THE ORIGIN OF THE GALACTIC CENTER NONTHERMAL RADIO FILAMENTS: YOUNG STELLAR CLUSTERS

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ABSTRACT

The unusual class of magnetized nonthermal radio filaments, threads, and streaks, with their unique physical characteristics, is found only within the inner couple of degrees of the Galactic center. Also, a number of young, mass-losing, and rare stellar clusters are recognized as lying in the Galactic center region. The latter characteristic of the Galactic center region is used to explain the origin of the nonthermal radio filaments. We consider a mechanism in which the collective winds of massive W-R and OB stars within a dense stellar environment produce shock waves that can accelerate particles to relativistic energies. This mechanism is an extension of a model originally proposed in 1996 by Rosner & Bodo, who suggested that energetic nonthermal particles are produced in a terminal shock of mass-losing stars. The large-scale distribution of the magnetic field in the context of this model is argued to be neither poloidal in geometry nor pervasive throughout the Galactic center region.

Subject headings: ISM: clouds — ISM: general — radio continuum: ISM — shock waves — supernova remnants — X-rays: ISM

1. INTRODUCTION

Over the last two decades radio continuum observations of the Galactic center region have revealed a large number of systems of nonthermal radio filaments (NRFs) or nonthermal filaments (NTFs) within the inner 2° of the Galactic center (see, e.g., Yusef-Zadeh, Morris, & Chance 1984; Liszt 1985; Morris & Yusef-Zadeh 1985; Bally & Yusef-Zadeh 1989; Gray et al. 1991; Anantharamaiah et al. 1991; Lang et al. 1999a; LaRosa et al. 2000). Some of the general characteristics of the filaments are as follows:

1. The transverse dimensions of the long NRFs are roughly a fraction of a parsec at the Galactic center distance of 8.5 kpc, and their length is on the order of tens of parsecs.
2. Most of the long and bright filaments are aligned to within about 30° of the rotation axis of the Galaxy, but recently some have been found to be running parallel to the Galactic plane. The short and faint filamentary structures, known as the “streaks,” with lengths less than a few parsecs, do not appear to be preferentially oriented perpendicular to the Galactic plane.
3. Many of the individual filaments, or the so-called threads, break up into multiple (at least two) subfilaments that flare at their endpoints. Some filaments show a gentle curvature and kinks along their lengths. The brightness of some filaments peaks in midpoints as they gently curve.
4. The combination of strongly linearly polarized emission from NRFs and radio spectral index distribution suggests a nonthermal synchrotron origin.
5. The rotation measure (RM) values of the NRFs range between a few hundred and several thousand rad m⁻², and the polarization measurements indicate that the NRFs trace the magnetic field, with an equipartition strength ranging between several and hundreds of microgauss.
6. The NRFs show a wide range of spectral index values based on radio continuum observations. Some filaments may occur in isolation, with a steep spectral index, or may be part of a network of parallel filaments, with a relatively flat or inverted spectral index. A number of them show a steepening of the spectral index at higher frequencies between 6 and 2 cm. Since the NRFs are fairly extended and interferometric measurements using different array configurations have different surface brightness sensitivity to extended emission, the spectral index measurements could suffer from this systematic uncertainty.
7. A number of NRFs appear to be located in the vicinity of star-forming regions.

Theoretically, it has been challenging to understand the nature of these filaments, which resemble extragalactic radio jets but are not accompanied with any obvious source of acceleration of charged particles to relativistic energies. Although a number of detailed models have been considered, there is no consensus as to the origin of the NRFs. These models suggest that molecular and ionized gas clouds, mass-losing stars, Galactic winds, and the magnetic activity of the massive black hole at the Galactic center play a role in the processes that lead to the production of the NRFs (see, e.g., Heyvaerts, Norman, & Pudritz 1988; Benford 1988, 1997; Morris & Yusef-Zadeh 1989; Serabyn & Morris 1994; Nicholls & Le Strange 1995; Bally & Yusef-Zadeh 1989; Serabyn & Güsten 1991; Rosso & Pelletier 1993; Ryutov, Derzon, & Matzen 2000; Lesch & Reich 1992; Rosner & Bodo 1996, hereafter RB96; Dahlburg et al. 2002; Shore & LaRosa 1999; Bicknell & Li 2001a). In most models, the magnetic field is strong, and its global geometry in the central region of the Galaxy is considered to be poloidal and static. However, some recent models have argued that the magnetic field is local and dynamic (LaRosa, Lazio, & Kassim 2001).
A review of a plethora of theoretical models of NRFs can be found in a number of publications (e.g., Yusef-Zadeh 1989; Morris 1996; Morris & Serabyn 1996; Bicknell & Li 2001b). It is beyond the scope of this paper to discuss the many assumptions that have been made in these models. Observationally, systems of NRFs are known to have some generic physical characteristics, as described above, but notable differences between them have also been observed. Here the observational properties of individual NRFs are summarized. We also describe H II complexes found in the vicinity of NRFs; their direct interactions with each other are inconclusive. Following the summary, we examine the origin of the NRFs and concentrate on the idea set forth by RB96, who suggested that mass-losing stellar sources are responsible for accelerating nonthermal particles. We expand this idea and argue that the nonthermal emission from the Galactic center filaments originates from the shocked region of the colliding stellar winds of young clusters or young stellar binary systems in star-forming regions. The model predicts young and compact stellar clusters with multiple W-R–OB binary systems or young, massive binary systems with their corresponding H II regions distributed in the vicinity of NRFs.

2. CASE-BY-CASE CHARACTERISTICS OF NRFs

G0.2−0.0 (Radio Arc and its extensions).—The prototype filamentary structure of the radio continuum Arc resolves into a set of more than a dozen vertical filaments with lengths of about 30 pc, distributed symmetrically with respect to the Galactic equator (Yusef-Zadeh et al. 1984; Yusef-Zadeh & Morris 1987a, 1987b, 1988). The Radio Arc is known to be the best example of a network of NRFs running perpendicular to the Galactic plane. The NRFs generally show an inverted spectrum, with $\alpha = +0.3$ (Inoue et al. 1984; Tsuboi et al. 1986; Seiradakis et al. 1985; Sofue, Reich, & Reich 1989; Reich, Sofue, & Matsuo 2000), where $F_\nu \propto \nu^\alpha$, with the exception of one steep-spectrum filament to the south of the Arc with $\alpha = -0.4$ between 90 and 20 cm (Anantharamaiah et al. 1991). The vertical filaments of the Arc extend toward latitudes $-0.75 < b < +0.75$ as they become more diffuse, weaker in their surface brightness (Sofue & Handa 1984). High-resolution radio continuum images show that the emission from the extensions of the Arc is dominated by diffuse structures, as well as a number of weak and coherent filamentary features running in the direction away from the Galactic plane (see Fig. 4b of Yusef-Zadeh 1989; also see Yusef-Zadeh et al. 1990; F. Yusef-Zadeh, W. Cotton, & J. Hewitt 2003, in preparation).

As the filaments of the Arc cross the Galactic equator, a dense cluster of young and mass-losing WN or OF stars is found near G0.18−0.04. The Quintuplet cluster contains 10$^3$ stars and has an angular size of $\sim 25''$ (1 pc), with an age estimated to be 3–5 Myr (see, e.g., Figer, McLean, & Morris 1999b). Prominent molecular and ionized gas clouds (G0.18−0.04 and G0.11−0.11) are also distributed in the vicinity of the Quintuplet cluster (Serabyn & Morris 1994; Tsuboi, Ukita, & Handa 1997; Yusef-Zadeh, Roberts, & Wardle 1997).

G0.08+0.15 (Northern Thread).—This isolated, linearly polarized filamentary structure, which extends for about 12′ (30 pc), shows a curvature in the direction away from the rotation axis of the Galaxy (Morris & Yusef-Zadeh 1985; Yusef-Zadeh 1986; Lang, Morris, & Echevarria 1999b). The filament breaks up into at least two parallel components in its northwestern extension, and its brightness peaks close to its midpoint. The spectral index value is estimated to be $\alpha = -0.6$ between 6 and 90 cm but steepens to the value of $\alpha = -2$ between 2 and 6 cm (Anantharamaiah et al. 1991; Lang et al. 1999b). The equipartition magnetic field is estimated to be 140 $\mu$G, with a synchrotron lifetime of $4 \times 10^4$ yr, assuming that the break in the spectrum of the filament occurs at 6 cm (Lang et al. 1999b). The spectral index distribution appears to be constant along the filament.

A massive cluster of hot stars known as the Arches cluster is found in the vicinity of the terminus of G0.08+0.15 closest to the Galactic plane. This consists mainly of 150 O star candidates with stellar masses greater than 20 $M_\odot$. The Arches cluster is $\sim 15''$ across, with an estimated density of $3 \times 10^5 M_\odot$ pc$^{-3}$ within the inner 9″ (0.36 pc) of the cluster (see, e.g., Cotera et al. 1996; Serabyn, Shupe, & Figer 1998; Blum et al. 2001). There is considerable ionized and molecular material that appears to be associated with the Arches cluster. The stellar, ionized, and molecular materials are all distributed in the vicinity of the southern end of the Northern Thread (Yusef-Zadeh 1986; Serabyn & Güsten 1991).

G359.96+0.09 (Southern Thread).—This structure is similar to the Northern Thread in its extent and its morphology, except that it is running within 12′ of the rotation axis of the Galaxy without any evidence of curvature. The endpoint of the filament closest to the Galactic plane lies about 30″ north of two H II regions known as H1 and H2, which are thought to be excited by O6 and O7 zero-age main-sequence (ZAMS) stars, respectively (Yusef-Zadeh & Morris 1988; Zhao et al. 1993). Recent near-IR observation detected an emission-line star at the peak of H2 (Cotera et al. 1999). Also, IRS 16, which is known to be a massive cluster of hot stars at the Galactic center, is located about 4′ southeast of the endpoint of the filament. Similar to the Arches and the Quintuplet clusters, the IRS 16 cluster is also associated with molecular and ionized gas clouds at the Galactic center (see, e.g., Genzel, Hollenbach, & Townes 1994).

G359.43−0.09 (Sgr C).—One of the brightest radio continuum sources near the Galactic center, Sgr C resolves into multiple filaments and a circular H II region (Liszt 1992; Liszt & Spiker 1995). The filaments extend for 10′ toward positive latitudes, with a spectral index $\alpha = -0.5$ between 90 and 20 cm (LaRosa et al. 2000). The filaments appear to end abruptly inside a molecular cloud H II complex with a velocity of $-65$ km s$^{-1}$ (Liszt 1992; Liszt & Spiker 1995). This H II complex is also known to coincide with a source of infrared emission at 350 $\mu$m (Hunter et al. 2000). An O5.5 V star is suggested to be responsible for ionizing the thermal component of Sgr C.

G359.54+0.18 (Ripple).—The ripple filament is another isolated filamentary structure that resolves into multiple parallel components, with a terminus that flares in the direction toward the Galactic plane. The brightness of the filaments peaks at the midpoint, where subfilaments lie closest to each other (Bally & Yusef-Zadeh 1989). The spectral index is $\alpha = -0.8$ between 90 and 20 cm (Anantharamaiah et al. 1991). Linear polarization measurements show that the magnetic field traces the filament (Yusef-Zadeh, Wardle, & Parastaran 1997b). Recent Chandra observations show X-ray emission from the northern filament of G359.54+0.18 (Liu, Wang, & Lang 2003). A dense molecular cloud and an H II region are observed at
the interface of the eastern edge of the filaments before they deviate from a straight line and flare (Staguhn et al. 1998).

*Streaks.*—A number of small-scale linear filaments, or the so-called streaks, are observed throughout the region in the Northern and Southern Threads, the southern extension of Sgr C, and Sgr A. These features are very similar to the long NRFs of the Arc but are shorter, with a length ranging between 1' and 5'. The surface brightness of the streaks is typically 5–10 times fainter than that of the long filaments, and there is no sign of bending. It is not uncommon to observe streaks having orientations very different from the general direction of the prominent NRFs (F. Yusef-Zadeh et al. 2003, in preparation). The polarization and spectral index estimates of these faint features have not been determined. The terminus of some of these filaments appears to end at a compact, circular-like H II region. G0.02+0.04 is an excellent example of a streak that ends inside the H II region H4, which is known to be excited by an O8.5 ZAMS star (Lang et al. 1999b; Zhao et al. 1993).

G359.1−0.2 (Snake).—Perhaps the most striking example of isolated NRFs is the “Snake” (Gray et al. 1991, 1995). The morphology of the Snake is distinguished somewhat from that of other Galactic center filaments by its narrow (<10") width, its long (≈20") extent, and two uncharacteristic kinks along its length. In addition, the Snake is unusual in that it shows a gradient in spectral index at the location of the kinks (Gray et al. 1995). The spectral index along the filament is generally constant and flat between 6 and 20 cm, with the exception of the major kink, where the spectrum steepens to $\alpha = -0.5$. Submilabulation has also been detected in the vicinity of the kinks (Gray et al. 1995). The equipartition magnetic field is estimated to be 88 $\mu$G, with a synchrotron lifetime of $\approx 8 \times 10^5$ yr (Gray et al. 1995).

Toward the northern end of the Snake near the Galactic plane, there is a cluster of H II knots near G359.16−0.04 (Caswell & Haynes 1987). The filament ends in the H II knots, and morphological arguments have been used to associate the Snake with the H II complex (Uchida et al. 1996).

G358.85+0.47 (Pelican).—This linearly polarized feature extending for 7' in its length, unlike any other prominent NRFs, runs along the Galactic plane (LaRosa et al. 2001; Lang et al. 1999a). The orientation of the magnetic field follows the linear filament, which consists of two subfilaments that flare at their ends. The angular separation of G358.85+0.47 from the Galactic center is 1.3', which places the angular distance of this source farthest from the Galactic equator when compared with other NRFs. The spectral index between 90 and 20 cm is estimated to be $\alpha = -0.8$, and it steepens to $-1.5$ between 6 and 20 cm (LaRosa et al. 2000; Lang et al. 1999a).

G359.85+0.39. —This new system of isolated NRFs shows subfilaments and flaring at an angular distance of 0.5' from the Galactic center (LaRosa et al. 2001). Unlike other systems of NRFs, with the exception of the Snake, G359.85+0.39 displays a gradient in its spectral index distribution (LaRosa et al. 2001). The spectral index value varies smoothly from $\alpha = -0.15$ to $-1.1$ in the direction away from the Galactic plane, as discussed below.

G359.79+0.17.—Another system of NRFs showing multiple filaments and a curvature in the direction away from the rotation axis of the Galaxy is G359.79+0.17 (Yusef-Zadeh & Morris 1987b; Lang et al. 1999b). The spectral index value between 20 and 90 cm is estimated to be $\alpha = -0.6$ (Anantharamaiah et al. 1991).

3. A MODEL: COLLIDING WINDS OF A STELLAR CLUSTER

A number of theoretical models have proposed interstellar mechanisms as a means of achieving the acceleration of particles to explain the nonthermal nature of NRFs. Most of these models require strong, organized, large-scale, interstellar magnetic fields. The models additionally require specific relative motions of Galactic winds, molecular clouds, H II regions, and supernova remnants. Here we expand on the model originally proposed by RB96, who have used a stellar mechanism for the acceleration of particles to relativistic energies. In analogy to the shock acceleration of the solar wind, RB96 proposed that terminal shocks of mass-losing stars are natural places for the acceleration of particles to high energies. They considered that under strong and weak interstellar medium (ISM) magnetic fields, the size of the wind bubble created by a mass-losing massive star determines the transverse size of the filaments. Once the electrons are accelerated at the wind terminal shock, they tag along the ISM field and flow along with the Alfvén velocity as they emit synchrotron radiation. The length of the filaments is then determined as the by-product of the Alfvén speed and synchrotron lifetime at radio frequencies. This model, then, implies that mass-losing stars with fast winds are embedded within each individual NRF.

The RB96 model can be applied to any mass-losing stellar system in the Galaxy but does not specifically address the rarity of the NRFs, which are observed only in the Galactic center region. Here the RB96 model is extended to explain the origin of NRFs, by using young, compact stellar clusters to accelerate particles to high energies. We believe that this is a more viable acceleration mechanism for the production of prominent NRFs, such as the Radio Arc or Sgr C, than the individual stellar wind sources. This implies that the unusual population of young stellar clusters, which are formed only in the Galactic center region, is tied to the origin of the unique filamentary structures observed in the same region.

3.1. Unusual Stellar Clusters near the Galactic Center

As noted above, it appears that many of the prominent NRF systems are morphologically associated with star-forming regions. Stellar clusters near the Galactic center are a record of the history of unusual star formation in this unique region. The association of the NRFs with star-forming sites has in fact been argued previously but in a different context (see, e.g., Serabyn & Morris 1994; Morris & Serabyn 1996). These authors argue that the acceleration of relativistic particles is due to the reconnection of the magnetic fields at the ionized surfaces of molecular clouds in star-forming regions. A necessary condition for the acceleration at the cloud surface is that the cloud has to have a relatively large velocity with respect to an ISM that itself is threaded by a large-scale organized magnetic field. Also, this model assumes that the poloidal component of the magnetic field dominates the global geometry of the field in the ISM of the Galactic center.

At present, three young (<20 Myr) clusters have been discovered within a projected distance of 35 pc of the center of
the Galaxy—the IRS 16, Arches, and Quintuplet clusters. Two other sources, namely, the Sgr A East and H1–H8 H ii regions, appear to be associated with emission-line stars (Cotera et al. 1999). Additional young stellar clusters are difficult to detect by infrared techniques because of the large differential extinction toward the Galactic center and the source confusion in near-IR wavelengths. For example, the 20 km s−1 giant molecular cloud (GMC) M−0.13−0.08, which is known to lie near the Galactic center, has a column density of ≈10^{23} cm−2, which corresponds to a visual extinction of ≈430 mag (Coil & Ho 1999). Thus, the total number of embedded young clusters in the Galactic center region, such as the Arches cluster, is very uncertain (Figer et al. 2002). Observationally, a systematic search has recently been conducted to find extended near-IR and X-ray sources with spectra resembling those of the young stellar cluster candidates, using the Two Micron All-Sky Survey (2MASS) and Chandra surveys of the nuclear bulge of the Galaxy (Dutra & Bica 2000, 2001; Law & Yusef-Zadeh 2003). Dutra & Bica (2000) find a total of 58 star cluster candidates within the projected distance of 600 pc from the Galactic center.

Our motivation to investigate the nature of NRFs and associate them with star-forming regions comes from the recent finding of massive young clusters in the Galactic center region. All the known stellar clusters within the inner 50 pc show emission-line stars and are known to be associated with thermal, ionized, and molecular gas clouds (see, e.g., Nagata et al. 1995; Cotera et al. 1996, 1999; Serabyn et al. 1998; Figer et al. 1999a; Krabbe et al. 1991). It has been suggested that massive stars might have preferentially formed in this region (Morris & Serabyn 1996) and that the initial mass function of one of the young stellar clusters, the Arches cluster, is flat (Figer et al. 1999a). The formation of a number of detected young clusters in this region is not that unusual, since the initial conditions for star formation in the nucleus of our Galaxy are different from those found elsewhere in the Galaxy. For example, it is well known that the temperature, pressure, and velocity dispersion of the population of molecular clouds, as well as the turbulent pressure of the ionized medium, are much larger in the inner 200 pc of the Galaxy than in the Galactic disk (see, e.g., Morris & Serabyn 1996 and references therein). In addition, the gas clouds experience an unusually high tidal field in the environment of the Galactic center (Bally et al. 1988). Theoretically, Portegies Zwart et al. (2001, 2002a) carried out numerical simulations of the evolution of massive star clusters within ~200 pc of the Galactic center. These simulations include the effects of stellar evolution and physical collisions for individual and binary stars, as well as the Galactic tidal field. They conclude that the tidal dissolution time of a cluster is about 70 Myr, but because of the crowding of stars near the Galactic center, their projected densities drop below the background density within about 20 Myr. Using this selection effect, these authors predict that the inner 200 pc of the Galaxy could harbor some 10−50 young star clusters similar to the Arches and the Quintuplet clusters. The expected high number of compact clusters with a core radius less than a parsec is expected only in the inner 200 pc of the Galaxy. This is because the clusters in this region have to be compact in order to not be tidally disrupted and young because of their short relaxation time (see, e.g., Kim, Morris, & Lee 1999; Portegies Zwart et al. 2001). Similar reasoning is used to explain the high-pressure, high-density molecular gas distributed throughout the Galactic center region.

3.2. Nonthermal Emission from Colliding Winds

Additional motivation for a physical relationship between young clusters and the NRFs came from a recent discovery and successful modeling of relativistic particles generated within young binary systems. It is well known that W-R and OB stars lose strong ionized winds as they emit thermal radio continuum emission from an optically thick surface located at a distance hundreds of stellar radii away (Wright & Barlow 1975; Panagia & Felli 1975; see the review by Güdel 2002). In the case of binary systems of massive stars, the thermal emission from ionized wind can be enhanced by contributions from shocked stellar winds (Stevens 1995). More recently, it has been shown that OB stars and up to 50% of W-R stars show signatures of nonthermal synchrotron emission from regions beyond the optically thick surface of thermal emission (Leitherer, Chapman, & Koribalski 1995; Chapman et al. 1999; Dougherty & Williams 2000). The colliding-wind model of synchrotron emission was confirmed by Dougherty & Williams (2000), who showed evidence that most nonthermal W-R systems are binaries. Theoretical work to explain the generation of synchrotron radio emission involves first-order Fermi acceleration in shocks within the stellar winds (see, e.g., Bell 1978). At the contact discontinuity, where the winds of a binary system collide with each other, particles are accelerated, resulting in significant radiation (Eichler & Uslov 1993).

Considering that the densest known young clusters of W-R and OB stars in the Galaxy are distributed in the Galactic center region, it is natural to consider nonthermal emission arising from the collection of W-R stars or in young stellar clusters. The near-IR spectral type of stars in these clusters is consistent with ionized stellar winds arising from mass-losing WN and/or Of stars with mass-loss rates ≈(1−20)×10−5 M⊙ yr−1; lower limits to the terminal velocities of the winds range between 800 and 1200 km s−1 (Cotera et al. 1996). The colliding thermal winds of the Galactic center clusters have also been proposed to explain the detection of X-rays from the Arches and Quintuplet clusters (Yusef-Zadeh et al. 2002; Law & Yusef-Zadeh 2003). If indeed thermal X-rays are the result of colliding winds, previous studies of 30 Doradus support the idea that the binary fraction in a young compact cluster is extremely high (Portegies Zwart, Pooley, & Lewin 2002).

Although the evidence for thermal and nonthermal emission from individual mass-losing stars is well known, the nonthermal characteristics of W-R and OB stars in a young, compact cluster environment have not been studied extensively. The nonthermal emission from the shocked region of the colliding winds is believed to result from first-order Fermi acceleration, which could arise from young stellar clusters. Ozernoy, Genzel, & Usov (1997) have pointed out that the conditions that are necessary for diffusive shock acceleration are met by shocks in the colliding winds at the stellar core. Diffuse and compact nonthermal emission could arise from the contributions of three components: the individual tight binaries in the cluster, the colliding winds from any two nearby massive stars within the cluster, and the collision between the hot thermal cluster flow generated from an ensemble of colliding winds and the ISM. Each of these components is described below.
On the basis of X-ray observations, binary systems are expected to populate heavily the compact young star clusters (see, e.g., Portegies Zwart et al. 2002a). Radio observations by Dougherty & Williams (2000) show evidence of nonthermal emission from up to 60% of their sample of W-R stars. The radio luminosity ($L_R$) of typical W-R stars that are likely to be in binary systems is estimated to be $\approx 10^{30}$ ergs s$^{-1}$ (Chapman et al. 1999). The total nonthermal radio luminosity is estimated to be $\approx 10^{33}$ ergs s$^{-1}$, assuming that about 100 such massive binary systems are embedded within a dense and young stellar cluster. Recent detection of nonthermal radio emission from the Arches cluster at 327 MHz is consistent with this picture. The radio luminosity of the Arches cluster is estimated to be $4\pi D^2 \nu F_\nu \approx 2.6 \times 10^{30}$ ergs s$^{-1}$, assuming that $D$ is 8.5 kpc (Yusef-Zadeh et al. 2003). This estimate is a lower limit to the total nonthermal radio luminosity of the cluster because of the uncertainty in the spectrum of the Arches cluster at low frequencies. In addition, the flat spectrum of the cluster at high frequencies may arise from nonthermal emission generated from an ensemble of stellar shock winds with a flat spectral index, as described below.

Nonthermal emission from a young stellar cluster could also arise from the shocked zone where the winds from individual W-R or OB stars collide with each other. Because the separation between individual stars in the cluster is estimated to be between $10^{16}$ and $10^{17}$ cm, the contact discontinuity will be at a distance beyond the surface where thermal emission is opaque to its own radiation. Figure 1 shows a schematic diagram of the collision of a stellar wind bubble with the shocked gas produced from the colliding winds of the remaining stars in the cluster. Using the expected theoretical value of the nonthermal radio luminosity of the region of the collision from the winds of two W-R stars (Eichter & Usov 1993) and assuming that the mass-loss rate and the wind velocity are $\approx 4 \times 10^{-5} \, M_\odot \, yr^{-1}$ and 1000 km s$^{-1}$, respectively, the radio luminosity is found to be much less than $10^{33}$ ergs s$^{-1}$. The main reason is the low value of the ratio of flow time to synchrotron timescale ($\tau$ in eq. [16] of Eichter & Usov 1993). This low ratio results from the low value of the magnetic field when extrapolated from the surface of the stars. However, this luminosity is enhanced if the cluster is extremely compact, with an average size ranging between $10^{14}$ and $10^{15}$ cm. In this case, the average separation, $r$, between stars is small enough that the strength of the dipole magnetic field from the surface of the star ($\propto r^{-3}$) is sufficiently high to generate radio synchrotron emission from the diffuse shock acceleration of electrons.

The third, and perhaps the most significant, contribution to the total nonthermal emission from a young cluster could arise from the terminal shock of a cluster flow as it escapes the core of the cluster and encounters the ISM gas surrounding the cluster. The X-ray–emitting, shock-heated gas created by the collision of individual $\sim 1000$ km s$^{-1}$ stellar winds in the dense cluster environment is shown to be accelerated, attaining a flow velocity similar to the wind velocity of individual mass-losing stellar sources at the edge of the cluster (Canto, Raga, & Rodríguez 2000; Raga et al. 2001). This cluster flow is expected to collide with the ISM gas surrounding the cluster and to produce nonthermal radio emission. The seed relativistic particles that are generated within the binary systems of the cluster are shocked again at the boundary of the cluster. In the process of diffuse shock acceleration, energetic particles moving upstream of the shock may scatter more effectively from the strong turbulence convected with the incoming flow. The turbulent medium is known to produce strong scatter broadening of radio sources toward the Galactic center region (see, e.g., Lazio & Cordes 1998). Assuming that the fraction of nonthermal radio to X-ray luminosity, $L_R/L_X \approx 10^{-3}$, as observed in W-R stars (Chapman et al. 1999), is the same for binary stars and young compact stellar clusters, $L_R$ is estimated to be $\sim 10^{33}$ ergs s$^{-1}$. The estimated nonthermal radio luminosity of a young cluster is within a factor of a few of the measured radio luminosity of typical NRFs. In addition, the size of the core radius of a young cluster, less than a parsec, where many of the electrons are accelerated to relativistic energies, matches well with the observed lateral dimension of typical NRFs.

![Fig. 1.—Schematic diagram showing the origin of the relativistic particles when the winds from a single mass-losing stellar bubble and the cluster flow collide with the cluster flow and the ISM, respectively.](image)

3.3. The Galactic Center Magnetic Field Strength and Geometry

The gas pressure in the Galactic center region is known to be high, based on a number of molecular line observations of this region (see, e.g., Morris & Serabyn 1996 and references therein). The magnetic field pressure in this region is also considered to be high. However, much of the evidence for the milligauss magnetic fields throughout the Galactic center is based on morphological study of the NRFs and the argument that the filaments are interacting dynamically with dense molecular clouds. These arguments have widely been used to support a hypothesis that there is a strong, ordered, milligauss magnetic field with a poloidal geometry pervasive throughout the inner few hundred parsecs of the Galaxy. Here we examine if there is observational...
Once the nonthermal particles are generated, they diffuse out, depending on what the relative pressure of the ISM is to that of the stellar cluster. The nonthermal gas pressure of the cluster could be confined by either the external gas pressure or the magnetic pressure in the immediate vicinity of the cluster. Alternatively, the shocked stellar wind bubble could be confined by the initial magnetic field that is swept up by the initial stellar outflow (a more detailed discussion of this model will be given elsewhere). RB96 estimated the astrophysical radius of the mass-losing star in the case when $\beta$, the ratio of the ISM gas pressure to the magnetic pressure, is much greater or much less than 1. This radius ($R$), which sets the transverse dimension of the filaments, is estimated to be, in the limit of $\beta \ll 1$ (using eq. [2] of RB96),

$$R_{\text{strong}} = 0.035 \left( \frac{M_\odot}{10^{-6} M_\odot \text{ yr}^{-1}} \right)^{1/2} \left( \frac{v}{10^3 \text{ km s}^{-1}} \right)^{1/2} \left( \frac{B}{1 \text{ mG}} \right)^{-1} \text{ pc}.$$  

Similarly, when $\beta \gg 1$, the radius is determined by

$$R_{\text{weak}} = 1.7 \left( \frac{n_0}{1 \text{ cm}^{-3}} \right)^{-1/5} \left( \frac{L_{\text{wind}}}{10^{16} \text{ ergs s}^{-1}} \right)^{-1/5} \left( \frac{t}{10^4 \text{ yr}} \right)^{3/5} \text{ pc}.$$  

RB96 argued that the radius of the bubble created from the mass-losing star matches better with the transverse dimension (a fraction of a parsec) of the filament if the ISM magnetic field is weak.

### 3.3.1. Strong Magnetic Field

If the strong limit of the magnetic field, $\beta < 1$, were applied to the cluster model, the transverse dimension of the filament would increase by a factor of 10. These estimates assume that the mechanical luminosity of the cluster wind, $L_{\text{wind}}$, and the mass-loss rate of the cluster are 100 times larger than those of a typical mass-losing star. Because of the large mass-loss rate of the cluster, $M_\odot \approx 10^{-4} M_\odot \text{ yr}^{-1}$, the ram pressure of the cluster flow can be balanced at a radius of 0.35 pc by the strong ($B \sim 10^{-3} \text{ G}$) ISM magnetic field pressure; this sets the transverse dimension of the filaments associated with massive young stellar clusters. This implies the existence of large-scale, preexisting, organized flux tubes throughout the Galactic center region. The large-scale distribution of the magnetic field is expected to have a poloidal geometry in the Galactic center region. A strong magnetic field with this geometry has been considered in a number of models explaining the origin of NRFs. In this hypothesis, the relativistic electrons will illuminate the strong ISM field lines that surround the cluster. However, apart from a large number of assumptions that have been made, there are difficulties with this hypothesis, on the grounds that there is neither direct evidence of a pervasive strong magnetic field nor evidence for poloidal geometry of the magnetic field in the Galactic center region, as described below.

1. The streaks and G358.85+0.47, which have orientations along the Galactic plane, must lie much farther away from the Galactic center, where the geometry of the field diverges from being dipole and the magnetic field should be weaker than in the NRFs closer to the center (Lang et al. 1999a). However, the characteristics of the NRF G358.85+0.47, with its location at a high Galactic latitude, do not appear to be different from those of typical NRFs, with the exception of its orientation.

2. A large number of new NRFs have recently been detected at 20 and 90 cm in the vicinity of prominent well-known filaments; these new NRFs show curvature and orientations that differ from those of earlier, vertical NRFs (Nord et al. 2002; LaRosa et al. 2002; F. Yusef-Zadeh et al. in preparation).

3. The synchrotron lifetime ($\tau$) of a milligauss field requires a large Alfvén speed ($v_A$) and low density of ionized medium. For example, $\tau$ is only 6000 yr at 5 GHz, requiring a number density of ionized gas of $0.04 \text{ cm}^{-3}$ and $v_A \sim 10^4 \text{ km s}^{-1}$ to travel the 60 pc length of the Snake.

4. The strong magnetic field lines of the inner 100–200 pc need to be anchored to the plane, presumable to the dense cores of GMCs.

5. The anisotropic distribution of the structure function of the Faraday RM toward the NRF G359.5+0.8 indicates a geometry of the magnetic field that is inconsistent with a poloidal geometry of the field toward this source (Yusef-Zadeh et al. 1997b).

6. Zeeman measurements of OH (1720 MHz) masers associated with supernova remnant masers probe the magnetic field of molecular gas, with number densities ranging between $10^4$ and $10^5 \text{ cm}^{-3}$. The estimate of the magnetic field strength is close to that observed in supernova remnant masers distributed outside the Galactic center region (Brogan et al. 2000). Additional Zeeman measurements of thermal OH (1665 and 1667 MHz) were also made toward 13 positions of Galactic center molecular clouds. Many of these clouds lie in star-forming regions in the vicinity of NRFs. The 3 $\sigma$ upper limit to the line-of-sight magnetic field is 0.3 mG (Uchida & Güsten 1995). This constrains the magnetic field in magnetized molecular clouds anchoring the vertical field lines.

7. A number of studies have estimated the milligauss magnetic field along the NRFs by assuming that NRFs are dynamically colliding with molecular clouds. To identify the site of the interaction, a large-scale search for OH (1720 MHz) maser emission was made over the inner 8° × 1° ($l \times b$) of the Galactic center (Yusef-Zadeh et al. 1999). No evidence of maser emission is found where candidate molecular clouds are possibly interacting with NRFs.

8. Finally, the large-scale distribution of the magnetic field inferred from dust polarization measurements has shown a dominant component of toroidal geometry in the magnetic field distribution among a number of dust clouds that have been mapped in the Galactic center region (Novak et al. 2003).

Some of the difficulties with the large-scale, organized poloidal geometry of the milligauss field can be resolved by envisioning a picture in which the magnetic field is strong but not pervasive. The ISM pressure of the Galactic center region is nonuniformly distributed but is in pressure equilibrium with the magnetic field pressure. A schematic diagram in Figure 1 shows a region where the nonthermal gas from
the cluster illuminates the strong magnetic field flux tube, whose pressure is confined by the ISM gas pressure. The narrow magnetic flux tubes lie where the ISM and magnetic field pressures are high. The localized, one-dimensional magnetic flux tubes are expected to have a small volume filling factor distributed throughout the Galactic center region, as they are expected to be surrounded by a weak, magnetized medium. This implies that the high value of the RM distribution toward NRFs is due to the high density of ionized material \( n_e \). The high RM toward NRFs and bright Galactic center objects is known to be due to an external Faraday medium. Assuming a typical RM of \( \sim 3000 \) rad m\(^{-2}\), as has been measured toward a number of NRFs, and a size of the Faraday screen of 200 pc, the estimated line-of-sight magnetic field and electron density are estimated to be \( 2 \mu \)G and 10 cm\(^{-3}\), respectively. The estimate of the electron density and the size of the Faraday screen are also consistent with the value of the emission measure, \( 1 \times 10^4 \) cm\(^{-6}\) pc observed toward the Galactic center region (Mezger & Pauls 1979; Yusef-Zadeh et al. 1994). It is thought that the ionized medium coexists with the Faraday medium and acts as a scattering screen broadening background compact radio sources. (Yusef-Zadeh et al. 1994; Lazio & Cordes 1998).

The next question that arises in the context of the above model is why most NRFs lie perpendicular to the Galactic plane. The nonuniform distribution of the preexisting flux tubes filled with strong magnetic fields must be oriented perpendicular to the Galactic plane. Alternatively, it is more natural to consider the following: The orientation of the prominent NRFs could be the consequence of the environment in which they are born. These environmental factors could preferentially maintain NRFs that run perpendicular to the Galactic plane and suppress the NRFs running along the Galactic plane. One selection effect could be due to a density of molecular gas higher when distributed along the Galactic plane than away from the plane. GMCs with high densities and kinetic temperatures could limit the growth of NRFs along the equatorial plane, assuming that the magnetic pressure of the filaments is less than the molecular gas pressure in the Galactic plane of the Galactic center region.

The other effect is the differential rotation of the central region of the Galaxy, which is expected to distort and destroy many of the long NRFs oriented along the Galactic plane. The long NRFs directed perpendicular to the Galactic plane are more likely to survive than those oriented along the Galactic plane because of the ineffectiveness of the differential rotation in the direction away from the Galactic plane. The NRFs can survive if their \( \delta r/r \leq 0.1 \), where \( \delta r \) is the length of a linear filament when projected along the Galactic plane at a distance \( r \) from the Galactic center. For long filaments along the plane, the circular velocity of one end of the filament will be slower than the circular velocity of the end that is closer to the Galactic center; thus, the long filaments are dynamically distorted after a few rotations. This implies that the filaments along the Galactic plane must have short lengths, whereas the long filaments, such as the Snake or the Arc, can only survive if they are oriented perpendicular to the Galactic plane. As pointed out in §2, there does not appear to be a trend in the dominant orientation of the streaks with respect to the Galactic plane. Thus, they are not much affected by the above environmental factors.

3.3.2. Weak Magnetic Field

The relativistic particles emerging from the cluster flow can stream along the local magnetic field with a large value of \( \beta \). The size of the bubble surrounding the cluster will be 17 pc if the mechanical luminosity of the cluster, \( L_{\text{wind}} \approx 10^{38} \) ergs s\(^{-1}\), lasts for 10\(^5\) yr. This value of \( R \) is much larger than the size of a bubble produced by a mass-losing star as estimated by RB96. If the density of the surrounding medium is \( 10^3 \) cm\(^{-3}\), then \( R \) will be small enough to match the width of the NRFs. However, the estimated number density is too high, and it is unlikely that the shocked cluster flow will be collimated when the external magnetic field is weak unless the initial magnetic field of the cluster, which is swept up by the cluster flow, confines the bubble. We believe that when \( \beta > 1 \), the size of the shocked outflow from a massive binary system matches the width of the filaments better than that from young clusters, as RB96 had argued. However, this scenario can account for the energetics of the streaks but not the more luminous and prominent NRFs. Since the radio luminosity \( L_R \) of the streaks is about 0.1–0.01 times the \( L_R \) of the bright NRFs, a W-R–OB binary system could be the source of the relativistic particles. In this scenario, a local inhomogeneity in the ISM pressure allows the shocked gas to flow in the direction away from the binary system. When the particle pressure is higher than the magnetic field pressure, the nonthermal gas can diffuse along a “channel” that has a much lower magnetic field and thus suffers no radiation loss. Equilibrium stability analysis of this system has been studied in detail by Rossi et al. (1993), who found that the magnetic field can be amplified by filamentation instability driven by synchrotron cooling, provided that \( \beta > 1 \). However, it is not clear how the channel of low magnetic field with nonthermal gas is confined under the condition that \( \beta > 1 \). Also, the onset of instability is expected to occur typically after a synchrotron cooling timescale that corresponds to the length of the filaments divided by their Alfvén speed. If the energy spectrum of the relativistic particles is steep, the synchrotron cooling time could be long. This results in a gap between the onset of the filamentary structure and the filament origin, thus making the hypothesis difficult to test observationally.

3.4. The Association of Young Clusters with NRFs

3.4.1. The Brightness Distribution

The association of nonthermal, radio-emitting, young stellar clusters with NRFs implies that young clusters should be embedded within every system of prominent NRFs. However, the dynamics of star clusters and NRFs are known to be different from each other during the synchrotron lifetime of NRFs. The circular motion of stars and gas clouds range between 100 and 200 km s\(^{-1}\) in this region of the Galaxy. The gas clouds are much more subject to nongravitational (i.e., tidal and magnetic) effects, whereas compact young stellar clusters are subject to the effects of the dynamical friction. Thus, the long NRFs may get distorted as they follow the motion of the compact clusters.

The motion of the cluster with respect to the shocked bubble, which is confined by either magnetic field or gas pressure, distorts the symmetry at the point of origin (Weaver et al. 1977). If the space velocity of the cluster is 6 km s\(^{-1}\), the shocked bubble, with a size of 0.3 pc, becomes distorted over \( 10^5 \) yr, the lifetime of the outflow. Consequently, the filaments should become broadened and
somewhat asymmetric at the point of the origin because of the motion of the cluster and its shocked bubble. In addition, if we assume that the relative velocity between the NRFs and the acceleration site is between 1 and 10 km s\(^{-1}\), the NRFs will drift by about 0.01–10 pc during the synchrotron lifetime of NRFs ranging between 10\(^4\) and 10\(^6\) yr. Thus, the filaments can be bent at the filament origin.

Another characteristic of a number of NRFs is that their brightness peaks in the middle of the filaments. This peak emission does not appear to be in the vicinity of the stellar clusters responsible for their supply of relativistic particles. In the context of this model, we believe that the deviation of the orientation of the magnetic fields is likely to be responsible for an increase in the brightness of the filaments. A change in the orientation of the magnetic field, as has been observed in a number of prominent NRFs, suggests that there are internal oblique shocks reaccelerating particles to relativistic energies in midpoints where synchrotron emissivity is enhanced (a more detailed account of this picture will be given elsewhere).

### 3.4.2. The Spectral Index Distribution

The distribution of the spectral index is either steep for isolated filaments or flat for a network of filaments. In the context of the proposed model, the colliding winds in the core of a young cluster are shocked multiple times before the X-ray-emitting cluster flow gets shocked again as it reaches the surrounding ISM. Diffusive shock acceleration by a single shock is known to produce a power-law energy distribution (see, e.g., Blandford & Eichler 1987); for a single adiabatic shock, the expected index is \( \alpha = -0.5 \). A sequence of identical and nonidentical shocks are estimated to have an asymptotic spectrum, producing a power law with a flat spectral index \( \alpha = 0 \) (Pope & Melrose 1994; Melrose & Pope 1993). The spectrum due to fast shocks evolves more rapidly toward a flat spectrum than that of weak shocks. This implies that slower shocks have a flat spectrum over a smaller energy range (Pope & Melrose 1994).

Considering that the spectral index of the NRFs ranges over wide values, the diffuse shock acceleration mechanism due to multiple shocks predicts a flat spectrum for the synchrotron emission at the point of origin. Thus, the prediction of the model is that the origin of the NRFs should have a flat spectrum at high radio frequencies. The energy losses due to radiation and particle escape due to diffusive effects may steepen the spectrum away from the filament origin. An additional effect that can flatten or even invert the radio spectrum is the contribution of ionized thermal gas in star-forming regions. The strong radiation field of young, massive clusters ionizes dense molecular clouds (e.g., the Arches and Quintuplet clusters), and there should be much diffuse ionized gas in the environments from which NRFs are born (e.g., the Arc, Sgr A, and Sgr C). The bundle of NRFs associated with the Radio Arc and Sgr C is known to be surrounded by ionized thermal gas, as evidenced by the detection of strong Faraday rotation, as well as the detection of radio recombination line emission toward this system of NTFs (see, e.g., Anantharamaiah & Yusef-Zadeh 1989). The spectral index values become steeper in the direction away from the Galactic plane for these sources, as well as for the isolated filament G359.85+0.39 (LaRosa et al. 2001). This is consistent with the picture that thermal gas does not affect the intrinsic value of the spectral index away from the Galactic plane.

It is possible that thermal ionized gas is distributed in front of NRFs. Alternatively, thermal gas with electron density \( n_e \) (in units of cm\(^{-3}\)) might be uniformly mixed with nonthermal gas along the path length \( L \) (in parsecs) throughout this system of filaments. The apparent synchrotron emission in the latter situation is given by Salter & Brown (1988):

\[
I(\nu) \propto \nu^{-\alpha+2.1} \left[ 1 - \exp\left(-\nu_A/\nu^{2.1}\right) \right],
\]

where \( \nu_A = 0.5 n_e L^{0.5} \) MHz.

At very low frequencies, \( I(\nu) \propto \nu^{-\alpha+2.1} \), the spectrum is inverted if \( \alpha < 2.1 \). Low-frequency observations between 160 MHz and 1.4 GHz show that the Radio Arc has an apparent spectral index between 0.37 near G0.16–0.15 (Yusef-Zadeh et al. 1986). Considering the large uncertainty in the measured spectral index of G0.16–0.15 using different spatial resolutions where there is thermal and nonthermal emission on a wide range of angular scales, this is consistent with the inverted spectrum at low frequencies but with a steep index, \( \alpha = 1.7 \). At high frequencies, \( I(\nu) \propto \nu^{-\alpha} \nu_A^{2.1} \), high-resolution observations of the NRFs near the Arc have not detected 43 GHz emission from the filaments (Sofue, Murata, & Reich 1992), suggesting \( \alpha > 0.7 \), which is not inconsistent with the value of \( \alpha \) at low frequencies. The value of \( \nu_A \) is estimated to be about 600 MHz, corresponding to \( n_e \sim 400 \text{ cm}^{-3} \) toward G0.16–0.15, if we assume that the path length \( L \sim 9 \) pc. The value of \( \nu_A \) will be different along the long extent of the linear filaments.

As for the spectral index of the isolated filaments, the main question that arises is how to account for both the constant value of the spectral index along the filaments and a steepening of \( \alpha \) at higher frequencies for a given position along the filaments. A break in the spectrum is interpreted to be the consequence of spectral aging of synchrotron radiation, whereas the constancy of the spectral index along the filament requires shock reacceleration along the filaments. This is consistent with the interpretation of the change in the brightness distribution of the filaments at midpoints.

### 4. CONCLUSIONS

The hypothesis outlined above supports a stellar mechanism to accelerate particles by young dense clusters or massive binary systems using an efficient and well-known Fermi acceleration of cosmic rays. The population of young stellar clusters responsible for the origin of the NRFs is considered to be unique in the Galactic center region, as evidenced by the discovery of a number of young stellar clusters (e.g., the Arches cluster). We believe that it is not by accident that many of the prominent NRFs are distributed in the vicinity of \( \text{H\ II} \) regions associated with star-forming activity. This model, which is an expansion of an earlier model by RB96, predicts that compact young stellar clusters characterized by thermal and nonthermal emission with a flat spectrum should be found in the vicinity of individual NRFs in the Galactic center, whereas massive binary systems are responsible for the origin of the streaks, which are considered to be the scaled-down version of the prominent NRFs.

Both strong and weak magnetic field lines in the ISM of the Galactic center region are considered to be illuminated by the relativistic particles of the cluster, but each has its
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