THE MAGNETIC FIELD OF THE MILKY WAY

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ABSTRACT. Since its discovery 40 years ago as a confiner of cosmic rays and an aligner of interstellar dust grains, the Galactic magnetic field has been studied through emission and polarization of synchrotron radiation, Faraday rotation, Zeeman splitting, and effects on gas flows and morphology. The local field has a coherent, few microgauss, component roughly along the local spiral arm and a comparable chaotic component. Field direction in the plane is reversed one or more times both inside and outside the solar circle. Loops and spurs extend outside the plane and may merge with a general dipole, which is most conspicuous near the Galactic center. There may be a separate thick disc magneto-ionic component. Comparison with other galaxies, especially grand design vs. flocculent spirals should eventually prove fruitful. Parameters are not currently well enough known to rule out dipole or primordial origin.

1. HISTORY AND INTRODUCTION

Alfvén (1937) first suggested that cosmic rays might be a confined galactic phenomenon; and he (Alfvén 1949) and Fermi (1949) were discussing confinement by a 10 μG field (equipartition with galactic turbulence) at nearly the same time that Hall (1949) and Hiltner (1949) were discovering it via polarization of starlight correlated with interstellar reddening. Who first wrote or said "general Galactic magnetic field" in public has proven difficult to establish; the Alfvén reference cited by Hiltner (1949a) is a "ghost" and actually contains the prediction of MHD waves. J.L. Greenstein (1989 pr. comm.) recalls Fermi talking informally at Chicago about such a field several years before Greenstein and Davis (1951) presented the first essentially-correct model of interstellar polarization.

Some of the topics mentioned here are covered in greater detail elsewhere in this volume. Additional valuable references include other conference proceedings (Beck and Graeve 1987; Hollenbach and Thronson 1987), the books by Zeldovich et al. (1983) and Ruzmaikin et al. (1987) and the theoretical review by Sofue et al. (1986).

R. Beck et al. (eds.), Galactic and Intergalactic Magnetic Fields, 29–34.

2. DIRECT TECHNIQUES AND RESULTS

Maps of optical polarization vectors vs. Galactic coordinates (Mathewson and Ford 1974; Ellis and Axon 1978) reveal a coherent field in the plane with loops and spurs out of it (some, especially the North Polar Spur, the same as are seen in synchrotron emission and in the distribution of HI). These maps give a slightly misleading impression of the scales involved, since they look rather like images of whole external galaxies, but in fact show only structures within a kpc or less.

Studies of synchrotron emissivity (Phillips et al. 1981; Beuermann et al. 1985) and polarization (Spoelstra 1984) confirm that B is dominantly aligned with the disc. In addition to the spurs and loops, they reveal a small scale chaotic component about as strong as the ordered one. The emissivity arms are at least roughly the same as the Pop I arms; and the emissivity disc has thin and thick components, with $2z_o$ = 0.3 and 3 kpc respectively.

The galactic magnetic field can also be probed through its Faraday rotation of the polarization vectors of pulsars and extragalactic radio sources. Two recent studies of pulsars are not in complete agreement. Lyne and Smith (1989) find a local coherent field of 2-3 μG pointing to $l \approx 90°$, a reversal less than 1 kpc from us toward the Galactic center (and extending at least 1 kpc from the plane), and other reversals at all longitudes toward and away from the center. The random field component is at least as strong as the coherent one and has no single length scale but little coherence over more than 100 pc.

Rand and Kulkarni (1989) attempt local, bisymmetric spiral, and ring fits to their data, favoring a ring structure for the field. Their coherent component is only 1.6 μG and the random about 5 μG, with a size scale of about 55 pc. Reversals occur 2450 pc outside the solar circle and 650 and 3250 pc inside it.

Results derived from extragalactic sources are also somewhat discrepant. A critical issue is whether the field direction is slightly more or slightly less than 90°, as usually found from rotation measures and interstellar polarization respectively. Brett (1989) believes that neither can be firmly excluded. In addition, the nearby reversal toward the Galactic center seems to be associated with the North Polar Spur in a way suggesting to her that it might be a local, bubble, phenomenon, rather than a global one.

Vallée (1988) and Vallée et al. (1988) find evidence for four distinct spiral arms (Perseus, Orion = local, Sagittarius, Scutum), with B pointing to $l \approx 90°$ in all but Sag, and pitch angles suggestive of gas streaming directions rather than density wave arms. Broten et al. (1988) find, in addition, evidence for four of the well-known loops (Gum, Cetus, NPS, Monogem). Agafanov et al. (1988) disagree about the Perseus arm, finding its field to point toward $l = 280°$ rather than 90°. This seems in better accord with the pulsar results. They and Kesamanskii and Sutenkov (1987) report also a chaotic component at least as large as the coherent one. Finally, Andreasyan and Makarov (1987) find evidence for both a reversing, bisymmetric spiral disc field and for a halo field consisting of a dipole twisted by differential rotation. The Orion optical spiral arms points to $l \approx 75°$ by way of comparison.

3. LESS DIRECT TECHNIQUES

Cosmic rays need confining now even more than they did in 1949 (because we know rather more about their compositions and lifetimes). A beeline from the galactic center to us would take a particle through about 0.1 g/cm^2, but the ratio of secondary nuclides (e.g. LiBeB) to primary ones (e.g. CO) says they have passed through 3-6 g/cm^2. This corresponds to spending about 3 million years in the disc. But abundances of radioactive nuclides (U, Th, and Be^{10}) tell us that the average GCR has spent more like 30 million years on its way to us. Thus the geometry of the confining field must permit cosmic rays to get out of the disc (where they are presumably accelerated) and to get back into it as well (for us to observe them).

We expect moving ionized gas either to be guided by magnetic field lines or to take the field with it. The necessary degree of ionization probably exists even in dominantly neutral and molecular gas; completely neutral gas will also show correlations with field morphology if it is being shoved around by ionized material. Correlations between gas flows or morphology and magnetic field patterns have been pointed out for HI, especially shells (Colomb et al. 1980) and flows in loops and spurs (Verschuur 1989), supernova remnants (Roger et al. 1988), and contracting dark clouds (Meyer et al. 1987).

4. LOCALIZED CONCENTRATIONS, INCLUDING THE GALACTIC CENTER

There seems to be no doubt that field strength is, on average, higher in high density clouds, often sufficient to produce detectable Zeeman splitting of the 21 cm line. A major outstanding issue is whether B increases steeply enough with n to suggest flux conservation. Myers and Goodman (1988) vote no, and Garcia-Barreto et al. (1987) yes, though not for precisely the same clouds. Troland (1989) notes that B seems to be higher for a given n in regions where stars are currently forming. The field is, in any case, dynamically important in star formation (Shu and Lizano 1989; Elmegreen 1989).

In the vicinity of the Galactic nucleus, the field is stronger than average (mG rather than μG) and essentially perpendicular to the plane (Yusef-Zadeh and Morris 1988, who note resemblance to solar filaments; Sofue et al. 1987, who suggest a twisted dipole; Reich et al. 1987). A dissenting note is sounded by Werner(1988), whose analysis of the infrared polarization associated with the 3 pc dust ring strongly suggests azimuthal field lines. I do not pretend to understand the models (Benford 1988; Sofue and Fujimoto 1987; etc.)

5. OUTSIDE THE PLANE

The well-known loops and spurs (Sofue 1988) are widely regarded as manifestations of old supernova remnants and stellar wind bubbles (or mergers of them). To prevent false complacency, though, Haud (1988) has proposed that gas loops are really part of a polar ring structure around the Milky Way, largely unrelated to SNRs etc. In addition to these high-latitude structures, there is a 1500 pc scale-height thick disc in both electrons (Reynolds 1989) and synchrotron emissivity (Simard-Normandin & Kronberg 1980). It seems likely that this is the sum of older loops and spurs. In any case, a field component perpendicular to the gas disc helps to stabilize it against star formation (Schmitz 1987). Detailed field structures should be regarded as rather poorly determined in the sense that synchrotron polarization and dust grain orientation do not always show the same field direction for a given region (Beck et al. 1988).

We do not have any very good idea of what the galactic magnetic field would look like from outside. But it you mentally sketch a giant dipole around the knobbly plane shown by Sofue et al. (1986), with some field lines closed and some open to intergalactic space, that is perhaps as good a guess as any (Cox 1989, priv. comm.).

6. THE REST OF THE UNIVERSE

Naturally, we expect the Milky Way to resemble other spiral galaxies in its magnetic field configuration. From this point of view, M106, whose synchrotron arms are totally disjoint from its stellar and HII arms (Hummel et al. 1989) is probably not a good example! The very limited published studies of other spirals (e.g. Graeve & Beck 1988) tentatively suggest that those with bisymmetric fields (M33, M51, M81) are two-armed grand-design spirals, while those with axisymmetric fields (M31, IC342) are multiple-arm objects (Elmegreen 1989 pr. comm.). The Milky Way does, at rate show reverals in field direction with radius, but also has more than two arms. From this point of view, magnetic field mapping of a few face-on flocculent galaxies might be very interesting.

Theoretical considerations are addressed elsewhere in this volume. Dynamo models apparently produce m = 0 modes more easily than m = 1 (bisymmetric) ones (Chiba & Tosa 1989), but it is my impression that there are still more models that aren't galaxies than there are galaxies that aren't models (to paraphrase Anne Underhill in another context). The origin of galactic magnetic fields does not seem to be enormously better understood than it was when the field was less than half its present 40 year age and Zwicky proposed the mechanism "Dixitque Deus 'Fiat lux campusque magneticus'.".

ACKNOWLEDGEMENTS

Drs. Philipp Kronberg and Lodewijk Woltjer provided initial sets of ideas and references for this review. Lindy Brett, Bruce Elmegreen, Richard Rand, and Jacque Vallée were also enormously (and voluntarily) helpful. Many inadvertant contributors will recognize their ideas, I hope properly credited.

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KUNDT: You have reviewed the often claimed situation that the cosmic rays can leave the Galactic disk and re-enter it. Wouldn't the latter correspond to bath-tub bubbles moving downward? [1983, Astrophys. Space Sci. **90**, 59]

TRIMBLE: From an observational point of view, we know the Galactic cosmic rays must get back into the plane since that is where we see them. Theoretically, I suppose, one must think in terms of diffusion of individual particles along field lines, not of bubbles falling back down.

SOKOLOFF: There are some details in interpretation which are very important for the theory, but very difficult to observe when sitting within the Milky Way. They are (1) the question about BSS structure (one can initiate such a structure locally by field reversals), (2) the question: Are galactic magnetic fields connected with spiral arms or with the disk? From a theoretical point of view the second possibility is preferrable. I think that today we have no real observational information about these important questions. What do you think about it?

TRIMBLE: What you say is certainly true, but we also cannot deduce the global field structure of the Milky Way by analogy with other galaxies, because axisymmetric spiral, bisymmetric spiral, and ring structures apparently all exist. The evidence for field strength being smaller between arms comes from synchrotron emissivity - if the field is a uniform disk structure, n_e (the electron density) must drop a great deal between the arms.

KULSRUD: What is the evidence for the large-scale dipole field?

TRIMBLE: A strong dipole field is directly observed near the Galactic center (work by Morris, Yusef-Zadeh, and others). I expect that the large-scale field seen from far away would look dipolar just because of the way various multipoles depend on distance.