$ km $\cdot$ s^{-1} with respect to the field lines. This will induce a strong electric field within a layer at the cloud surface having a depth governed by the ability of the magnetic field to penetrate the cloud as a result of diffusion and shredding of the cloud surface. The electric field, in turn, drives a current. The resistance of the medium can be decreased, and thus the current can be increased, in proportion to the fractional ionization of the medium. Morris & Yusef-Zadeh (1989) suggested that the cloud surface would be naturally ionized by the critical ionization velocity phenomenon, although more recently, a cluster of stellar ionizing sources has been found nearby (Cotera *et al.* 1994). It remains to be seen whether the stellar sources of ionizing photons are sufficient to account for the ionization of the arched filaments, both in terms of geometry and in terms of the required ionization rate (Morris 1994).

Once created, the current moving along the cloud surface does not, ac-

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cording to the model, simply end at the cloud extremity, but instead turns to follow the magnetic field lines. The filaments in the linear portion of the radio Arc are identified with the current system following the field lines. According to Benford (1988), the filaments represent the coalescence of a large number current-carrying pinches. They presumably form a locally force-free magnetic field configuration (Yusef-Zadeh and Morris 1987b). After flowing through the Galactic plane and reaching some critical position coinciding with the end of the bright portion of the linear filaments, the current turns away from the magnetic field, and flows back to the origin of the circuit (the opposite extremity of the cloud providing the electromotive force) through a relatively low-density medium, forming the weak radio counter-arches (Seiradakis *et al.* 1985; Morris & Yusef-Zadeh 1989). It is not obvious how, or whether, this circuit model can be applied to filaments other than those in the Arc, although some of its elements may be relevant to all the filaments, including the idea that an induced electric field and the consequent current may be important where clouds interact with a magnetic field, and the notion that the filaments may represent locally force-free magnetic field configurations.

3.3. PARTICLE ACCELERATION BY FIELD LINE ANNIHILATION AROUND CURRENT PINCHES

Lesch & Reich (1992) adopt the notion that the filaments result from the coalescence of current-carrying pinches to form locally force-free, cylindrically symmetric configurations. Where there is a multiplicity of nearby filaments, as in the radio Arc, they attract each other for the same reason that parallel current-carrying wires having currents in the same direction attract each other: the locally toroidal component of the magnetic field surrounding each filament, induced by the axial component of the current, exerts a Lorentz force on the current-carrying particles in the other filament toward the first filament. However, the toroidal components of the two filaments are opposed in the region between the approaching filaments, so as they encounter each other, a large current density results as the field lines undergo reconnection. While ohmic dissipation transforms much of the magnetic energy into heat, the induced electric field accelerates some of the electrons to relativistic energies. These electrons then follow the magnetic field lines and define the synchrotron-emitting filaments. It remains to be seen how the particles which are accelerated between the filament cores, where the current flows along the straight symmetry line of the filament, migrate into the filament cores. Furthermore, this mechanism is not obviously operational in the case of the isolated threads.

One of the goals of the Lesch and Reich treatment is to account for the slowly rising spectral slope of the filaments in the radio Arc. They point

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out that the slope can be accounted for by an approximately monoenergetic electron energy spectrum or by an energy spectrum with a sharp lower cutoff energy. Noting that the reconnection mechanism gives an approximately equivalent acceleration to each electron, they identify this as the means to achieve a monoenergetic electron spectrum, and thus the slowly rising radio slope.

3.4. FILAMENT FORMATION BY THERMAL INSTABILITY IN A RELATIVISTIC GAS

Rosso & Pelletier (1993) note that the electric field induced by cloud motions through a magnetic field, as suggested in the earlier models, is sufficient, by itself, to accelerate electrons to relativistic energies. The reason for this is that, whereas most of the accelerated particles suffer frequent collisions and thereby dissipate their energy as ohmic heating, those particles which reach high velocities are less likely to suffer collisions because of the v^{-3} dependence of the collision cross-sections. They can thus become "runaway" electrons and may be identified with those responsible for the synchrotron radiation. This idea is more appealing for the G0.18-0.04 cloud and HII region (see Serabyn, in these proceedings), which is associated with the synchrotron filaments of the Arc than it is for the arched filament HII region, which shows no clear signature of synchrotron emission, except where it is tied to the synchrotron filaments at its northern extreme.

The nonthermal filaments are produced, according to the model of Rosso & Pelletier (1993), by a thermal instability accompanying the synchrotron losses of the relativistic particles. They find that the diffusion of relativistic electrons across the magnetic field lines is generally dominated by the contribution of electrostatic turbulence, described by a Bohm-like diffusion coefficient. This form of the diffusion law leads to a prediction for the width of the filaments which depends only on the magnetic field strength. For a milligauss field, they deduce a maximal width of 0.004 pc. The measured widths are more nearly a few tenths of a parsec, although there are insufficient studies to determine whether the filaments have smaller-scale substructure.

3.5. PARTICLE ACCELERATION BY FIELD LINE ANNIHILATION AT THE SURFACES OF MOLECULAR CLUMPS

The model which is most closely tied to the full set of existing observations is the one by Serabyn & Morris (1994), described separately by Serabyn in these proceedings. According to this model, the synchrotron-emitting electrons are accelerated by magnetic field line reconnection at the ionized

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surfaces of molecular cloud clumps as they move through a uniform, ambient field. Such molecular cloud clumps should thus be found to lie at the origin of all of the filaments.

3.6. COSMIC STRINGS

Chudnovsky *et al.* (1986) consider the hypothesis that the Galactic center filaments are low-mass-density cosmic strings which have been concentrated at the Galactic center. Indeed, the surprising rigidity and large radius of curvature of the filaments makes this hypothesis worth considering. The very large tension in cosmic strings would rapidly smooth out irregularities and eliminate all but the largest-scale curvature. This same tension, however, would accelerate the string laterally as it acts to straighten it. The string would then oscillate about its equilibrium position at relativistic speeds, notwithstanding the inertia of the plasma to which it is coupled. Such motion should be readily detectable, even at the Galactic center, but it is in fact not seen. In a study with a 4-year time base, Echevarria & Morris (1995) set limits of 0.03c – 0.06c on the lateral motion of two isolated threads.

Another argument against a superconducting string is that the magnetic field surrounding it should be predominantly azimuthal; that is, its projection onto the plane of the sky should be perpendicular to the filament rather than parallel, whereas a parallel field is observed in the Arc and in G359.54+0.18 (Yusef-Zadeh *et al.* in these proceedings). Another complication of cosmic string hypotheses is the apparent splitting of some of the filaments (*e.g.*, Fig. 4). It is easier to understand this as a diffusion of relativistic electrons between neighboring magnetic flux tubes, than it is to imagine and invoke split cosmic strings.

4. Some Implications of a Strong Magnetic Field

If the Galactic center filaments are an indication of a large-scale magnetic field of milligauss strength, they carry profound implications for physical processes taking place in this arena. Consequently, it is extremely important to demonstrate whether the field is truly ubiquitous and whether it is participating in galactic rotation.

As an example, if the presumed dipole magnetic field is not anchored in the disk clouds (and there is no evidence that it is), then the field may be rotating with a small or even zero velocity, in which case clouds orbiting near the Galactic center have a considerable velocity, on the order of 10^2 $\mathrm{km \cdot s^{-1}}$, in the rest frame of the field. The magnetic viscosity of the medium is then quite large, causing clouds to lose angular momentum at such a large rate that they spiral inwards on relatively short time scales. More

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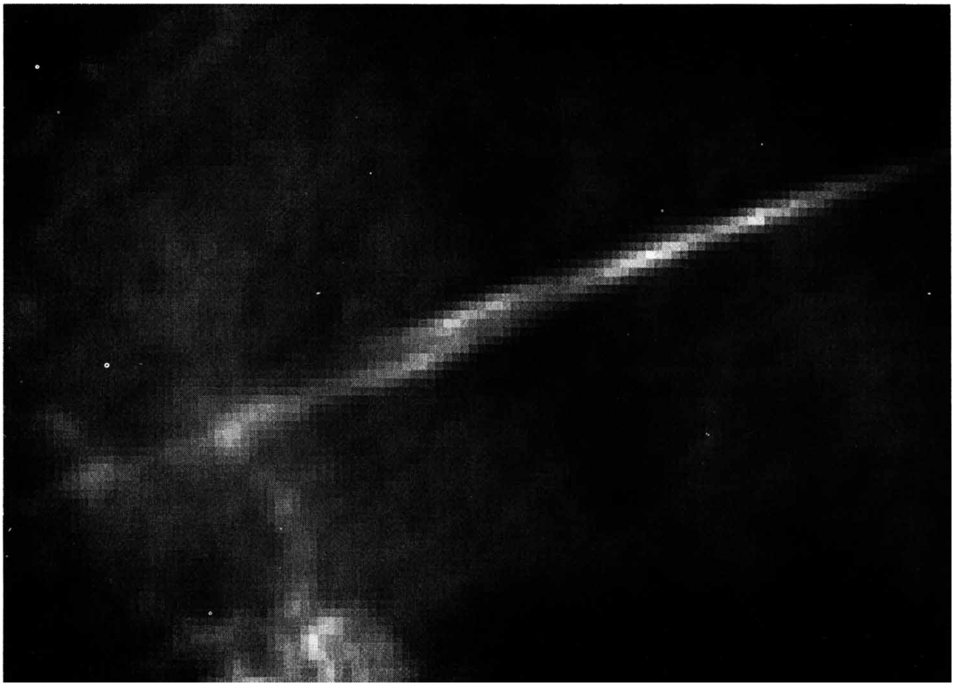

Figure 4. Radiograph at λ20cm of a split radio thread, from Echevarria & Morris 1995.

precisely, the viscous force on a cloud of radius r moving at speed v through an intercloud medium of density ρ_{icm} and magnetic field of strength B is $(\pi\rho_{icm})^{1/2}Bvr^2$. The dependence on ρ_{icm} occurs because of its effect on the Alfvén velocity. Therefore, for a cloud of diameter d and number density n, orbiting through an ambient medium of number density n_{icm} at a relative velocity equal to half the orbital velocity, the time scale for angular momentum loss by magnetic viscosity is

$$2.6 \times 10^7 \left(\frac{d}{7pc}\right)\left(\frac{n}{2\times 10^4 cm^{-3}}\right)\left(\frac{10\ cm^{-3}}{n_{icm}}\right)^{1/2}\left(\frac{10^{-3}\ G}{B}\right)\ years,$$

or ~25(R/25 pc) orbital times, at galactocentric radius R. This would add to the already rapid angular momentum loss by dynamical friction (Stark *et al.* 1991) to bring clouds into the Galactic center quickly.

The dynamical effects of a strong magnetic field on the low-density interstellar medium can be much more drastic. If the radial scale length of the vertical field is R_B, then radial magnetic forces equal gravitational

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forces when

$$\rho_{icm} \;=\; \left(\frac{B^2}{8\pi V_c^2}\right)\left(\frac{R}{R_B}\right) \;\sim\; 100\ cm^{-3}\left(\frac{B}{1\ mG}\right)^2\left(\frac{R}{R_B}\right),$$

where $V_c \sim 150\ \mathrm{km \cdot s^{-1}}$ is the circular orbital velocity in the region of interest. Thus, in the presence of a pervasive milligauss field, the interstellar medium will settle into corotation with the magnetic field when its density is on the order of tens of particles per cm^3. Data on the 21-cm HI line from the inner magnetosphere of the Galaxy may provide a useful probe of the strength and behavior of the central magnetic field, inasmuch as it is presumably formed in such a low-density medium.

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DISCUSSION

B. Gustafsson: As regards the question concerning abundance signatures that would show a tine span between the halo and the formation of the disk, I think one would expect a discontinuity in the α/Fe abundance ratios when passing from halo to disk stars of similar metallicities. One should look for that.

W. Jaffe: If the 1ρG fields are global in GC, is the material bound? ie is $\triangle B^2 < \frac{GMP}{r}$ ie $V_A^2 \lessgtr V_{orbit}^2$

Morris: If the field is poloidal, as is indicated, then the magnetic pressure need be confined only parallel to the galactic plane. One might imagine that this is accomplished by a ring current which is somehow driven by an inflow of matter, or simply by the inflow of matter itself, as a result of inevitable momentum losses. The field cannot diffuse outward through this matter. The answer to the question, "where is the field anchored?" is an interesting one. Perhaps it is bound to bulge & halo gas, but it does not seem to be anchored to gas in the plane.

I. King: Is there evidence that the arches and the filaments are not at separate points along the line of sight?

Morris: The evidence for interaction is circumstantial, but strong. Yusef-Zadeh & Morris (1988) point out that, along a well-defined line where the molecular cloud underlying the arched filaments ends, both filamentary systems undergo sharp discontinuities in brightness and/or polarization. Furthermore, one can draw a detailed one-to-one correspondence between filaments in the two systems.

G. Verschuur: I am concerned that you maintain that these filaments are unique to the galactic center. The WSRT has been used to map the

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distribution of galactic polarized radiation and very long thin filaments are common. This is seen in the work of Wieringa & de Bruyn, as well as the work of Spoelstra & myself. I would suggest that it would might be fruitful to treat filaments as common and consider only that the source of illumination is unique to the galactic center. Are you aware of the filaments I am referring to?

Morris: –

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