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The Strength and Structure of the Galactic Center Magnetic Field

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Abstract. This paper summarizes recently obtained, strong evidence for a weak global field in the Galactic center (GC): the existence of a large-scale region of diffuse, low-frequency, non-thermal emission coincident with the central molecular zone. The overall energetics of this emission, considered along with constraints on GC cosmic ray energy density and diffusion, indicate clearly that the magnetic field pervading this region is $\sim 10\ \mu$G. For completeness, additional points on the orientation of the GC nonthermal filaments, rotation measures of extragalactic sources seen through the GC, and comparison with other normal spiral galaxies are also reviewed.

1. Introduction

Many physical processes in the Galactic center (GC) region depend on the characteristics of the magnetic field. It controls the lifetimes of high energy electrons as well as the energization and transport of cosmic rays. Magnetic fields also affect, for instance, the accretion of ambient gas onto the central engine, star formation, and the dynamics of the local interstellar medium. At present there no consensus on the strength and structure of the magnetic field. The controversey centers on whether there is a strong (of order 1 mG) globally organized magnetic field ([1], [2]) or a weak (of order 10 μG) global field with strong enhancements occurring only in localized regions ([3]; [4]; [5]).

2. Diffuse Non-thermal Source

Recent observations with the Very Large Array (VLA) at 4-meter wavelength (74 MHz) and with the Green Bank Telescope (GBT) at 1-meter wavelength (330 MHz) have revealed a large region ($6^\circ \times 2^\circ$) of diffuse nonthermal emission ([3]; [6]). Assuming equipartition, a minimum energy analysis using the formulation outlined in [7], yields a total energy of 4×10^{51} ergs and a magnetic field of 15 μG in the inner $1.5^\circ \times 0.5^\circ$ of this region. It is within this central region that the GC nonthermal filaments (NTFs) are found. These minimum energy values were found assuming that the ratio of the energy per proton to that of the electrons, is $\mathbf{K} \sim 100$ ([7]).

The corresponding particle energy density is 5.6 eV cm^{-3}. The energy required to power this diffuse non-thermal source is of order 1 supernova (SN) every 10^5 yr, consistent with the rate required to generate the observed soft X-ray emission in this region ([8]). The rate of massive star formation in the inner 50 pc is estimated to exceed that in the disk by a factor of 250 ([9]) and can supply the required production rate for SNe. Thus in [3], we proposed that the diffuse radio source reflects the collective synchrotron emission from residual relativistic electrons of the cumulative SN activity in the GC.

The actual energy density within this diffuse emission region depends upon the estimated radio flux densities at the two wavelengths and the spectral index between them. At 4-meter wavelength, the flux density estimate may be affected by thermal absorption. We obtain an *upper* limit for the spectral index of $\alpha = -0.7$ (for a radio flux density $S \propto \nu^{\alpha}$). This steep spectral index, characteristic of older (aged) electrons, is similar to that of the long-wavelength synchrotron background ([10]) commonly assumed to be produced by electrons originally accelerated in supernova remnant shocks and subsequently diffusing through the Galaxy.

This scenario, however, assumes equipartition, an assumption that would not be justified if these electrons were accelerated in a single energetic event. Let us assume this is the case and that they subsequently propagate in a 1 mG magnetic field. The observed synchrotron emission (approximately 1000 Jy beam^{-1} at 1-meter wavelength, observed with a $39'$ beam at the GBT) would be accounted for by an electron energy density, with energies of order 1 MeV, of 0.04 eV cm^{-3}. Extrapolating to the GeV range, for those particles relevant to the meter-wavelength emission detected, using the observed spectrum gives an electron energy density in the 1 GeV range of only 7×10^{-3} eV cm^{-3}, more than an order of magnitude below the value in the local interstellar medium (0.2 eV cm^{-3}, [11]).

There is no direct measurement of the electron energy density in the GC in the MeV to GeV range. An indirect measure can be obtained from diffuse γ-ray emission. Diffuse Galactic γ-ray emission is produced by the interaction of high-energy cosmic rays with interstellar material, as well as a relatively uncertain contribution from unresolved compact sources (e.g., pulsars, X-ray binaries). Thus, γ-ray emission can be expected to peak where the cosmic ray density is high, the gas density is high, or there is a high concentration of compact objects. A recent re-analysis of all available EGRET data toward the GC ([12]) suggests that the diffuse γ-ray emission is consistent with a cosmic-ray density at least as high as the local value, with a possible additional contribution from the Radio Arc or compact objects.

Although there is a strong GC wind that can advect cosmic rays out of the region at a rate perhaps 100 times faster than in the local disk, the injection rate from SN-generated cosmic rays is also at least 100 times greater in the GC. The near balance between these competing effects yields a particle energy density consistent with the local value. Moreover, a diffuse *TeV* γ-ray emission region has been discovered recently in the central molecular zone ([13]; [14]). While this is not the energy range relevant for synchrotron emission, extrapolation of their results to lower energies also implies an electron energy density comparable to the local value. The upcoming GLAST[1] γ-ray mission will be able to measure diffuse emission at energies around 1 GeV ([14]) and should be able to probe the relevant electron energies directly.

A second indirect constraint on the GC cosmic ray energy density comes from observations of the H_3^+ ion ([15]; [16]). The formation of H_3^+ is thought to be powered by cosmic ray ionization and observed H_3^+ column densities can be used to estimate ζ, the cosmic ray primary ionization rate. For GC clouds, [14] estimate $\zeta \sim 2\text{–}7 \times 10^{-15}$ s^{-1}, substantially higher than the local value, 3×10^{-17} s^{-1} ([17]). Although cloud dynamics may influence these analyses ([18]), again they indicating that the electron energy density within the GC is at least as high as the local value and potentially much higher.

Finally, low energy cosmic rays (tens of keV to MeV) also may generate the X-ray emission

[1] http://www-glast.standford.edu/

from molecular clouds such as Sgr B2. While it was first thought the X-ray emission from these clouds was florescence from an X-ray event associated with the central object ([19]), it is now thought that ionization by low energy cosmic rays can naturally generate this emission. Collectively these results are incompatible with an anomalously low GC cosmic ray energy density.

The diffuse non-thermal source extends about 400 pc on either side of the GC. Assuming that the bulk of high energy electrons responsible for this emission is generated in the inner 50 to 100 pc, they must diffuse at least 300 pc. A number of processes govern the diffusion of high energy particles in the ISM: magnetohydrodynamic (MHD) turbulence in the background medium, self-generated waves, and stochastic magnetic field ([20]). For particles with GeV energies, it is often assumed that scattering from self-generated waves (SGW) (and the resulting pitch angle scattering) is the primary mechanism, and, if there are tangled fields or a high level of background waves, then the diffusion will be even slower. Thus the SGW-dominated diffusion provides a lower limit for the diffusion time. The diffusion coefficient scales as $D_\theta \equiv \langle(\Delta\theta)^2\rangle/\Delta t \propto \Omega(\delta B/B)^2$, where Ω is the electron gyrofrequency in the background magnetic field B and the waves have amplitude δB (e.g., [21]), corresponding to a spatial diffusion coefficient $D_{\rm sp} = c^2/D_\theta$. The observed isotropy of cosmic rays indicates that $\delta B/B \sim 10^{-4}$. Using this value and a magnetic field of 15 μG, the time for a GeV electron to diffuse 300 pc is $\sim 3 \times 10^4$ yr, considerably less than the synchrotron lifetime of 10^7 yr in this field. However, in a 1 mG field, the time required would be $\sim 3 \times 10^6$ yr, orders of magnitude longer than the radiative lifetime of the electrons in such a strong field. The spatial diffusion is faster in the lower field since it takes more time to turn a particle (the rigidity is higher) resulting in a longer mean free path.

In summary, we conclude that the large-scale magnetic field in the GC region is weak, ~ 10 μG. We turn now to assessing the consistency of this conclusion with other evidence taken as indicators of strong fields such as the NTFs and the recently discovered, infrared double helix nebula ([22]).

3. Topology of the NTFs

Prior to the observation of the diffuse nonthermal source, the NTFs (Figure 1; for reviews see [1]; [2]) were used to infer both the strength and topology of the GC magnetic field. More recently, with the discovery of the diffuse nonthermal source and additional NTFs, at issue is whether these are locally generated structures or simply flux tubes that are part of a global field. Rotation measures studies of the NTFs indicate that their magnetic fields are aligned along the filaments (e.g., [23]; [24]). An estimate for the magnetic field strength is inferred from their regidity in the presence of large turbulent pressures from the surrounding gas. Equating the ram pressure with the internal magnetic field pressure gives field strengths of order 1 mG ([25]). To date, a dozen isolated NTFs—as well as a dozen or so bundled NTFs in the Radio Arc—have been identified unambiguously with polarization observations ([2]). There are, however, many tens of additional filamentary candidates that have been discovered with wide-field imaging ([26]; [27]). Their orientations do not appear to be random: most are more or less perpendicular to the Galactic Plane. However, two recently confirmed NTFs lie at large angles with the plane and an explanation of their unexpected orientation is central for understanding the GC magnetic field.

Randomly oriented NTFs were revealed following the development of improved techniques for wide-field, long-wavelength imaging ([28]; [29]; [30]). Earlier, ([31]) had proposed that the perpendicular orientation could be explained by a global, dipolar field centered on the GC. In this scenario the NTFs are interpreted as the flux tubes of a global field that are fortuitously visible only because high energy electrons are locally accelerated. A pervasive 1 mG field was invoked to confine the NTFs and prevent them from expanding rapidly on the Alfvén timescale, since the internal pressure corresponding to a localized field would exceed the ambient thermal pressure

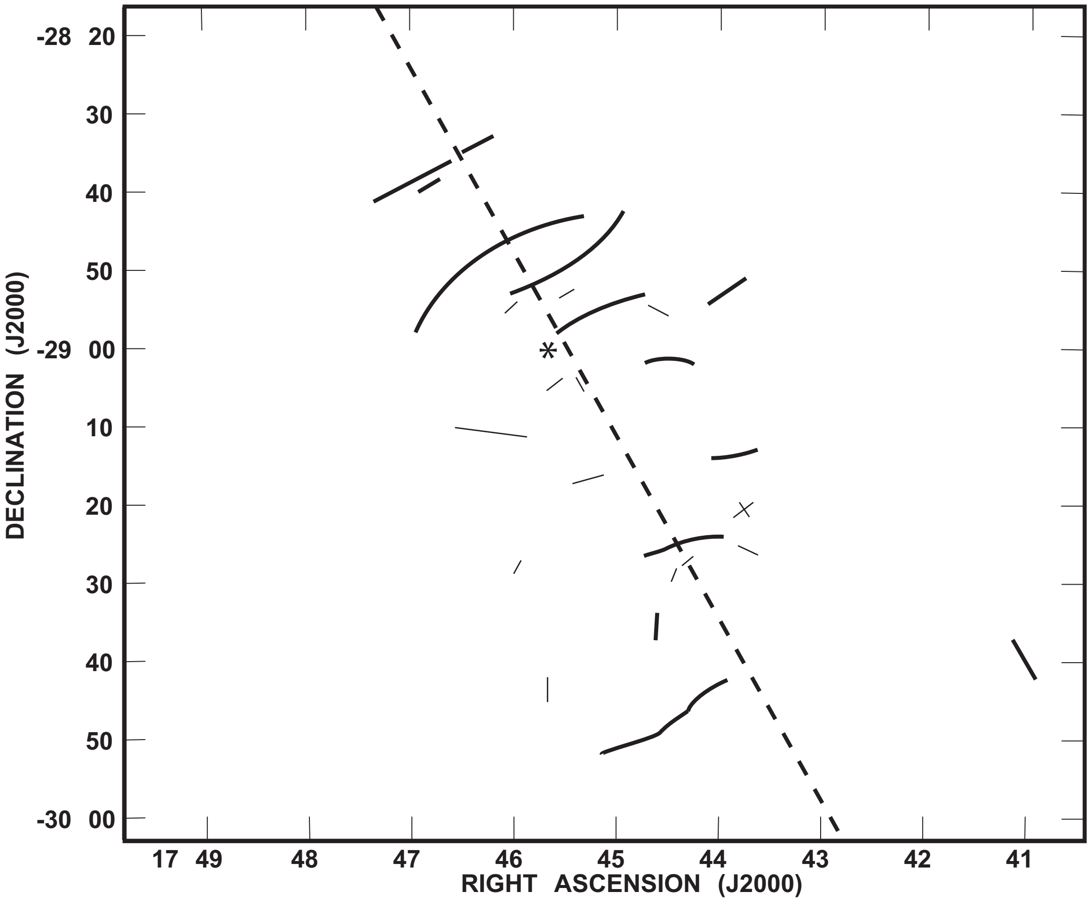

Figure 1. A schematic of the 1-meter wavelength VLA image from [2]). The bold lines depict the confirmed NTFs and the thin lines are the candidates. The Galactic plane is shown as the dashed line.

by orders of magnitude. However, the existence of oblique NTFs contradicts this interpretation. For example, NTF 359.32−0.16 is only 15 pc (in projection) from the Sgr C NTF, and it is not possible to satisfy $\nabla \cdot \mathbf{B} = 0$ if both are part of the same global field. Polarization observations of additional oblique NTF candidates (G359.43+0.13) with the Australia Telescope Compact Array (ATCA) telescope are underway. If confirmed as further examples of oblique NTFs, they would present additional challenges for the global field paradigm. It may be possible to explain them within a global model by asserting that they are a "local" phenomenon generated by a different process than is responsible the longer perpendicular NTFs. However, the surface brightness of the oblique NTFs is generally only a factor of 4 lower than the larger filaments and small changes in the field strength, the particle density or both can explain this difference easily. Aside from their lengths, these objects exhibit the same phenomenology and it seems contrived to propose they are a separate class of NTFs.

Moreover, a pervasive magnetic field is not required to explain the origin of the NTFs. Several dynamical mechanisms have already been suggested. ([32]) suggested the NTFs are (cometary-like) magnetic wakes generated through the interaction of molecular clouds with the GC wind, and are thus necessarily confined laterally by the ram pressure of the strong GC wind. Another attractive idea is that of ([4]) who propose the NTFs are part of a cascade of flux ropes generated by a turbulent dynamo. It is interesting to note that this process may provide the seed flux ropes for the cometary wake model. In both scenarios, the strong magnetic fields within the NTFs are generated locally and do not require a global field.

4. Discussion & Conclusions

Recently, 8-μm *Spitzer* observations of a helical structure some 300 pc from Sgr A have been interpreted as a large-scale torsional Alfven wave ([22]). The estimate of the magnetic field strength in this structure is of order 100 μG. However, there is no direct evidence that this structure is generated magnetically. It also may be interpreted as a dynamical structure formed through a hydrodynamic instability (e.g., the Kelvin-Helmholtz instability). This explanation is especially attractive given its association with the Ω lobe, thought to be part of a large-scale outflow from the GC (e.g., [33]). For instance, a helical-like structure—the Honeycomb Nebula—has been observed in the vicinity of the 30 Dor star-forming region of the Large Magellanic Cloud ([34]; [35]). The structure has a scale of approximately 30 pc, and ([36]) have proposed that it is produced by the blast wave from a younger SN interacting with an older supernova shell that has undergone a Rayleigh-Taylor instability. In this context, additional multiwavelength observations of the Double Helix nebula will be required to confirm whether it is a magnetic or dynamic feature. It is likely that many, if not all, of these processes are operating somewhere at some time in the GC region and are also relevant to other active star forming regions.

Other important observations that constrain the GC magnetic field are the infrared observations of dust polarization ([37]) and rotation measure studies ([38]). The dust polarization traces the magnetic field in the dense molecular gas and reveals clearly a toroidal field in those regions. The relationship between this toroidal field and that in the ionized medium is not clear and requires further theoretical study. ([38]) observed a number of extragalactic sources through the GC region and found that the rotation measures (RMs) towards these sources was significantly smaller than the RMs toward the NTFs ($\sim$ 500 rad m^{-2} compared to $\sim$ 5000 rad m^{-2}). They infer that the mean global field in the GC region must be less than 50 μG. Lastly, there is no evidence for strong magnetic fields in the nuclear regions of other normal spiral galaxies. ([39]) suggest that strong starbursts may have magnetic fields that exceed minimum energy estimates considerably, but, for more normal spiral galaxies, the magnetic field strength appears to scale with the observed surface gas densities, indicating magnetic pressures comparable to the hydrostatic pressures. Since a weak field picture emerges from a number of different lines of evidence, we recommend that both a weak magnetic field value ($\sim$ 10 μG) and a strong field value ($\sim$ 1 mG) be used when making estimates for physical processes and parameters in the GC.

We end with the observation that whatever is happening in the central star forming region of our Galaxy is a pale shadow of the activity seen in starburst systems but likely represents many of the same phenomena. Thus, future work could include assessing the extent to which insights from the GC, especially related to the organization and strength of the magnetic field and the cosmic ray distribution, can be scaled up to the several orders of magnitude greater rates of star formation seen in such systems.

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