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THE GALACTIC CENTER ISOLATED NONTHERMAL FILAMENTS AS ANALOGS OF COMETARY PLASMA TAILS

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ABSTRACT

We propose a model for the origin of the isolated nonthermal filaments observed at the Galactic center based on an analogy to cometary plasma tails. We invoke the interaction between a large-scale magnetized galactic wind and embedded molecular clouds. As the advected wind magnetic field encounters a dense molecular cloud, it is impeded and drapes around the cloud, ultimately forming a current sheet in the wake. This draped field is further stretched by the wind flow into a long, thin filament the aspect ratio of which is determined by the balance between the dynamical wind and amplified magnetic field pressures. The key feature of this cometary model is that the filaments are dynamic configurations, and not static structures. As such, they are local amplifications of an otherwise weak field and not directly connected to any static global field. The derived field strengths for the wind and wake are consistent with observational estimates. Finally, the observed synchrotron emission is naturally explained by the acceleration of electrons to high energy by plasma and MHD turbulence generated in the cloud wake.

Subject headings: Galaxy: center — ISM: magnetic fields — ISM: structure — MHD — radiation mechanisms: nonthermal

1. INTRODUCTION

The isolated nonthermal filaments (hereafter NTFs) in the Galactic center (hereafter GC) have not been satisfactorily explained since their discovery by Morris & Yusef-Zadeh (1985). It is generally accepted that these are magnetic structures emitting synchrotron radiation, since their emission is strongly linearly polarized, with the magnetic field generally aligned with the long axis of the filaments (Bally & Yusef-Zadeh 1989; Gray et al. 1995; Yusef-Zadeh, Wardle, & Parastaran 1997; Lang, Morris, & Echevarria 1999). These structures are notable for their exceptionally large length-to-width ratios, of order 10–100, and their remarkable linearity (Yusef-Zadeh 1989; Morris 1996).

To date, seven objects have been classified as NTFs. Six of these point perpendicularly to the Galactic plane, but the most recently discovered NTF is parallel to the plane (Anantharamaiah et al. 1999). The filaments have lengths up to 60 pc and often show feathering and subfilamentation on a smaller transverse scale when observed at high spatial resolution (Liszt & Spiker 1995; Yusef-Zadeh et al. 1997; Lang et al. 1999; Anantharamaiah et al. 1999). The observed radio 20/90 cm spectral indices (defined as the source flux, S, varying as ν^{α}) show a range, $-0.3 < \alpha < -0.6$ (LaRosa et al. 1999). To date there is no strong evidence that the spectral index varies as a function of length along the NTF (Lang et al. 1999; Kassim et al. 1999). Last, it appears that all well-studied NTFs may be associated with molecular clouds and/or H II regions (Serabyn & Morris 1994; Uchida et al. 1996; Stahgun et al. 1998).

Several different types of models have been proposed for the filaments. These include magnetic field generation by an accretion disk dynamo, with subsequent transport of field into the interstellar medium (Heyvaerts, Norman, & Pudritz 1988); electrodynamic models of molecular clouds moving with velocity $\boldsymbol{v}$ across a large-scale ordered magnetic field, $\boldsymbol{B}$, resulting in current formation by $\boldsymbol{v} \times \boldsymbol{B}$ electric fields and subsequent pinching of these currents into filaments (Benford 1988, 1997; Lesch & Reich 1992); magnetic reconnection between a molecular cloud field and the large-scale ordered field (Serabyn & Morris 1994); and particle injection into interstellar magnetic field ropes at a stellar wind termination shock (Rosner & Bodo 1996). Nicholls & Le Strange (1995) proposed a specifically tailored model for G359.1−0.2, also called the "Snake." They invoke a high-velocity star with a strong stellar wind that is falling through the galactic disk, to create a long wake, which they call a "star trail." They must, however, fine-tune their model in order to obtain radio emission from the trail by requiring the high-energy electrons to be injected into the trail from the supernova remnant G359.1−0.5.

Although each of these models can in principle explain the particle acceleration and radio emission, none except for the specialized star-trail scenario has satisfactorily accounted for the observed structure of the filaments. For instance, Rosner & Bodo (1996) employ a stellar wind termination shock as the source of high-energy particles that they assume are loaded onto preexisting interstellar field lines. The width of the resulting NTF scales with the radius of the stellar wind bubble. Synchrotron cooling leads, through a thermal instability, to collapse of the filaments and amplification of the internal magnetic field. The streaming of the particles along these otherwise quiescent field lines is assumed to produce the observed long threads. However, MHD stability is a problem for this model and, indeed, for all models listed above, because magnetic fields left to their own devices will deform through a rich variety of modes. These range from kink and sausage instabilities for ideal MHD to tearing modes for resistive plasmas (e.g.,

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Parker 1979; Cravens 1997). Unless very special magnetic field configurations and boundary conditions are imposed, and these are difficult to achieve even in the laboratory, the length and thinness of the NTFs cannot be explained as static structures.

In this paper, we adopt the viewpoint that the filaments are not static structures but are rather dynamical structures embedded in a flow. In a flow, the growth of many of the local instabilities is suppressed by the advection. We propose a model in which the advection of a weak *galactic* field in a large-scale outflow from the central region is amplified locally by encounters with interstellar clouds. We find that several key elements of the previously published scenarios are natural consequences of this cloud-wind interaction picture.

2. THE COMET MODEL

The key feature of the physical interaction between a comet and the magnetized solar wind was identified by Alfvén (1957) and elaborated by many subsequent studies (e.g., Russell et al. 1991; Luhmann 1995; Cravens 1997). As the magnetic field that is carried in the wind plasma encounters the comet, the field progress is retarded through the coma because the magnetic diffusion times are much longer than the advective timescale. Mass loading of the solar wind from the coma produces a velocity gradient, $\partial v_w / \partial x$, where x is the cross-tail direction. The external field drapes over the coma and is stretched by the wind, ultimately forming a current sheet in the antisolar direction. This field-line draping, for a molecular cloud, is depicted in Figure 1.

Remote observations show that cometary streamers routinely display aspect ratios of 100 or more (Jockers 1991). Direct in situ plasma measurements of comet Giacobini-Zinner have confirmed the overall picture of magnetic field draping. In particular, these encounter measurements show that the central tail axis consists of a plasma sheet with very low magnetic field (Siscoe et al. 1986). This sheet is surrounded by a low-density plasma that is threaded with the draped wind magnetic field that has been compressed and amplified by the flow. Transverse pressure balance requires that the draped field be about a factor of 5–10 stronger than the ambient field, with amplification occurring because of flux conservation and field-line stretching. This is our basic cometary analogy, that the ambient field is anchored in the cloud and that the field-line tilt and amplification result from the shearing between the wake and the external wind. This picture, which explains solar system scale phenomena rather well, is more than a mere analogy. Any magnetized wind that impacts a finite blunt body with low resistivity will deflect around the object and drape the field along the wake flow. The field diffusion time is $t_d = L^2/\eta$, where here L is the cloud radius and η is the resistivity. For the GC, this timescale is many orders of magnitude larger than the wind advection time. Consequently, the field evolution around the molecular cloud is similar to the cometary case, provided that the field is ordered on the cloud size scale, L.

We now explore the consequences of this scenario for the NTFs. Consider a galactic-scale wind with a mass-loss rate $\dot{M}$. This wind need not emanate only from the GC. With the broad spatial distribution of star-forming regions in the inner galaxy, we would anticipate a roughly cylindrical—not radial—outflow, which would be sampled by clouds moving in whatever orbits they happen to have relative to the plane. Consequently, the wakes so produced should generally be perpendicular to the plane. For simplicity, however, we will assume here a compact source. The number density in the wind is given by $n_W = \dot{M} v_{w,3}^{-1} r_{100}^{-2}$ cm^{-3} for a mass-loss rate in $M_\odot$ yr^{-1}, a wind speed $v_{w,3}$ in 10^3 km s^{-1}, and a distance r_{100} in 100 pc. For a cloud to survive in a postulated galactic-scale wind, its internal pressure must at least balance the ram pressure of the background. We assume that the cloud pressure is given by $P = \rho_c \sigma_c^2$, where ρ_c is the cloud mass density and σ_c its internal velocity dispersion. Hence, for a wind of density ρ_w and speed v_w, the required cloud density is given by $\rho_c = \rho_w (v_w/\sigma)^2$. It has been inferred from *Ginga* and *ASCA* X-ray observations that the inner Galaxy displays a strong wind (Yamauchi et al. 1990; Koyama et al. 1996). The average wind density within a radius of 80 pc of the GC is around 0.3 cm^{-3}, with a temperature of 10 keV and an expansion velocity of about 3000 km s^{-1} (Koyama et al. 1996). These parameters correspond to a mass-loss rate of 10^{-2} $M_\odot$ yr^{-1} for a wind speed of around 1000 km s^{-1}, which yields a

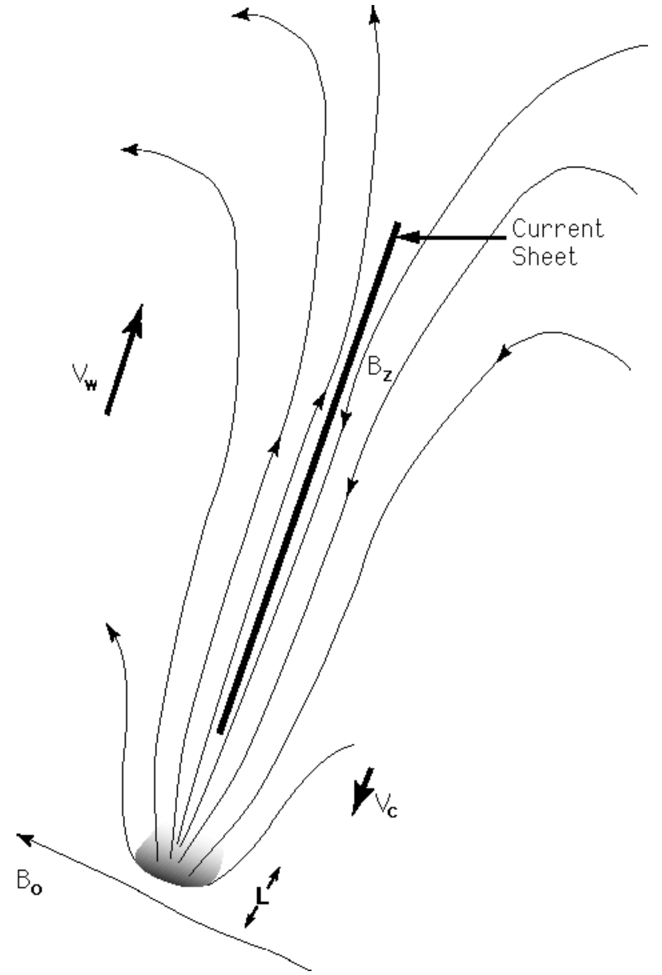

FIG. 1.—Schematic of the interaction of a magnetized wind encountering a molecular cloud of radius L. The wind velocity is $\boldsymbol{v}_w$ and the cloud velocity is $\boldsymbol{v}_c$. The advected wind magnetic field $\boldsymbol{B}_0$ is impeded by the cloud, and we show how successive field lines or flux ropes are stretched and draped by the flow around the cloud into a long, thin wake. The draped field, denoted $\boldsymbol{B}_z$, is oppositely directed in the wake and forms a current sheet along the wake mid-plane. Solar system studies indicate that such a plasma–magnetic field configuration leads to particle acceleration through turbulent dissipation, and we therefore identify such a wake as a nonthermal filament.

critical cloud density of order $n_c \geq 10^3$ cm^{-3} for $\sigma = 20$ km s^{-1} (a typical line width for molecular clouds in the GC region; see Morris & Serabyn 1996), although clouds nearer the center will need higher densities to survive. This density estimate is a lower limit. For clouds to survive in the GC tidal field they must have densities of at least an order of magnitude above this (e.g., Güsten 1989). The effect on the cloud population is that massive, dense clouds will survive, while lower density, low-mass clouds likely disperse on a dynamical timescale, and thus the cloud population may depend on galactocentric distance. Dense clouds form wakes by geometrically blocking and deflecting the wind. We identify this wake, drawn out by the wind, with the NTFs. This scenario is sketched in Figure 1. Thus follows the essential predictive feature of our model: since the filaments are not static structures, the classic MHD instabilities do not limit the aspect ratio as they would for a static equilibrium field.

What determines the structural properties of the wake, i.e., its aspect ratio and length? Given that $t_d \gg L/v_w$, the draped field is stretched by the wind. If δv is the boundary layer shear between the wind and cloud wake and Δ is a characteristic width for the layer (of order L, the cloud radius), then the axial field, B_z, as a function of distance z behind the cloud is given by the induction equation, $\partial B_z/\partial t = (\partial v/\partial x) B_0$, where B_0 is the external field and x is the cross-tail direction. This has the approximate solution

$$B_z = B_0 \frac{\delta v}{\Delta} \frac{z}{v_w} . \tag{1}$$

The axial field will continue to amplify until the draped magnetic field pressure balances the ram pressure of the wind. In other words, when the wake Alfvén speed equals the wind speed, $B_z/(4\pi\rho_0)^{1/2} = v_w$, the field can no longer be stretched. This provides a critical length

$$z_c = 5 \times 10^2 n^{1/2} v_{w,3}^2 \Delta/(B_{0,\mu}\, \delta v_3) , \tag{2}$$

where $\delta v_3 = \delta v/10^3$ km s^{-1}, n is the number density, and $B_{0,\mu}$ is the external field in μG. Thus, for $n \approx 1$ cm^{-3} and $B_{0,\mu} \approx 10$, the predicted aspect ratio is $z_c/\Delta \approx 50$. Notice that stronger ambient fields lead to shorter wakes.

We now address the question of stability for the filaments. In the MHD case, the velocity shear must exceed the Alfvén speed to produce a growing mode for the Kelvin-Helmholtz instability (KHI). Other classical instabilities, such as the streaming, sausage, and kink modes, have a similar criterion (e.g., Wang 1991). Nonlinear models by Malagoli, Bodo, & Rosner (1996) find that the fastest growing mode has a wavenumber given by $k\Delta \approx 0.05$. The KHI can therefore be suppressed if the draped field amplification length is less than $2\pi/k$. Hence, for stability $z_c \leq 40\pi\Delta$. With this constraint, we find a lower limit on the external wind field strength, $B_{0,\mu} \geq 40 n^{1/2} v_{w,3}/\delta v_3$. Equipartition for the wind plasma gives $B_{0,\mu} \approx 20$ for the parameters derived from the *ASCA* data, which is in surprisingly good agreement with the stability constraint. Thus the expected amplified field strength is $B_z \approx 2$ mG for z/Δ, which is given by equation (2).

Thus the key parameters that can be derived from our model are the aspect ratio, which depends on the wind parameters, and the magnetic field strength in the filament. The required input parameters are the background density and pressure and the assumption of equipartition for the magnetic field strength. The observed aspect ratios can then be explained using equation (2) with wind parameters consistent with the *ASCA* data. There are no direct measurements of the magnetic fields in the filaments. An estimate for the magnetic field can be derived from the observed synchrotron luminosities using a minimum energy analysis. The synchrotron luminosities are around 10^{33}–10^{34} ergs s^{-1} (Gray et al. 1995; Lang et al. 1999; Kassim et al. 1999) and yield a magnetic field of $\sim$0.1 mG, about an order of magnitude smaller than our model result. Another estimate for the field strength comes from assuming that the particles traverse the length of an NTF in a time equal to their synchrotron lifetime. The synchrotron lifetime is $t_{1/2} = 1.20 \times 10^4 B_{z,\mathrm{mG}}^{-2} E_{\mathrm{GeV}}^{-1}$ yr, where $B_{z,\mathrm{mG}}$ is the axial field in milligauss and E is the electron energy in GeV (e.g., Moffet 1975). Without reacceleration, assuming that the electrons are injected near one end and radiate as they stream at the Alfvén speed (e.g., Wentzel 1974), the observed filament lengths give a field strength of 1 mG for a length scale of 30 pc. Fields strengths of 1 mG have also been derived from dynamical arguments by Yusef-Zadeh & Morris (1987). We therefore conclude that our estimate of 1 mG is very reasonable and that the minimum energy analysis of such structures, which assumes static and/or equilibrium conditions, may produce misleading results. Note that the synchrotron lifetime argument indicates that reacceleration or acceleration along the length of the filament is not required, although as we now discuss acceleration along the filament is expected in our picture.

Finally, since the NTFs are radiating via synchrotron emission, we address the question of particle energization. The observed emission requires only a very small population of relativistic particles, of order 10^{-5} cm^{-3}. The maximum energy that is available for conversion to high-energy particles is $VB_z^2/8\pi$, where V is the volume of the wake. The maximum mean energy per particle that results from this conversion is 10 GeV. This is more than enough to explain the radio emission. A number of mechanisms that may be responsible for particle acceleration are natural consequences of this MHD configuration. The wake must contain a current sheet. Such structures have been extensively studied in space plasmas. The simulation of sheared helmet plumes in the solar corona by Einaudi et al. (1999) is particularly relevant to our scenario. They show that a current sheet embedded in a wake flow is unstable to the generation of a local turbulent cascade without destruction of the large-scale advected structure. Such cascades efficiently accelerate particles through wave-particle interactions (Miller et al. 1997). This turbulent acceleration would therefore occur along the entire length of the filament, and thus spectral aging would not be observed in this scenario.

3. DISCUSSION AND CONCLUSIONS

There are two broad schemes for inferring the magnetic field configurations for the isolated nonthermal filaments. One is to assume that they represent local enhancements of an otherwise weak, but invisible, pervasive field. The other is to assume that one is seeing a region, e.g., a flux tube, that happens to be locally illuminated but is part of otherwise extensive and uniform strong magnetic field. We explicitly adopt the local enhancement picture and propose a dynamical mechanism that can amplify the field to much higher strength and still be stable.

The common explanation for the stability of the isolated NTFs invokes the existence of a pervasive background magnetic field that pressure-confines the filaments (e.g., Morris 1998). Nonetheless, this field still leaves the stability question unresolved for the following reasons. A force-free equilibrium background field that is presumably anchored in the turbulent gas of the Galactic center will not be stable. For instance, the solar corona has a pervasive field that suffers both local and global instabilities. Moreover, to stabilize a filament, a pervasive field must have a pressure gradient perpendicular to the filaments, so the field cannot be uniform. If it has gradients and curvature, a static magnetic field is likely to be unstable, although if the field is anchored in the Galactic halo it may avoid this problem (see Chandran, Cowley, & Morris 1998). In contrast, as we have argued in this paper, stability is not an issue for a dynamical model.

The simplest geometry predicted by the cometary analogy is that every filament should be associated with a molecular cloud on the side toward the galactic plane. This is seen for the Sgr C filament (Liszt & Spiker 1995) and the Snake (Uchida et al. 1996). The model does not, however, require this, and more complex geometrical arrangements are certainly possible in which environmental clouds interact with or are superimposed on the filaments almost anywhere along their lengths. For instance, Yusef-Zadeh & Morris (1987) find that a milligauss field suffices to stabilize the filaments against ram pressure by colliding molecular clouds. We note that this is precisely the field strength produced dynamically by the cometary model.

Santillan et al. (1999) have recently published numerical MHD simulations of cloud collisions with a magnetized galactic disk. Although these are ideal MHD and not of wind flow, they clearly demonstrate that field-line draping occurs as the interstellar clouds move through a large-scale background field. In particular, their Figure 4 shows the formation of a narrow, straight tail for the cloud slamming into a transverse field imbedded in a planar gas layer. Dynamically, this simulation differs from wind flow because the cloud is slowed by the environmental gas. Yet the essential physical process is the same and closely resembles the simulations of cometary tail evolution by Rauer et al. (1995). This cloud-wind interaction, which may destroy the clouds if their masses are low enough (see Vietri, Ferrara, & Miniati 1997), is able to generate long magnetized tails with large aspect ratios.

In addition, a final state, where the cloud is completely dissipated, could still permit the survival of the filament and has a cometary analog. There are many instances in comets where the tail completely separates from the coma and yet maintains structural coherence as it is advected in the solar wind (e.g., Brandt & Niedner 1987). These so-called disconnection events could also occur in our picture. In such instances, there would be no cloud at either end of the filament.

We close by emphasizing that our aim here has been the exploration of the consequences of a general scenario that can serve as a framework for more quantitative calculations of the physical properties of the Galactic center filaments. Although we use the special conditions at the GC to constrain the mechanisms, the model is not constructed specifically to explain the NTFs. Instead, they result from the conditions that likely arise in any starburst galactic nucleus (see Mezger, Duschl, & Zykla 1996) and should be observable in such environments.

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