The Origin of the Galactic Center Nonthermal Radio Filaments: Young Stellar Clusters

F. Yusef-Zadeh
Department of Physics and Astronomy, Northwestern University, Evanston, IL 60208
(zadeh@northwestern.edu)

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ABSTRACT

The unusual class of magnetized nonthermal radio filaments (NTF), threads and streaks with their unique physical characteristics are 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 to lie 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 WR 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 by Rosner and Bodo (1996), 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 have neither poloidal geometry nor pervasive throughout the Galactic center region.

Subject headings: Galaxy: center – ISM: magnetic fields — ISM: general — shock waves — radio continuum: 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 (NTF)\(^1\) within the inner two degrees of the Galactic center (e.g., Yusef-Zadeh, Morris and Chance 1984; Liszt 1985; Morris and Yusef-Zadeh 1985; Bally and 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 pc at the Galactic center distance of 8.5 kpc and their length is of the order tens of parsecs.

2. Most of the long and bright filaments are aligned to within about 30\(^0\) 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 peak in midpoints as they gently curve.

4. The combination of strongly linearly polarized emission from NRFs and radio spectral index distribution suggest a nonthermal synchrotron origin.

5. The rotation measure (RM) values of the NRFs range between a few hundred to several thousand rad. m\(^{-2}\) and the polarization measurements indicate that the NRFs

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\(^1\)NRF are used to distinguish them from nonthermal X-ray filaments
trace the magnetic field with an equipartition strength ranging between several to hundreds of micro-Gauss.

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 λ6 and 2cm. 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 that resemble extragalactic radio jets but are not accompanied with any obvious source of acceleration of charged particles to high energy relativistic energies. Although a number of detailed models have been considered, there is no consensus as to the origin of the nonthermal filaments (NRFs). These models suggest that molecular and ionized gas clouds, mass-losing stars, Galactic winds, and 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 (e.g., Heyvaerts et al. 1988; Benford 1988, 1998; Morris and Yusef-Zadeh 1989; Serabyn and Morris 1994; Nicholls and LeStrange 1995; Bally and Yusef-Zadeh 1989; Serabyn and Güsten 1991; Rosso & Pelletier 1993; Ryutov et al. 2000; Lesch and Reich 1992; Rosner and Bodo 1996; Dahlburg et al. 2002; Shore and La Rosa 1999; Bicknell and 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 (La Rosa, Lazio and 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 and Serabyn 1996; Bicknell and 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 HII 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 Rosner and Bodo (1996), 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 WR–OB binary systems or young massive binary systems with their corresponding HII 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, Morris and Chance 1984; Yusef-Zadeh and Morris 1987a,b,c). 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 inverted spectrum $\alpha=+0.3$ (Inoue et al. 1984; Tsuboi et al. 1985; Seiradakis et al. 1985; Sofue et al. 1989; Reich et al. 2000) where $F_\nu \propto \nu^\alpha$ with the exception of one steep spectrum filament to the south of the Arc with
\begin{itemize}
\item $\alpha = -0.4$ between 90 and 20 cm (Anantharamaiah et al. 1991). The vertical filaments of the Arc extend toward positive and negative latitudes $-0.75^\circ < b < +0.75^\circ$ as they become more diffuse, weaker in their surface brightness (Sofue and 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; Yusef-Zadeh et al. 1990; Yusef-Zadeh and Cotton 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 Myrs (e.g., Figer et al. 1999a). 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 and Morris 1994; Tsuboi et al. 1997; Yusef-Zadeh, Roberts & Wardle 1997).

G0.08+0.15 (Northern Thread): The 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 and Yusef-Zadeh 1985; Yusef-Zadeh 1986; Lang, Morris and 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 $4 \times 10^4$ years 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 of mainly 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 (e.g., Cotera et al. 1996; Serabyn, Shupe & Figer 1998; Blum et al. 2001). There is considerable ionized and molecular material that appear 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 and Güsten 1991).

**G359.96+0.09 (Southern Thread):** Similar to the Northern Thread in its extent and its morphology except that it is running within 12\(^\circ\) 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 HII regions known as H1 and H2 which are thought to be excited by O6 and O7 ZAMS, respectively (Yusef-Zadeh & Morris 1987c; 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 four arcminutes 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 (e.g., Genzel, Hollenbach and 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 HII region (Liszt 1992; Liszt and Spiker 1995). The filaments extend for 10' toward positive latitudes with a spectral index \(\alpha=-0.5\) between 90 and 20cm (LaRosa et al. 2000). The filaments appear to end abruptly inside a molecular cloud HII complex with a velocity of \(-65\) kms\(^{-1}\)(Liszt 1992; Liszt and Spiker 1995). This HII complex is also known to coincide with a source of infrared emission at 350 \(\mu\)m (Hunter et al. 2000). An O5.5V 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 peak at the midpoint where subfilaments lie closest to each other (Bally and 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 and Parastaran 1997). Recent Chandra observations show X-ray emission from the northern filament of G359.54+0.18 (Lu, Wang and Lang 2003). A dense molecular cloud and an HII region are observed at the interface of the eastern edge of the filaments before they deviate from a straight line and flare (Staghun 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' – 5'. The surface brightness of the streaks is typically five to ten times fainter than the long filaments and there is no sign of bending. It is not uncommon to observe streaks having orientations very different than the general direction of the prominent NRFs (Yusef-Zadeh and Cotton 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 HII region. G0.02+0.04 is an excellent example of a streak that ends inside the HII region H4, which is known to be excited by a O8.5 ZAMS (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 other Galactic center filaments by its narrow (<10") width, its long (≈20") extent, and by 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 20cm with the exception of the major kink where the spectrum steepens to $\alpha = -0.5$. Subfilamentation 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 $\approx 8 \times 10^5$ years (Gray et al. 1995).

Toward the northern end of the Snake near the Galactic plane, there is a cluster of HII knots near G359.16-0.04 (Caswell and Haynes 1987). The filament ends in the HII knots and morphological arguments have been used to associate the Snake with the HII 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 $1.3^0$, which places the angular distance of this source furthest from the Galactic equator when compared with other NRFs. The spectral index between 90 and 20cm is $\alpha = -0.8$ and steepens to $-1.5$ between 6 and 20cm (LaRosa et al. 2000; Lang et al. 1999).

**G359.85+0.39:** This new system of isolated NRFs shows subfilaments and flaring at an angular distance of $0.5^0$ 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 and Morris 1987b; Lang et al. 1999b). The spectral index value between 20 and 90cm 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, HII regions and supernova remnants. Here we expand upon the model originally proposed by Rosner and Bodo (1996; 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 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 radiate synchrotron radiation. The length of the filaments is then determined as the byproduct of 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 systems 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 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 are
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 nonthermal filamentary 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 to star forming sites has in fact been argued previously but in a different context (e.g., Serabyn and Morris 1994; Morris and Serabyn 1996). These authors argue that the acceleration of relativistic particles is due to the reconnection of the magnetic fields at the ionized surface 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 interstellar medium which itself is threaded by 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 Myrs) clusters have been discovered within a projected distance of 35 pc of the center of the Galaxy – the IRS 16, the Arches and the Quintuplet clusters. Two other sources, namely the Sgr A East HII regions and the H1-H8 HII regions appear to be associated with emission line stars (Cotera et al. 1999). Additional young stellar clusters are difficult to detect by infrared techniques due to the large differential extinction toward the Galactic center and due to the source confusion in near-IR wavelengths. For example, the 20 kms\(^{-1}\)GMC (M-0.13–0.08) which is known to lie near the Galactic center has a column density of \(\approx 10^{24}\) which corresponds to a visual extinction of \(\approx 430\) magnitudes (Coil and 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 sources and X-ray sources resembling the spectra of young stellar cluster candidates using the 2MASS and Chandra surveys of the nuclear bulge of the Galaxy (Dutra and Bica 2000, 2001; Law and Yusef-Zadeh 2003). Dutra and 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 come from 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 (e.g., Nagata et al. 1995; Cotera et al. 1996, 1999; Serabyn et al. 1998, Figer et al. 1999b; Krabbe et al. 1991). It has been suggested that massive stars might have preferentially formed in this region (Morris and Serabyn 1996) and that the initial mass function of one of the young stellar clusters, the Arches cluster, is flat (Figer et al. 1999b). 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 is different than those found elsewhere in the Galaxy. For example, it is well known that the temperature, pressure, velocity dispersion of the population of molecular clouds as well as the turbulent pressure of ionized medium are much larger in the inner 200 pcs of the Galaxy than in the Galactic disk (e.g., Morris and Serabyn 1996 and the 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, 2002) 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, physical collisions for individual and binary stars as well as Galactic tidal field. They conclude that the tidal dissolution time of a cluster is about 70 Myrs but because of the crowding of stars near the Galactic center, their projected densities drop below the background density within about 20 Myrs. Using this selection
effect, these authors predict that the inner 200 pc of the Galaxy could harbor some 10 to 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 pc 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 not to be tidally disrupted and young because of their short relaxation time (e.g., Kim, Morris and 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 WR 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 and Barlow 1975; Panagia and 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 WR stars show signatures of nonthermal synchrotron emission from regions beyond the optically thick surface of thermal emission (Leithere et al. 1995; Chapman et al. 1999; Dougherty & Williams 2000). The colliding wind model of synchrotron emission was confirmed by Dougherty and Williams (2000), who showed evidence that most nonthermal WR systems are binaries. Theoretical work to explain the generation of synchrotron radio emission involves first order Fermi acceleration in shocks within the stellar winds (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 (Eicher and Usov 1993).
Considering that the densest known young clusters of WR 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 WR 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 \( \approx (1 - 20) \times 10^{-5} M_\odot \text{yr}^{-1} \); lower limits to the terminal velocities of the winds range between 800 and 1200 kms\(^{-1}\) (Cotera \textit{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 the Quintuplet clusters (Yusef-Zadeh \textit{et al.} 2002; Law and 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 and Lewin 2002).

Although the evidence for thermal and nonthermal emission from individual mass-losing stars is well known, the nonthermal characteristics of WR 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 and Usov (1996) 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 with the ISM. Each of these components is described below.

Based on X-ray observations, binary systems are expected to populate heavily the compact young star clusters (e.g., Portegies Zwart \textit{et al.} 2002). Radio observations by Dougherty and Williams (2000) show evidence of nonthermal emission from up to 60%
Radio luminosity \( (L_R) \) of typical WR stars which are likely to be in binary systems is estimated to be \( \approx 10^{29} \text{ erg s}^{-1} \) (Chapman et al. 1999). The total nonthermal radio luminosity is estimated to be \( \approx 10^{31} \text{ erg s}^{-1} \) 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. Radio luminosity of the Arches cluster is estimated to be \( 4\pi D^2 \nu F_{\nu} \approx 2.6 \times 10^{30} \text{ ergs s}^{-1} \), 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 WR 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 nonthermal radio luminosity of the region of the collision from the winds of two WR stars (Eichler and Usov 1993) and assuming that the mass-loss rate and the wind velocity are \( \approx 4 \times 10^{-5} M_\odot \text{ yr}^{-1} \) and 1000 km s\(^{-1}\), respectively, the radio luminosity is found to be much less than \( 10^{31} \text{ erg s}^{-1} \). The main reason is the low value of the ratio of flow time to synchrotron time scale \( (\eta \text{ in equation 16 of Eichler and Usov (1993)}) \). 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 \( 10^{14} - 15 \)
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 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 (Cantó et al. 2000; Raga et al. 2002). This cluster flow is expected to collide with the ISM gas surrounding the cluster and produces 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 (e.g., Lazio and Cordes 1998). Assuming that the fraction of nonthermal radio to X-ray luminosity $L_R / L_X \approx 10^{-3}$, as observed in WR stars (Chapman et al. 1999), is the same for binary stars and young compact stellar cluster, $L_R$ 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 <pc, where many of the electrons are accelerated to relativistic energies, matches well with the observed lateral dimension of typical NRFs.
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 (e.g. Morris and Serabyn 1996 and the references cited therein). The magnetic field pressure in this region is also considered to be high. However, much of the evidence for the mG 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 mG magnetic field with a poloidal geometry pervasive throughout the inner few hundred pc of the Galaxy. Here we examine if there is observational support for this widely accepted view of the magnetic field distribution near the Galactic center; in addition, we study the limit of weak and strong ISM magnetic fields in the context of the young cluster model.

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 either by 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 astrosphere radius of the mass-losing star in the case when $\beta$ the ratio of the ISM gas 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 $\beta << 1$ (using eqn. (2) of RB96)

$$R(\text{strong}) = 0.035 \left( \frac{M_\odot}{10^{-6} M_\odot \text{ yr}^{-1}} \right)^{0.5} \times \left( \frac{v}{10^3 \text{ km s}^{-1}} \right)^{0.5} \times \left( \frac{B}{mG} \right)^{-1} \text{ pc}$$
Similarly, when $\beta >> 1$, the radius is determined by

$$R(weak) = 1.7 \left( n_0/1 cm^{-3} \right)^{-1/5} \times \left( L_{wind}/10^{36} ergs s^{-1} \right)^{1/5} \times (t/10^4 yr)^{3/5} \text{ pc}$$

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

3.3.1. Strong Magnetic Field

Applying the strong limit of the magnetic field $\beta < 1$ 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 $L_{wind}$ 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 $\dot{M}_w \approx 10^{-4} M_\odot \text{ yr}^{-1}$, the ram pressure of the cluster flow can be balanced at a radius at a fraction 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 pre-existing 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. The 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 both on the grounds that there is neither direct evidence of a pervasive strong magnetic field nor the 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 further away from the Galactic center where the geometry of the field diverges from being dipole and the magnetic field should be weaker than the NRFs closer to the center (Lang et al. 1999). However, the characteristics of G358.85+0.47 NRF with its location at a high Galactic latitude do not appear to be different than 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 NTFs show curvature and orientations that differ from earlier vertical NTFs (Nord et al. 2002; LaRosa et al. 2002; Yusef-Zdeh, Cotton and Hewitt 2003).

3. The synchrotron lifetime ($\tau$) of a mG field requires large Alfvén speed ($v_a$) and low density of ionized medium. For example, $\tau$ is only 6000 years at 5 GHz, requiring a number density of ionized gas of $0.04 \text{ cm}^{-3}$ and $v_a \sim 10^4 \text{ kms}^{-1}$ 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, presumably to the dense cores of giant molecular clouds.

5. The anisotropic distribution of the structure function of the Faraday rotation measure toward the NRF G359.5+0.8 indicates a geometry of the magnetic field which is inconsistent with the poloidal geometry of the field toward this source (Yusef-Zadeh, Wardle and Parastaran 1997).

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 $10^4-5 \text{ cm}^{-3}$. 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 (1665/67 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 3σ upper limit to the line of sight magnetic field is 0.3 mG (Uchida and Güsten 1985). This constrains the magnetic field in magnetoionized molecular clouds anchoring the vertical field lines.

7. A number of studies have estimated mG 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 $8^0 \times 1^0 (l \times b)$ 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. Lastly, the large-scale distribution of the magnetic field inferred from dust polarization measurements have 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 mG 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 non-uniformly distributed but is in pressure equilibrium with the magnetic field pressure. A schematic diagram of Figure 1 shows a region where the non-thermal 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 magnetoionized medium. This implies that the high value of the RM distribution toward NRFs is due to high density of ionized material $n_e$. The high rotation measure (RM) toward NRFs and bright Galactic center objects is known to be due to an external Faraday medium. Assuming a typical RM $\sim 3000$ rad m$^{-2}$, as have 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 electrons density are estimated to be $2 \mu$G and $10$ cm$^{-3}$. 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 and Pauls 1979; Yusef-Zadeh et al. 1994). It is thought that the ionized medium co-exists with the Faraday medium and acts as a scattering screen broadening background compact radio sources. (Yusef-Zadeh et al. 1994; Lazio and 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 non-uniform distribution of the pre-existing 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 higher density of molecular gas distributed along the Galactic plane than away from the plane. Giant molecular clouds 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 much 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 due to 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 trajectory of one end of the filament will be slower than the circular velocity of the other end which 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 section 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 $10^5$ years. 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 $10^5$ cm$^{-3}$, then $R$ will be small enough to match the width of 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 instead of young clusters matches better with the width of the filaments as RB96 had argued. However, this scenario can account
for the energetics of the streaks and not the more luminous and prominent NRFs. Since radio luminosity $L_R$ of the streaks is about 0.1 to 0.01 times $L_R$ of the bright NRFs, a WR-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 a 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) where they 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 time scale which 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 to 200 kms$^{-1}$ in this region of the Galaxy. The gas clouds are much more subject to non-gravitational (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 cluster.

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

Another characteristic of a number of NRFs is that their brightness peak 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 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 prominent NRFs , suggests that there are
internal oblique shocks re-accelerating partilces 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 spectral index is either steep for isolated filaments or flat for
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 recognized to produce a power law energy distribution (e.g., Blandford and Eichler
1987); for a single adiabatic shock, the expected indices are $\alpha = -0.5$. A sequence of identical
and non-identical shocks are estimated to have an asymptotic spectrum producing a power
law with a flat spectral index $\alpha = 0$ (Pope and Melrose 1994; Melrose and 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 and 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 of the
synchrotron 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 radio spectrum is
the contribution of ionized thermal gas in star forming regions. The strong radiation field
of young massive clusters ionize 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 nonthermal filaments (e.g. Anantharamaiah and
Yusef-Zadeh 1989). The spectral index values become stepper in the direction away from
the Galactic plane for these sources as well as 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 \( n_e \text{ cm}^{-3} \) are uniformly mixed with nonthermal gas along the path length \( L \text{ (pc)} \) throughout this system of filaments. The apparent synchrotron emission in the latter situation is given by Salter and Brown (1974)

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

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

At very low frequencies \( I(\nu) \propto \nu^{-\alpha+2.1} \), the spectrum is inverted if \( \alpha < 2.1 \). Low frequency observations of the Arc 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 of the measured spectral index of G.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 steep \( \alpha = 1.7 \). At high frequencies, \( I(\nu) \propto \nu^{-\alpha} \times \nu_A^{2.1} \); 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 \( L \sim 9 \text{ pc} \). 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 the constant value of the spectral index along the filaments and yet 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 re-acceleration along the filaments. This is consistent with the interpretation of the change
in the brightness distribution of the filaments in 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., Arches cluster). We believe that it is not by accident that many of the prominent NRFs are distributed in the vicinity of HII 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 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 own difficulties. In particular, we argue that present observations place strong constraint on the idea that strong, pervasive magnetic field with a poloidal geometry is distributed in the Galactic center region. In the context of the model presented here, we proposed that the ISM of the Galactic center region has a non-uniform distribution of strong magnetized flux tubes, which are confined by high gas pressure, but with small volume filling factor. We also discussed the brightness and spectral index distributions of NRFs and concluded that shock re-acceleration of particles must be taking place along the filaments. This implies a mechanism which is known to operate in young stellar objects as well as extragalactic radio sources, a more detailed account of which will be given elsewhere.
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Fig. 1.— A schematic diagram showing the origin of the relativistic particles when the winds from a single mass-losing stellar bubble as well as the cluster flow collide with the cluster flow and the ISM, respectively.