TURBULENT ORIGIN OF THE GALACTIC CENTER MAGNETIC FIELD: NONTHERMAL RADIO FILAMENTS

Stanislav Boldyrev 1 and Farhad Yusef-Zadeh 2

Received 2005 July 30; accepted 2005 December 12; published 2006 January 19

ABSTRACT

A great deal of study has been conducted over the last 20 years on the origin of the magnetic activity in the Galactic center. One of the most popular hypotheses assumes a milligauss magnetic field with poloidal geometry, pervading the inner few hundred parsecs of the Galactic center region. However, there is growing observational evidence for the large-scale distribution of a much weaker field of $B \lesssim 10 \mu$G in this region. Here we propose that the Galactic center magnetic field originates from turbulent activity, which is known to be extreme in the central hundred parsecs. In this picture, the spatial distribution of the magnetic field energy is highly intermittent, and the regions of strong field have filamentary structure. We propose that the observed nonthermal radio filaments appear in (or, possibly, may be identified with) such strongly magnetized regions. At the same time, the large-scale diffuse magnetic field is weak. Both results of our model can explain the magnetic field measurements of the Galactic center region. In addition, we discuss the role of ionized outflow from stellar clusters in producing the long magnetized filaments perpendicular to the Galactic plane.

Subject headings: Galaxy: center — ISM: general — MHD — turbulence

1. INTRODUCTION

The presence of a magnetic field is ubiquitously inferred in the interstellar medium. Although its origin and large-scale (Galactic scale) structure are still debated, observations suggest that the Galactic field strength is on the order of a few milligauss (e.g., Zweibel & Heiles 1997). Moreover, the fluctuating part of the field is comparable in strength to the large-scale component, and the field is roughly in equipartition with the gas pressure and the cosmic-ray pressure. Less consensus has been reached about the origin, structure, and strength of the magnetic field in the center of the Galaxy (central few hundreds of parsecs). The earliest study of large-scale magnetic activity in this region dates back to the discovery of nonthermal radio filaments more than 20 years ago (Yusef-Zadeh et al. 1984). These filaments are fairly straight, about 10 to 100 pc long, and about a fraction of a parsec wide. The linear polarization of these filaments indicates that they radiate as a consequence of synchrotron emission from energetic, nonthermal particles following the magnetic field lines (the origin of these particles being a separate issue). The rigidity and the linearity of the filaments distributed within the central zone of molecular gas, with high density and velocity dispersion, have been used to make an estimate of the magnetic field. This dynamical argument suggested a milligauss field (Yusef-Zadeh & Morris 1987; Serabyn & Güsten 1991; Morris & Serabyn 1996; Bicknell & Li 2001). In the intervening years, a number of additional filaments have been discovered (see the review by Yusef-Zadeh 2003; Lang et al. 1999; Reich 2003; Nord et al. 2004; LaRosa et al. 2004; Yusef-Zadeh et al. 2004). In early works, nonthermal radio filaments were detected predominantly perpendicular to the Galactic plane. This prompted theories suggesting that a strong magnetic field, on the order of 1 mG, is uniformly pervasive in the Galactic center and relativistic electrons are injected into this preexisting field at some places, thus “lighting up” the corresponding magnetic field lines. One such theory assumed that the magnetic flux was already strong enough in the proto-Galaxy and was then confined to the Galactic disk during its formation. The subsequent matter inflow into the center further concentrated the poloidal flux (see, e.g., Sofue & Fujimoto 1987; Benford 1988; Morris 1994; Chandran et al. 2000). Alternatively, certain local mechanisms have been proposed to explain the production of nonthermal radio filaments (see, e.g., Rosner & Bodo 1996; Shore & LaRosa 1999; Yusef-Zadeh 2003). In one model, the magnetic field is amplified by thermal instability (Rosner & Bodo 1996), whereas in another the filaments are considered to be magnetized wakes produced as the result of an interaction of the molecular clouds with a Galactic center wind (Chevalier 1992; Shore & LaRosa 1999).

The conventional theory that assumes a milligauss magnetic field with poloidal geometry, surrounding the Galactic center, needs to explain not only the origin of $\sim 4 \times 10^{54}$ ergs of energy trapped in the magnetic field within a 100 pc radius, but also the mechanism of anchoring the strong magnetic field lines. Moreover, this theory has recently encountered a number of serious observational challenges. First, more than 80 radio filaments have already been detected, and their directions do not always run perpendicularly to the Galactic plane (e.g., Lang et al. 1999; LaRosa et al. 2004; Nord et al. 2004; Yusef-Zadeh et al. 2004). Second, a number of arguments based on Zeeman and Faraday rotation measurements toward the Galactic center, as well as on estimates of the synchrotron lifetime, suggest that the strength of the pervasive magnetic field should not exceed 100 $\mu$G (Uchida & Güsten 1995; Yusef-Zadeh 2003; LaRosa et al. 2005). Third, the anisotropic property of the scattering medium, which is thought to be seated in the Galactic center region, shows a random orientation of scatter-broadened OH/IR stars in the central 50’ of the Galactic center (van Langevelde et al. 1992; Frail et al. 1994). The combined anisotropy of OH/IR stars and OH (1720 MHz) masers, as well as the anisotropy of the rotation measure of the nonthermal filament G359.1 $-$ 0.54 (Yusef-Zadeh et al. 1997), is inconsistent with a strong poloidal space-filling magnetic field pervading the Galactic center region. Fourth, the recent discovery of X-ray emission from three nonthermal filaments (Lu et al. 2003; Sakano et al. 2003) has suggested that X-ray emission from G359.90 $-$ 0.06 could be produced by inverse Compton scat-
tering (ICS) of far-infrared photons from dust by the relativistic electrons responsible for the radio synchrotron emission (Yusef-Zadeh et al. 2005). The production of X-ray emission from ICS allows an estimate of the magnetic field strength on the order of 0.1 mG within this nonthermal filament. Fifth, sub-millimeter polarization measurements of dust emission from several Galactic center molecular clouds show that the large-scale distribution of the magnetic field follows a toroidal geometry along the Galactic plane (Novak et al. 2000; Chuss et al. 2003). And last, the recent discovery of diffuse nonthermal structure in the Galactic center by LaRosa et al. (2005) imposes even stronger limitations on the large-scale magnetic field strength, suggesting that the pervasive magnetic field in the Galactic center is rather weak, on the order of 10 µG. This is consistent with earlier measurements of the rotation measure distribution of extragalactic radio sources projected toward the Galactic center (Roy 2004) and with observations of the nonthermal filament G359.1−0.2 (Gray et al. 1995), which indicate a magnetic field strength for the Faraday screen ranging between 1 and 10 µG.

In other words, several observations indicate that although the magnetic field in the nonthermal filaments may be strong, it is not representative of the large-scale, pervasive magnetic field in the Galactic center. A theory of the Galactic center is thus in demand that would provide a robust explanation for both the weak pervasive magnetic field and local, randomly oriented, strongly magnetized filamentary structures. In the present Letter, we attempt to propose such a unifying explanation. We suggest that, quite generally, the magnetic structure of the Galactic center can be derived from its strong turbulent activity. We argue that the pervasive magnetic flux in the Galactic center is quite weak but that the magnetic field is significantly amplified locally, so that the regions of strong field have filamentary structures as an inevitable consequence of the magnetic dynamo mechanism associated with such turbulent activity. We then propose that the nonthermal radio filaments are observed in (and might be identified with) such strongly magnetized regions. The physical picture of a strongly turbulent Galactic center is motivated by radio observations of compact sources that indicate heavily scatter-broadened radio sources toward the inner degree of the Galactic center (van Langevelde et al. 1992). The most extreme scattering medium in the Galaxy is argued to be located within the inner few hundred parsecs of the Galactic center (Yusef-Zadeh et al. 1994; Lazio & Cordes 1998). This scattering medium is considered to be denser than in the disk, $n_e \sim 1$ cm$^{-3}$, by 1 to 2 orders of magnitude (Lazio & Cordes 1998).

2. INHOMOGENEOUS MHD TURBULENCE

Magnetohydrodynamic turbulence is generally investigated, both analytically and numerically, in idealized homogeneous and isotropic settings. However, astrophysical turbulence is almost always inhomogeneous and anisotropic. In situations where the outer scale of turbulence (the correlation scale of turbulent fluctuations) is much smaller than the scale of turbulent intensity variation, the approximation of homogeneity works well. However, as we show in the next section, in the Galactic center these two scale lengths are of the same order. In this case, the effect of magnetic field amplification by turbulent motion should be considered in conjunction with another effect—magnetic field expulsion from the region of stronger turbulence. In the present section, we propose a description of magnetic field structure in inhomogeneous turbulence.

As first noted by Batchelor (1950), when fluid viscosity and resistivity are negligible, and if the magnetic field acting back on the fluid is weak, the evolution equation for the magnetic field, $\dot{B} = \nabla \times (\nu \times B)$, formally coincides with the equation for the vorticity, $\omega = \nabla \times v$. When a weak, diffuse magnetic field is amplified by turbulence, it is randomly stretched and folded, so that its magnetic energy distribution becomes spatially intermittent. Analogously to the distribution of vorticity in hydrodynamic turbulence (see, e.g., She et al. 1990; Frisch 1995; Kaneda et al. 2003), the strongest field is concentrated in filamentary structures, where it reaches equipartition with the turbulent energy (e.g., Nordlund et al. 1992). The characteristic rate of field amplification is the turbulent-eddy turnover rate, and the characteristic length of the filamentary structures is the outer scale of turbulence.

If the magnetic field were confined to the turbulent region (as, e.g., in most numerical simulations), the number of filamentary structures would increase until the magnetic field became strong everywhere (see, e.g., Cattaneo 1997). If, however, turbulence is confined to some spatial region but the magnetic field is not, then the so-called diamagnetic effect comes into play. Namely, quite generally, large-scale magnetic flux tends to be expelled from the turbulent region. In other worlds, when the intensity of fluid turbulence varies in space, the large-scale magnetic field is transported in the direction of weaker turbulence (Zel’dovich 1956; Parker 1975; Vainshtein & Kichatinov 1983; Landau et al. 1995). The characteristic time for flux expulsion is the turbulent diffusion time. Denote by $L_0$ the largest scale of turbulence and by $v_0$ the eddy turnover velocity at this scale; then this time is estimated as $\tau_\pi = L_0^2/\eta_\pi$, where $\eta_\pi = l_\pi v_0$ is the turbulent diffusivity. As we discuss in the next section, the size of the turbulent region in the Galactic center is comparable to the outer scale of turbulence or may be bigger by a factor of a few, $L \geq L_0$. We may therefore conjecture that in a steady state, the magnetized filamentary structures have a chance to diffuse out of the turbulent region, so that the magnetic field does not become strong everywhere in the turbulent region. Rather, the strongest field is embedded in magnetic flux tubes.

We propose that these magnetic structures are the places where the Galactic center nonthermal radio filaments appear. In this model, relativistic particles may be pervasive (say, cosmic rays), while the regions of strong magnetic field are spatially intermittent and the average magnetic field is weak. The synchrotron emissivity, which is proportional to $B^{1+\gamma/2}$, where $\gamma$ is the spectral index of the power-law energy spectrum of relativistic particles (Salter & Brown 1988) and $B$ is the component of the magnetic field perpendicular to the line of sight, is enhanced along the filaments as the magnetic field is amplified. For example, in the case of a steep spectrum of relativistic particles measured at high frequencies, with $\gamma \sim 3$ (Yusef-Zadeh et al. 2005; Anantharamaiah et al. 1991; Lang et al. 1999), the synchrotron emission may increase by 2 orders of magnitude with respect to the background emission if the magnetic field is amplified by only a factor of 10, assuming that the cosmic-ray particle density is constant. In the case of a low value of $\gamma \sim 2$, as measured at low frequencies (LaRosa et al. 2000), the synchrotron emissivity could increase only by a factor of 30. Alternatively, however, the relativistic particle density may not be constant. For example, these particles could be injected locally by compact sources that produce relativistic particles (Yusef-Zadeh & Königl 2004). We now apply the
above general arguments to estimate the parameters of the nonthermal radio filaments.

3. MAGNETIC FIELD STRUCTURE IN THE GALACTIC CENTER

We consider the characteristic gas distribution in the Galactic center to consist of four phases: cold, cool, warm, and hot (Oka et al. 2005). The cold phase is a molecular gas whose temperature is $T_{\text{cold}} \sim 70$ K and density is $n_{\text{cold}} > 10^{5}$ cm$^{-3}$. These molecular clouds occupy only a small fraction of space, with the filling factor $f_{\text{cold}} \sim 0.01$. The cool phase consists of atomic hydrogen with temperature $T_{\text{cool}} \sim 250$ K and density $n_{\text{cool}} \sim 10^{2}$ cm$^{-3}$. Its filling factor can be large, $f_{\text{cool}} \sim 0.5-1$. The warm phase is ionized gas, with temperature $T_{\text{warm}} \sim 5 \times 10^{4}$ K, density $n_{\text{warm}} \sim 10^{-2}$ cm$^{-3}$, and filling factor $f_{\text{warm}} \sim 0.5$ based on the scattering measure of the Galactic center sources (Lazio & Cordes 1998). The hot phase of the Galactic center has been modeled to have two plasma components, a soft component with $kT \sim 0.8$ keV and a hard one with $kT \sim 8$ keV (e.g., Munoz et al. 2004; Koyama et al. 1996). The mean electron density of the hot gas is estimated to be $n_{e} \sim 0.3-0.4$ cm$^{-3}$, and the filling factor is $f_{e} \ll 1$ if much of the gas is diffuse and is dominated by cool and warm phases (Koyama et al. 1996).

Considering that all these phases coexist with each other, it is difficult to argue that they are in thermal equilibrium. Rather, observations of molecular and atomic line emission (e.g., Tsuboi et al. 1999; Oka et al. 2005; Geballe et al. 2005) suggest that these phases are turbulent, with a turbulent velocity dispersion on the order of $v_{t} \sim 10-50$ km s$^{-1}$. We therefore believe that it is reasonable to assume that their turbulent energies, rather than thermal energies, are of the same order and that strong turbulence plays an essential role in the Galactic center gasdynamics.

To estimate the outer scale of the turbulence, we need to specify possible mechanisms of turbulence generation. We may first assume that the turbulence is stirred through supernova explosions and take the rate of explosions in the central 50 pc to be about one per 10$^{3}$ yr (Figuer et al. 2004; LaRosa et al. 2005). Assuming that a supernova shell expands with velocity $v_{\text{sh}} \sim 10^{3}$ cm s$^{-1}$, we deduce that the outer scale of turbulence in the Galactic center environment is $l_{o} \sim 30$ pc. [A shell expands uninterrupted by another supernova explosion up to a radius $l_{e}$ during a time $l_{e}/v_{\text{sh}}$.] Another supernova will distort the expanding shell if the condition $l_{e}/(50 \text{ pc}) \sim (v_{\text{sh}}/l_{e}) \times 10^{3} \text{ yr}$ is satisfied, which leads to the above magnitude of $l_{o}$. This value provides a simple, but quite rough, estimate. A more plausible consideration is that the large-scale turbulence is not uniform and isotropic. Stronger turbulence may be produced by massive star formation activity in the Galactic center, which appears to occur predominantly in star clusters. In this picture, turbulence could be driven by strong stellar winds from these young massive clusters. These winds can collide on scales characterized by the distance between mass-losing stars within a cluster or clusters themselves, $\sim 10-20$ pc along the Galactic plane. The winds could also be correlated on much larger scales, $\sim 100$ pc perpendicular to the Galactic plane (where the gas density drops off), driving thermal gas away in this direction.

A number of studies have recently suggested that the high-pressure environment of the Galactic center went through a mini-starburst 10 million years ago (e.g., Bland-Hawthorn & Cohen 2003). In particular, the large-scale $1^\circ \Omega$-shaped lobe structure (Sofue & Handa 1984) shows the largest concentration of nonthermal filaments in the Galactic center region. This large concentration of magnetic filaments appears in the vicinity of the footprints of the large-scale lobe where the bright H II complex of Sgr C (e.g., G359.5-0.0; Yusef-Zadeh et al. 2004; Nord et al. 2004), as well as the radio continuum arc ($\sim 0.2$ pc), is located. We suggest that the presence of the longest and brightest vertical nonthermal filaments is phenomenologically tied to the origin of the $\Omega$-shaped lobe structure. In this picture, the outer scale of the turbulence stretching the field lines is in the direction away from the plane and is identified with the past activity of the collision of the winds and supernovae. In particular, an anisotropic distribution of thermal and nonthermal gas in the direction along and away from the Galactic plane can naturally explain the fact that the longest filaments run predominantly perpendicular to the Galactic plane. In this picture, we speculate that the outer scale of turbulence could be an order of magnitude larger away from the plane than parallel to the plane.

When strong turbulence is switched on in a highly conducting medium permeated by a weak, diffuse magnetic field, the field is amplified by random fluid motion, under the dynamo mechanism (e.g., Kazantsev 1968; Moffatt 1978; Vainshtein & Kichatinov 1983; Kulsrud & Anderson 1992; Schekochihin et al. 2002). As discussed in the previous section, at the initial stage of amplification the strong-field regions have a filamentary morphology (e.g., Nordlund et al. 1992). The magnetic field inside these filamentary structures increases until the Lorentz force is strong enough to prevent further field amplification. This happens in several dynamical, eddy turnover times, $\tau \sim l_{o}/v_{t} \sim 10^{3}-10^{4}$ yr. The balance of the Lorentz force inside a filamentary structure and the surrounding turbulent forces gives the magnetic field inside the structure, $B_{z} \sim 0.1 \mu$G. The length of a filamentary structure cannot exceed the outer scale of turbulence $l_{o}$, since the strongest eddy that can stretch the structure has scale $l_{e}$. The characteristic distance between filamentary structures is also on the order of $l_{o}$. However, shorter and weaker structures are possible; they can appear closer to each other, since they are created by smaller and less energetic eddies.

Assume now that the mean magnetic field in the Galactic center is roughly comparable to that in the rest of the Galaxy, $B_{z} \lesssim 10 \mu$G. The field is amplified by turbulent motion locally. Consider the regions of space where the field is amplified by at least a factor of 10 (i.e., $B_{z} > 0.1$ mG). Such strongly magnetized filamentary structures should be encountered with a rather small probability, that is, they should have a rather small volume filling factor. To illustrate this, one can use the probability density function of magnetic field strength. Since the pervasive field $B_{z}$ is weaker than the value dictated by equipartition with turbulent energy, this function can be obtained from the kinematic dynamo theory. In the well-investigated homogeneous and isotropic case, this theory predicts that such a function is lognormal, $P(B) dB = (C/\pi)^{1/2} \exp \left[-C \times \log^{2}(B/B_{0})/\sigma_{0}^{2}\right] dB/B_{0}$, where $C$ is some coefficient $C \sim l_{o}/(v_{t}, \lambda)$.

This prediction is in good agreement with numerical simulations, (e.g., Cattaneo 1996; Schekochihin et al. 2004). If the field amplification time is approximately the eddy turnover time, then $C \sim 1$ (this crude estimate suffices for our illustrative purposes). Using this formula one can estimate that the probability (or the volume filling factor) of filaments with $B > 10 B_{0}$ is quite small, $f \sim 10^{-4}$. Assuming that the number of the strongest filaments per outer scale of turbulence is of order 1, and the length of such filaments is $l_{f}$, we estimate $l_{f} \sim f l_{o}^{2}$. We then find the width of the filaments as $l_{f} \sim 0.01 l_{o}$. This rough estimate is in agreement with observations (Yusef-Zadeh et al. 2004).
Interestingly, the theory of MHD turbulence may also allow us to explain another peculiar and puzzling property of nonthermal radio filaments. Quite often, these filaments are observed to be split into multiple filaments running parallel to each other. In fact, there are more such multipllets than single, isolated filaments (see, e.g., Lang et al. 1999; Yusef-Zadeh et al. 2004). We may speculate that such multiple filamentary structure could be identified with a folded structure of the magnetic field inside strongly magnetized regions, as is consistently observed in numerical experiments (see, e.g., Cattaneo 1996; Schekochihin et al. 2004).

In conclusion, we have proposed a new interpretation of the magnetic field structure in the Galactic center region, where numerous unique nonthermal filaments have been detected. The main idea of our approach is that the magnetic field distribution in the Galactic center environment is inherently and universally related to the strong turbulent activity observed in this region. Such turbulence locally amplifies the diffuse background magnetic field and concentrates the strong field into thin and elongated, randomly oriented filamentary structures. The distribution of the longest filamentary structures can be anisotropic, however, because of the anisotropic character of the large-scale turbulence driven by collisions of stellar winds. The nonthermal radio filaments originate inside such structures or may possibly be identified with these structures themselves. The proposed turbulent origin of nonthermal filaments in the Galactic center distinguishes our approach from other theories in that our model is mainly driven by observations, it is based on quite general results of the theory of turbulence, and it resorts to a minimum of nonstandard assumptions.

We are grateful to Samuel Vainshtein and Ellen Zweibel for useful discussions. The work of S. B. was supported by the NSF Center for Magnetic Self-Organization in Laboratory and Astrophysical Plasmas at the University of Chicago.

REFERENCES

Anantharamaiah, K. R., Pedlar, A., Ekers, R. D., & Goss, W. M. 1991, MNRAS, 249, 262
Batchelor, G. K. 1950, Proc. R. Soc. London A, 201, 405
Benford, G. 1988, ApJ, 333, 735
Bicknell, G. V., & Li, J. 2001, ApJ, 548, L69
Bland-Hawthorn, J., & Cohen, M. 2003, ApJ, 582, 246
Cattaneo, F. 1997, in SCORe '96: Solar Convection and Oscillations and Their Relationship, ed. F. P. Piparo, J. Christensen-Dalsgaard, & C. S. Rosenthal (Dordrecht: Kluwer), 201
Chandran, B. D. G., Cowley, S. C., & Morris, M. 2000, ApJ, 528, 723
Chevalier, R. 1992, ApJ, 397, L39
Chuss, D. T., Davidson, J. L., Dotson, C. D., Hildebrand, R. H., Novak, G., & Vaillancourt, J. E. 2003, ApJ, 599, 1116
Figer, D. F., Rich, R. M., Kim, S. M., Morris, M., & Serabyn, E. 2004, ApJ, 601, 591
Frail, D. A., Diamond, P. J., Cordes, J. M., & van Langevelde, H. J. 1994, ApJ, 427, L43
Frisch, U. 1995, Turbulence (Cambridge: Cambridge Univ. Press)
Geballe, T. R., Oka, T., Goto, M., Usuda, T., McCull, B. J. 2005, BAAS, 206, No. 37.01
Gray, A. D., Nicholls, J., Ekers, R. D., & Crum, L. E. 1995, ApJ, 448, 164
Kaneda, Y., Ishihara, T., Yokokawa, M., & Itakura, K., & Uno, A. 2003, Phys. Fluids, 15, L21
Kazantsev, A. P. 1968, Soviet Phys.–JETP, 26, 1031
Koyama, K., Maeda, Y., Sonobe, T., Tachisaka, T., Tanaka, Y., & Yamauchi, S. 1996, PASJ, 48, 249
Kulsrud, R. M., & Anderson, S. W. 1992, ApJ, 396, 606
Landau, L. D., Lifshitz, E. M., & Pitaevskii, L. P. 1995, Electrodynamics of Continuous Media (2nd rev. ed.; Oxford: Butterworth-Heinemann)
Lang, C. C., Anantharamaiah, K. R., Kassim, N. E., & Lazio, T. J. W. 1999, ApJ, 521, L41
LaRosa, T. N., Brogan, C. L., Shore, S. N., Lazio, T. J. W., Kassim, N. E., & Nord, M. E. 2005, ApJ, 626, L23
LaRosa, T. N., Kassim, T. N., Lazio, T. J. W., & Hyman, S. T. 2000, ApJ, 119, 207 (erratum 119, 3145)
LaRosa, T. N., Nord, M. E., Lazio, T. J. W., & Kassim, N. E. 2004, ApJ, 607, 302
Lazio, T. J. W., & Cordes, J. 1998, ApJ, 505, 715
Lu, F. J., Wang, Q. D., & Lang, C. C. 2003, AJ, 126, 319
Moffatt, H. K. 1978, Magnetic Field Generation in Electrically Conducting Fluids (Cambridge: Cambridge Univ. Press)
Morris, M. 1994, in The Nuclei of Normal Galaxies, ed. R. Genzel & A. I. Harris (NATO ASI Ser. C, 445) (Dordrecht: Kluwer), 185
Morris, M., & Serabyn, E. 1996, ARA&A, 34, 645
Muno, M. P., et al. 2004, ApJ, 613, 326
Nord, M. E., Lazio, T. J. W., Kassim, N. E., Hyman, S. D., LaRosa, T. N., Brogan, C. L., & Duric, N. 2004, ApJ, 128, 1646
Nordlund, Å., Brandenburg, A., Jennings, R. L., Rieutord, M., Ruokolainen, J., Stein, R. F., & Tuominen, I. 1992, ApJ, 392, 647
Novak, G., Dotson, J. L., Dowell, C. D., Hildebrand, R. H., Renberger, T., & Schleuning, D. A. 2000, ApJ, 529, 241
Oka, T., Gabele, T. R., Goto, M., Usuda, T., & McCall, B. J. 2005, ApJ, 632, 882
Parker, E. N. 1975, ApJ, 202, 523
Reich, W. 2003, A&A, 401, 1023
Rosner, R., & Bodo, G. 1996, ApJ, 470, L49
Roy, S. 2004, Bull. Astron. Soc. India, 32, 205
Sakano, M., Warwick, R. S., Decourcheille, A., & Predehl, P. 2003, MNRAS, 340, 747
Salter, C. J., & Brown, R. L. 1988, in Galactic and Extragalactic Radio Astronomy, ed. G. L. Verschuur & K. I. Kellermann (Berlin: Springer), 1
Schekochihin, A. A., Boldyrev, S. A., & Kulsrud, R. M. 2002, ApJ, 567, 828
Schekochihin, A. A., Cowley, S. C., Taylor, S. F., Maron, J. L., & McWilliams, J. C. 2004, ApJ, 612, 276
Serabyn, E., & Güsten, R. 1991, A&A, 242, 376
She, Z.-S., Jackson, E., & Orszag, S. A. 1990, Nature, 344, 226
Shore, S. N., & LaRosa, T. N. 1999, ApJ, 521, 587
Sofue, Y., & Fujimoto, M. 1987, PASJ, 39, 843
Sofue, Y., & Handa, T. 1984, Nature, 310, 545
Tsuboi, M., Handa, T., & Ukitake, Y. 1990, ApJ, 129, 1
Uchida, K. I., & Güsten, R. 1995, A&A, 298, 473
Vainshtein, S. I., & Kichatinov, L. L. 1983, Geophys. Astrophys. Fluid Dyn., 24, 273
van Langevelde, H. J., Fraij, D. A., Cordes, J. M., & Diamond, P. J. 1992, ApJ, 396, 686
Yusef-Zadeh, F. 2003, ApJ, 598, 325
Yusef-Zadeh, F., Cotton, W., Wardle, M., Melia, F., & Roberts, D. A. 1994, ApJ, 434, L63
Yusef-Zadeh, F., Hewitt, J. W., & Cotton, W. 2004, ApJ, 574, 521
Yusef-Zadeh, F., & Königl, A. 2004, in ASP Conf. Ser. 322, Formation and Evolution of Massive Young Star Clusters, ed. H. J. G. L. M. Lamers, L. J. Smith, & A. Nota (San Francisco: ASP), 201
Yusef-Zadeh, F., & Morris, M. 1987, ApJ, 320, 545
Yusef-Zadeh, F., & Zeldovich, Ya. B. 1956, Zh. Eksp. Teor. Fiz., 31, 154
Zweibel, E. G., & Heiles, C. 1997, Nature, 385, 131