8. Magnetic and High-Energy Phenomena

MAGNETIC PHENOMENA IN GALACTIC NUCLEI

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Abstract. The magnetic environment of the Galactic nucleus contrasts sharply with that of the Galactic disk. The inner few hundred parsecs of our Galaxy appear to be dominated by a strong (~milligauss) and uniform dipole field which dominates the pressure within the central intercloud medium. An attractive hypothesis for the origin of the central vertical field is that it results from the concentration of protogalactic field by radial inflow of gas throughout the Galaxy's lifetime. The predominant orientation of the magnetic field within dense molecular clouds is parallel to the galactic plane, which can be understood in terms of the strong tidal shear to which these clouds are subjected . The contrasting geometries of the cloud and intercloud fields allow for magnetic field line reconnection at cloud surfaces, which, under the right circumstances, could produce the relativistic electrons which delineate the nonthermal radio filaments near the Galactic center with their synchrotron emission. The characteristics of the Galactic center "magnetosphere" should be generalizable to all gas-rich spiral galaxies. Inadequate spatial resolution currently prevents us from exploring magnetic fields in other galactic nuclei to the same depth as in the Galactic center, but existing evidence is consistent with similar magnetic geometries elsewhere.

1. Magnetic Field Probes

The five different ways in which the magnetic field near the center of our Galaxy and other galaxies has been studied are summarized in Table 1. The first three involve observations of intrinsically polarized, nonthermal radio continuum emission, the fourth is classical Zeeman studies of radiofrequency line emission, and the fifth is an infrared/submillimeter probe: mea-

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surement of the polarization of thermal emission from magnetically aligned dust grains.

TABLE 1. Magnetic Field Probes

Method	field strength information?	field component
radio continuum:		
morphology	partial	plane of sky
polarization angle	no	plane of sky
Faraday rotation measure	partial	line of sight
radio lines (OH, HI, CN, etc.):		
Zeeman effect	yes	line of sight
far-IR & sub-mm continuum:		
polarization of dust emission	partial	plane of sky

Morphology: The Nonthermal Filaments (NTF's). Among the most striking features evident in images of radio continuum emission of the Galactic center are thin filamentary structures on scales of several tens of parsecs. They occur both in isolation and in bundles of parallel strands. About 9 such systems are known (*c.f.*, Morris 1996). Their strong polarization reveals their nonthermal character, presumably owed to synchrotron emission. Their continuous filamentary nature is ascribed to magnetic confinement of streaming, relativistic particles within a narrow flux tube.

Orientation of the Intrinsic Polarization Vector. Independent of the orientation of the NTF's, the direction of the magnetic field lines within the filaments is revealed by the orientation of the intrinsic polarization vectors, because the dominant E-vector of polarized synchrotron emission is oriented perpendicular to the magnetic field lines. Obtaining the intrinsic polarization vectors requires that the measured polarization be corrected for Faraday rotation by the intervening medium. Not surprisingly, the magnetic field orientation inferred in this way agrees with the presumption that the filaments delineate the magnetic field (Tsuboi *et al.* 1986; Yusef-Zadeh *et al.* 1997; Lang & Morris, this volume). In other galaxies, where filaments have not yet been identified, polarization vector orientations have been the best way of inferring the magnetic field geometry.

Faraday Rotation. Since the rotation measure is proportional to the line-of-sight integral of the product of electron density and line-of-sight magnetic field, it probes the field in the medium lying in the foreground of polarized sources. In general, the magnetic structure of the Faraday-rotating foreground medium is complex, but in some cases, it shows filamentary structure of its own (*i.e.*, Inoue *et al.* 1989), or it can be associated with the polarized source, and thereby give useful constraints on the local conditions there.

Zeeman Measures. While Zeeman measures are, in principle, the best way to measure line-of-sight magnetic field strengths, their application to OH and HI in the Galactic center has so far produced only a few tantalyzing positive results (Killeen *et al.* 1992; Plante *et al.* 1995), yielding strengths of a few milliGauss in a few locations within the circumnuclear disk. Further away from the center, Uchida & Güsten (1995) found only upper limits of a few tenths mG on line-of-sight fields measured with a 10-arcminute beam. Their results can perhaps be understood in terms of cancellations of the differential circular polarizations along the line of sight and within the large beam. Yusef-Zadeh *et al.* (1996) have identified seven compact sources of 1720 MHz *maser* emission within the Sgr A complex, and have used Zeeman measurements to infer fields of 2 - 4 mG. No Zeeman measures have yet been successfully carried out toward other Galactic nuclei.

Polarization of Thermal Far-Infrared and Submillimeter Continuum Emission from Magnetically Aligned Dust Grains. Almost any magnetic alignment mechanism leads to the alignment of the rotational axes of dust grains with the magnetic field, whether the mechanism operates by direct magnetic torquing of the dust grains (the classical Davis-Greenstein mechanism, and its many modern variations; *e.g.*, Hildebrand 1988; Roberge 1996; Lazarian 1996) or via an intermediary such as streaming ions set in motion by moving magnetic field lines (Lazarian 1994; Roberge *et al.* 1995). As a result, the mean projection of the long axis of the grains, and thus the dominant E-vector of thermal grain emission, is expected to be perpendicular to the magnetic field lines. (Note that, in any localized source of polarized emission, one must be sensitive to the possibility that non-magnetic alignment mechanisms such as radiative alignment or alignment by Gold streaming be operating, although these mechanisms are so far not in evidence.) Far-IR polarization measurements made in the Galactic center have yielded up to ~10% polarization, which is about the limit of what might be expected from grain alignment processes (Hildebrand & Dragovan 1995). Submillimeter polarization measurements should be the mainstay of this technique in the next several years (Novak, this volume). So far, polarimetry of thermal dust emission has been used only for studies of our Galaxy, but the extension of this technique to other galaxies is only a matter of time.

2. The Magnetic Field in the Intercloud Medium

The NTF's supply the best information we have on the magnetic field in the intercloud medium (ICM). However, they sample the field only at privileged locations, where relativistic particles have somehow been generated and are illuminating the local flux tubes with their synchrotron emission. The morphology of the NTF's carries a great deal of information, however; we see that they are usually, if not always, interacting with molecular clouds, and yet they suffer only minor distortions, at most, from these interactions, indicating a substantial magnetic rigidity (*e.g.,* Morris & Yusef-Zadeh 1989; Tsuboi *et al.* 1997; Staguhn 1997). One can therefore estimate the magnetic field strength by equating the magnetic pressure with either the turbulent pressure within clouds (obtained from their internal velocity dispersion of $\sim$15 km s^{-1} and their typical densities of 10^4 cm^{-3}) or with the ram pressure of the clouds assuming a typical intracloud velocity dispersion of 10 - 20 km s^{-1}. In this way, one finds typical magnetic field strengths in the NTF's of a few milligauss.

While such a strong field might be in pressure balance at its interface with molecular clouds, there is no known confinement mechanism in the ICM which can compete with the pressure of a milligauss magnetic field. The pressures in the Galactic center are 2 to 3 orders of magnitude higher than those in the Galactic disk (Spergel & Blitz 1992), but even the hot plasma occupying the volume overlying the central molecular zone (CMZ) in which the NTF's are found (Koyama *et al.* 1996) falls short by a few orders of magnitude of being able to confine the NTF's. Therefore, they are either transient features, expanding at the very high Alfvén speeds of the ICM ($\sim 10^3$ km s^{-1}, giving an expansion time scale of 300 yr, barely enough to form them even if the formation process propagates along their length at lightspeed), or the magnetic field is itself of roughly uniform strength throughout the central $\sim$100 pc region where the NTF's are found. The latter seems the only realistic alternative.

The NTF's are all oriented roughly perpendicular to the Galactic plane, indicating that the global field structure is dipolar. They show some curvature, perhaps owed to divergence above and below the plane, but they are undistorted by the galactic gas layer itself. Because the NTF's fade out about 30 or 40 pc from the plane, they do not reveal the full vertical extent of the dipole field. The polarized plume of emission from the radio Arc indicates a vertical extent of at least ±150 pc (Seiradakis *et al.* 1985; Tsuboi *et al.* 1986). The horizontal extent of the inferred dipole field is comparable to the size of the CMZ toward negative longitude ($\sim$140 pc), but at positive longitude, where the CMZ extends to as much as 230 pc, the NTF's are so far seen only out to projected distances of $\sim$40 pc (Yusef-Zadeh *et al.* 1990). It is tempting to imagine that the central dipole field is coextensive with the CMZ, and that the implied ring current circulates near the outer edge of the CMZ.

The strong, central dipole field in our Galaxy can have a significant dynamical effect on clouds orbiting through it. If the field is not participating in the general rotation of the Galaxy, then the time scale for magnetic viscosity to extract the angular momentum of a cloud, and therefore cause it to migrate inward, can be relatively short ($\sim 10^8$ years; Morris & Serabyn 1996). Also, the hot coronal plasma at the Galactic center, evidenced by observations of diffuse x-rays (Koyama *et al.* 1996 or 7) and which has approximately the same scale as the CMZ, should be confined and, if it lies at the base of a Galactic wind, directed by the dipole magnetic field.

3. Magnetic Fields in Clouds

Polarized thermal infrared emission has been the most revealing probe of the magnetic field within clouds near the Galactic center. The first such study, carried out at 10 μm, was of the Northern Arm of Sgr A West, a linear, ionized stream apparently being tidally drawn toward the galactic center (most recently discussed by Aitken *et al.* 1996). Aitken *et al.* (1991) showed that the magnetic field is aligned along the length of this structure, and they suggested that this geometry has resulted from the inevitable tidal shear that this cloud has undergone, regardless of the initial field geometry.

Polarized 100 μm emission from the larger-scale (1 - 10 pc) circumnuclear disk shows that the dominant field direction lies within the plane of that disk. Hildebrand *et al.* (1993) discuss how a combination of differential rotation and radial motions within the disk can account for the well-ordered distribution of polarization vectors. In another cloud near the Galactic center, the cloud underlying the thermal, arched filaments of the Radio Arc (Serabyn & Güsten 1987; Morris & Yusef-Zadeh 1989), the magnetic field is found to be highly ordered on 1 - 15 pc scales, and to be oriented along the ionized, thermal filaments at the cloud surface (Morris *et al.* 1995, 1998). These filaments are largely oriented parallel to the Galactic plane, though their curvature follows the ridge of the cloud, and the filaments and implied field direction subtend about a 45° angle with respect to the galactic plane at their southern extremity.

The Sgr B2 cloud (discussed by Novak, in these proceedings) is a special case because of its large far-IR opacity. This is the only cloud known so far in which the orientation of the polarization vectors is affected by absorption within the cloud itself. When correction is made for absorption, the orientation of the magnetic field is rather uniform, and oriented at about 50° with respect to the Galactic plane. The cloud underlying the Sickle (G0.18-0.04) also shows a striking uniformity of magnetic field direction (figure 1, from Morris *et al.* 1998), and in this case, the implied field is parallel to the Galactic plane.

The generalities to be drawn from extant polarization observations of Galactic center clouds are: 1) within a single cloud, the magnetic field

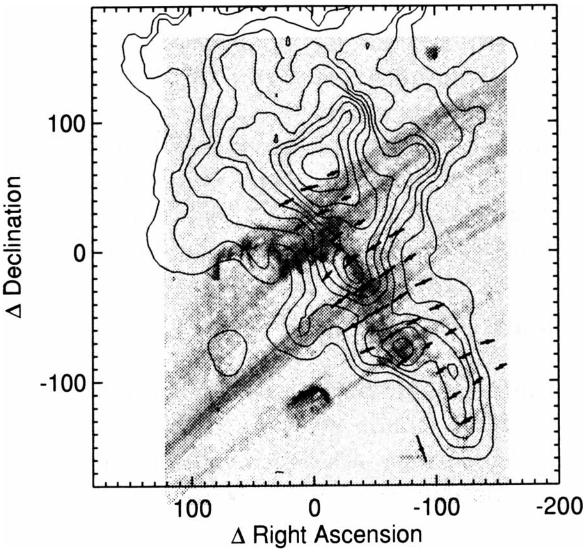

Figure 1. Figure 1. The HII region G0.18-0.04 and radio filaments of the Arc (gray-scale, representing 6-cm continuum intensity) and contours of CS J=3-2 line emission (from Serabyn & Güsten 1991). The 60-μm polarization vectors are superimposed, with length of the line segment proportional to % polarization (for reference, the southernmost, non-conforming point at -88", -153" has 12% polarization)

direction sampled with a 1 or 2-pc beam is typically quite uniform, 2) the % polarizations of far-IR emission from galactic center clouds are large, up to 10%, consistent with the notion that the field is both strong and relatively uniform on scales > 1 pc, and 3) there seems to be a tendency for the cloud fields to be oriented along the Galactic plane, although there are deviations from this trend of up to ~50°. The latter point contrasts markedly with the implied vertical orientation of the magnetic field of the intercloud medium. It is tempting to ascribe cloud field orientations to shear in all cases, given the strong tidal fields present in this region, and the fact that molecular line surveys show that many, if not most, of the clouds are describable as streams of molecular material subtending a large azimuthal angle at the galactic center. Because the magnetic field in a highly sheared, conducting medium becomes predominantly parallel to the shear direction regardless of the initial field orientation, and because cloud shear near the galactic center is usually parallel to the Galactic plane, it is natural to appeal to tidal shear in order to understand the tendency for cloud fields to be aligned along the Galactic plane.

4. Origin of the Nonthermal Filaments

Of the models which have been offered to account for the NTF's (see Morris 1996), we mention only two here. Serabyn & Morris (1994) note that the filaments of the Radio Arc are linked to high density molecular clumps within the "25 km s^{-1}" cloud and which are abutting the ionized surface of that cloud. Indeed, every sufficiently well-studied NTF appears to coincide somewhere along its length with the ionized surface of a molecular cloud (*e.g.*, Uchida *et al.* 1996; Staguhn *et al.* 1997). This led Serabyn & Morris (1994) to hypothesize that particles are accelerated at ionized cloud surfaces by field line reconnection between the fields in the cloud and the ICM. The dramatic difference between the predominant orientations of cloud and intercloud fields facilitates this process. Figure 1 illustrates how the NTF's of the radio arc, which define the field direction in the intercloud medium, are orthogonal to the field within the molecular cloud, which is perpendicular to the polarization vectors shown. The ionized surface of the cloud is evident as the sickle-shaped HII region, G0.18-0.04.

A recent alternative was offered by Rosner and Bodo (1996), who propose that the relativistic electrons illuminating the NTF's are produced in the termination shocks of stellar winds, and that this process defines the transverse dimensions of the NTF's. In general, each filament would require a separate stellar wind, and the presence of bundles of NTF's would be ascribable to clusters of windy stars. The presence of the responsible stars or stellar winds has not yet been demonstrated for most NTF's, but there is one location where this hypothesis is very appealing: the "Pistol" nebula, consisting of ejecta from the apparent LBV star at its center (the so-called "Pistol Star"; Figer *et al.*, in these proceedings).

5. The Pistol Nebula (G0.15-0.05), and Other Spherical Pistons

The Pistol Nebula has a rough cylindrical symmetry (Yusef-Zadeh & Morris 1987), with its long axis parallel to the magnetic field, as defined by the NTF's, so it seems possible that the nebula has been shaped by the ambient field (although LBV winds are generally not very symmetric, so this could be a coincidence). The Rosner & Bodo hypothesis is supported by the fact that two NTF's appear to originate (or at least undergo brightness discontinuities) at the edges of the Pistol Nebula, that is, from the termination shock of the wind from the Pistol Star. This can be seen in Figure 1.

Spherical pistons of many varieties – OH/IR star winds, planetary nebulae, hot star winds, novae, supernovae – should all serve as probes of the ambient Galactic center field, because all of these would be deformed into an elliptical geometry at some radius by the pressure of the magnetic field. AGB stars with mass loss rates of 10^{-5} $M_{\odot}$ yr^{-1} and a typical wind velocity of 15 km s^{-1}, for example, will expand a distance perpendicular to the field lines equal to $4 \times 10^{16}\ B^{-1}$ cm, or 0.36 arcsec, where the ram pressure of the wind is counteracted by the ambient magnetic pressure. The wind is unimpeded along the field lines, however, so contours of CO emission from such as object would be elliptical, with a narrow dimension of only 0.7".

6. Origin of the Central Dipole Field

The strong central field of the Galaxy could conceivably result from a turbulent mean-field dynamo, although no dynamo mechanism has yet been offered which gives a strong, vertical flux through the Galactic center region. An alternative, and more straightforward hypothesis for the strong central field is that it represents a concentration of magnetic flux carried toward the center over the lifetime of the Galaxy by radial inflow of partially ionized matter into which the magnetic flux is effectively frozen. This idea, originally suggested by Sofue and Fujimoto (1987), has been discussed by Morris (1994) and considered in detail by Chandran *et al.* (1998).

Magnetic flux threading the gas which comprised the protogalaxy can be divided into components parallel and perpendicular to the global rotation axis. Differential rotation winds and amplifies the perpendicular component, which now dominates the Galactic disk, and various dynamo mechanisms can provide further amplification (*e.g.*, Ruzmaikin *et al.* 1988). Its strength saturates as the rate of amplification is balanced by the rate of loss due to ambipolar diffusion out of the Galactic gas layer. The component parallel to the Galactic rotation axis cannot diffuse radially outward, however, not only because the radial extent of the Galaxy is far larger than the vertical extent, but primarily because the gas carrying the magnetic flux is moving radially inwards at a rate exceeding the outward rate of ambipolar diffusion. This inexorable inward flux of gas and field is the result of angular momentum loss caused by a variety of common processes: shocks in spiral arms and bars, dynamical friction of clouds in the field of stars, torques exerted by a bar, dilution of the orbiting gas by low angular momentum material from the halo and elsewhere, and perhaps magnetic viscosity.

The vertical component of the field is therefore trapped in the Galaxy, and is concentrated over time in the central regions. Most of the gas which goes in with the field forms stars or perhaps leaves as part of a Galactic wind (Morris & Serabyn 1996), but the loss of this gas from the interstellar reservoir does not affect the magnetic field strength. The $\sim 5 \times 10^7\ M_\odot$ of gas presently constituting the CMZ is but a small fraction of the amount of gas which has apparently migrated into the Galactic center region over the Galaxy's lifetime. Flux conservation can be used to estimate either the primordial field strength or the distance from which gas has migrated to the center during a Hubble time. Chandran *et al.* (1998) adopt a time-averaged accretion rate equal to the currently estimated value of 0.3 $M_\odot\ yr^{-1}$ (Morris & Serabyn 1996) to deduce a protogalactic magnetic field strength of 0.25 μgauss on a scale of 13 kpc, although if the average accretion rate is larger, as seems probable given the presumably larger merger rate and higher gas fraction in the early universe, the implied primordial field strength and accretion scale are correspondingly smaller and larger, respectively.

These initial field strength estimates apply only to galactic scale structures. Fluctuations having substantially smaller wavelengths are likely to be eliminated by field line reconnection as vertical field lines of opposite sign are brought together by compression, differential rotation, and turbulent interchange (Chandran *et al.* 1998). Therefore, the mean protogalactic field strength would probably be a few times larger than that estimated by simply scaling the current central field. The energy of the reconnected field is dissipated as thermal energy at a rate of $\sim 10^4$ $L_\odot$, and could thereby be an important contributor to the heating of gas in the CMZ.

The explanation of the central dipole field of our Galaxy as concentrated protogalactic field is one which should be widely applicable to spiral galaxies, inasmuch as the basic physical elements are universal. In studies of galactic nuclei, it should therefore be kept in mind that the central magnetic field may strongly affect observed physical processes.

7. Other Galaxies

The magnetic field in other galaxies is sampled at scales of kiloparsecs, rather than parsecs, so detailed comparisons with our Galaxy are not yet possible. Nonetheless, there are two lines of inquiry suggesting that dipole magnetic fields may be important in at least a fair fraction of galactic nuclei. First, a number of galaxies which are relatively active, and therefore bright in the radio, show radio continuum structures perpendicular to the galactic plane at the nucleus, reaching heights of a few kiloparsecs (*e.g.*, Hummel *et al.* 1983; Duric & Seaquist 1988). These structures could represent gas which has been channeled out of the central regions by a dipole field, although channeling by ambient disk gas is the current paradigm. Second, a number of galaxies show linearly polarized radio emission from their nuclear regions indicative of a poloidal field. These include: NGC1808 (Dahlem *et al.* 1990), NGC4631 (Golla & Hummel 1994), and M82 (Reuter *et al.* 1994). The task of tying these large-scale results to magnetic fields in the central few hundred parsecs of these galaxies remains to be done.

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