FLUCTUATIONS IN THE GALACTIC MAGNETIC FIELD

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ABSTRACT. We discuss small scale structure in the Galactic magnetic field as inferred from Faraday rotation measurements of extragalactic radio sources. The rotation measure data suggest a continuum of length scales extending from parsec scales down to at least 0.01 pc and perhaps to as small as 10^9 cm. Such turbulence in the magnetic field comprises a reservoir of energy that is comparable to the energy in the large scale field.

1. Introduction

Three measureable line integrals are useful for discussing the Galactic magnetic field. These are the rotation measure (RM, from polarization observations), the dispersion measure (DM, from pulsar timing), and the scattering measure (SM, from radio wave scattering). SM is an integral of the wavenumber spectrum $n_e^2(\vec{q})$ of the electron density over length scales less than about 1 AU:

$$SM = \int_0^D ds \int_{\leq 1\, AU} d^3q \; n_e^2(\vec{q}).$$

Combinations of RM, DM, SM may be used to infer the nature of small scale variations in n_e, $\vec{B}$, and their product $n_e\vec{B}$. Here we emphasize the discussion of the magnetic field. The main topics discussed are: (1) Distinguishing intrinsic and Galactic RMs; (2) Distinguishing large scale **systematic** $\vec{B}$ and small scale **random** $\vec{B}$; (3) The wavenumber spectra of $\delta\vec{B}$ and δn_e; and (4) Energetics of $\delta\vec{B}$ 'turbulence.'

2. Rotation Measures

Rotation measures vary between the lobes of double radio sources; most of this appears due to magnetoionic material in the Galaxy because the rms RM is strongly

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correlated with galactic latitude b [1,2]. Cases with large intrinsic RMs are diagnosed using depolarization vs. frequency and eliminated. The difference $\Delta RM(\delta\theta) = RM(\theta+\delta\theta) - RM(\theta)$ may be used to study the length scales of electron density and magnetic irregularities. A contribution to $\Delta RM(\delta\theta)$ arises even if there is only a large scale magnetic field and a uniform electron density. However, this 'geometric' contribution is demonstrably much smaller than that from small scale irregularities, at least when looking at sources at small galactic latitudes.

The mean square of $\Delta RM(\delta\theta)$ is the 'structure function' of RM, which measures the characteristic angular scales of RM. Estimates of the structure function [1,2,3] from various samples of extragalactic sources show that: (1) For fixed $\delta\theta$, the structure function amplitude is much larger for a sample of sources in the galactic plane than at or near the North Galactic Pole; (2) For $b \approx 0°$, the structure function is significantly larger than that seen for a sample with $b \approx 90°$ for *all* $\delta\theta > 10^{-3}$ deg. This signifies the presence of irregularities as small as 0.01 to 0.1 pc for assumed interstellar distances of 1 to 10 kpc to the material.

3. Turbulence in δn_e and $\delta\vec{B}$

Pulsar intensity scintillations and angular broadening of pulsars, masers, and AGNs indicate electron density variations with a wavenumber spectrum of the form

$$P_{n_e}(q) = C_n^2 q^{-\alpha}, \tag{1}$$

with $\alpha = 11/3 \pm 1/3$ and including length scales $\ell \equiv 2\pi/q$ *at least* in the range of 10^9 to 10^{14} cm and possibly extending to much larger (e.g. pc) scales [4, 5].

If the product quantity $\delta(n_e B_{\|})$ has a similar spectrum, the form of the structure function will be [1]

$$\langle[\Delta RM(\delta\theta)]^2\rangle \propto (\delta\theta)^{5/3},$$

where the 5/3 exponent holds for $\alpha = 11/3$ and if $\delta\theta$ is intermediate to the apparent angular sizes of the largest and smallest length scales present. This form is roughly consistent with the structure functions for selected regions of the sky, suggesting that the distribution of length scales in n_e and perhaps $B_{\|}$ indeed extends to parsec scales.

On theoretical grounds [6], it is reasonable to assume that fluctuations in RM are due to fluctuations in both n_e and B. In fact, the simplest way to understand the density variations is if they are *driven* by magnetic field and velocity fluctuations. Studies of MHD turbulence and propagation of MHD waves suggest

$$\frac{\delta n_e}{n_e} = \zeta\left(\frac{\delta B}{B}\right)^n$$

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with $\zeta \approx 1$ and $n = 2$ for MHD turbulence and $n = 1$ for obliquely propagating MHD waves. Using this relation with eqn (1) yields the ratio of the energy density in magnetic field fluctuations to the energy density of the large scale field:

$$\frac{U_{\delta B}}{U_B} = \left[0.55\left(\frac{C_n^2}{1\,m^{-20/3}}\right)\left(\frac{\ell_{pc}^{2/3}}{\zeta^2 n_e^2}\right)\right]^{1/n},$$

where C_n^2 is expressed in units of $(meters)^{-20/3}$, ℓ in pc. For an 'outer' scale $\ell_{pc} = 1$, $n_e = 0.025$ cm^{-3}, and $C_n^2 = 10^{-3.5}$, the ratio of energy densities is about unity. Larger values for both quantities obtain for lines of sight through the inner part of the Galaxy, but to some extent these will cancel. Thus it appears that the energy invested in small scale magnetic turbulence is about the same as what is in the large scale field. The ratio is larger if the outer scale is larger than 1 pc, as has been suggested by others [4, 7].

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4. References

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MOUSCHOVIAS: I would like to take exception with the strong exception you have just taken concerning the regularity of the interstellar magnetic field! Can you really say that you observed interstellar ***turbulence***? Aren't the field variations observed just local disturbances of an otherwise regular field due to phenomena such as HII regions, supernova remnants, bipolar outflows (or winds) etc.? For example, the field reversal at Galactic longitudes $40° < \ell < 60°$ is due to the North Polar Spur. Also, there are known small-scale distortions due to gravitational contraction of clouds. Can you really convert observed variations in electron density into reliable statements concerning tangled magnetic fields and interstellar *hydromagnetic* turbulence?

CORDES: All studies of the interstellar magnetic field indicate that fluctuations are equal to the amplitude of any systematic field. Luckily, the fluctuations are small enough so that a systematic field can be *identified*, but as yet there are no successful fits to the data that yield the structure of the large-scale field. It is by no means clear as to which came first, the large-scale field or the irregular field. Whether small-scale fluctuations in $\vec{B}$ comprise bonafide turbulence (in the sense of a cascade from large to small or small to large scales) is unknown. My use of the term 'turbulence' should be interpreted as a concise term for small-scale variations. There is compelling evidence from spacecraft and ground-based studies that the interplanetary medium contains turbulence manifested as fluctuations in both electron density and magnetic field. It is reasonable to at least contemplate that a similar situation holds in the interstellar medium. The existence of a broad spectrum of magnetic irregularities may be *required* to explain the smoothness of the cosmic ray energy spectrum, a point made recently by J.R. Jokipii. Supernova and stellar wind shocks may in fact drive turbulence in the interstellar medium.

VERSCHUUR: Preliminary observations of galactic background polarization together with Dr. T. Spoelstra revealed unresolved structure in the North Polar Spur of order 0.9 pc in either the rotating medium and/or the intrinsic magnetic field. Unfortunately the earth's gravitational field prevented our pursuing these measurements when the 300-foot telescope collapsed just before we were due to map the field in a section of the spur.

CORDES: In general, the fluctuations in polarization of Galactic synchrotron radiation depend on fluctuations in magnetic field and cosmic ray density and energy in emission regions and fluctuations in magnetic field and thermal electron density along the line of sight. Much could be learned from a detailed study like the one you initiated.

BERKHUIJSEN: We have analyzed what mechanisms could be responsible for the depolarization of the emission from the SW quadrant of M31 (see Berkhuijsen and Beck, this volume). Faraday dispersion *across* the 3' beam appears to be important. The dispersing cells should have a dispersion in RM $\sigma_{RM} < 3$ rad m^{-2} and size scales $d_\perp < 200$ pc if the depolarization occurs in M31, and $d_\perp < 0.4$ pc if it happens in our Galaxy. If the one-dimensional filling factor $f_\perp < 1$ the scales will be smaller. The sizes of the required cells in our Galaxy agree very well with your results.

CORDES: It would be interesting to investigate the depolarization as a function of angular resolution to test whether there is a spectrum of cell sizes. The log-log slope of the depolarization vs. resolution curve would be related to the shape of the RM irregularity spectrum.