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Interstellar magnetic fields

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Abstract. We review the observational properties of interstellar magnetic fields in the disk and halo of our Galaxy. These properties are inferred from a variety of observational methods, primarily based on polarization of starlight and dust thermal emission, Zeeman splitting, Faraday rotation, and synchrotron emission. We briefly present each of these methods and explain how it has contributed to our present knowledge and understanding of interstellar magnetic fields.

Key words. ISM: magnetic fields – (ISM:) cosmic rays – ISM: general

1. Introduction

It was Alfvén (1937) who opened the era of interstellar magnetic fields when he correctly pointed out that a magnetic field threading interstellar space could naturally explain the confinement of cosmic rays in our Galaxy. Pushing this notion one step further, Fermi (1949) wrote in a seminal paper on the origin of cosmic radiation that "cosmic rays are originated and accelerated primarily in the interstellar space of the Galaxy by collisions against moving magnetic fields." He went on to add, with surprising accuracy for the time, that "the magnetic field in the dilute matter is of the order of magnitude of 5×10^6 gauss, while its intensity is probably greater in the heavier clouds."

At about the same time, two major advances occurred in observational astronomy. First, Hall (1949) and Hiltner (1949a,b) independently discovered that the optical light from nearby stars is linearly polarized – a phenomenon that Davis & Greenstein (1951) attributed to anisotropic extinction by elongated dust grains which are aligned by a coherent interstellar magnetic field. Second, Kiepenheuer (1950) realized that the general radio continuum emission from our Galaxy is synchrotron emission – a process that implies the presence of relativistic electrons spiraling about the lines of force of an interstellar magnetic field.

Thus, more than 60 years ago, two pioneering theoretical ideas as well as two groundbreaking observational discoveries pointed to the existence of interstellar magnetic fields in our Galaxy. Since then, a multitude of observations have provided convincing evidence that strong interstellar magnetic fields do indeed pervade our Galaxy. It has also become clear, from a theoretical point of view, that these magnetic fields play a crucial role in the interstellar medium (ISM): not only are they responsible for the acceleration and confinement of cosmic rays, but they also have a profound impact on the spatial distribution, dynamics, and energetics of the interstellar matter.

Sixty years down the road, how much have we actually learned about interstellar magnetic fields in our Galaxy? What do we really

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know about their typical strength and direction, their overall configuration, their spatial distribution . . . ? The purpose of the present article is precisely to address these important questions. In the next four sections, we successively discuss the four main methods employed to detect and observe interstellar magnetic fields, and in the last section, we try to piece together the different observational results into a coherent picture (with admittedly a few remaining gaps).

2. Linear polarization of starlight and dust thermal emission

Interstellar dust grains generally have irregular shapes, which, in a directional stellar radiation field, cause them to feel radiative torques. These torques have two important effects (see Draine & Weingartner, 1996; Lazarian & Hoang, 2007; Hoang & Lazarian, 2008). First, they spin up the grains to suprathermal rotation about their short axes. Second, they gradually bring the grain spin axes into alignment with the local interstellar magnetic field. As a result, dust grains tend to line up with their long axes perpendicular to the local magnetic field.

The magnetically aligned dust grains collectively act like a polarizing filter for starlight. More precisely, since they preferentially block the component of starlight with polarization vector parallel to their long axes, the starlight that passes through is linearly polarized in the direction parallel to the interstellar magnetic field. In consequence, measuring the direction of starlight polarization directly reveals the magnetic field orientation in the plane of the sky. This technique applied to nearby stars indicates that the interstellar magnetic field in the Galactic plane within a few kpc of the Sun is horizontal, i.e., parallel to the Galactic plane, and nearly azimuthal (Mathewson & Ford, 1970), making a small angle $\simeq -7°$ to the azimuthal direction (Heiles, 1996).

In addition to polarizing starlight, the magnetically aligned dust grains also emit infrared thermal radiation in an anisotropic manner. Here, the direction of maximum emission is parallel to the long axes of the grains, i.e., perpendicular to the interstellar magnetic field (Hildebrand, 1988). It then follows that dust thermal emission is linearly polarized in the direction orthogonal to starlight. This prediction was nicely borne out by the 850 μm observations of the Archeops balloon experiment (Benoît et al., 2004), which led to the same magnetic field orientation in the Galactic plane as the starlight polarization study of 10^4 stars by Crutcher et al. (2003).

3. Zeeman splitting

In neutral (atomic or molecular) regions of the ISM that are sufficiently cold and dense, magnetic field strengths can be inferred from Zeeman splitting measurements.

Zeeman splitting of a given atomic or molecular spectral line results from the interaction between the magnetic moment of the valence electrons and an external magnetic field. The frequency-amplitude of Zeeman splitting, $\Delta\nu$, is directly proportional to the magnetic field strength, B, so that, in principle, it suffices to measure $\Delta\nu$ in order to obtain B in the region of interest. In practice, however, $\Delta\nu$ is usually too small compared to the line width to be measurable. Under these conditions, one measures instead the Stokes parameter V, which is directly proportional to the line-of-sight component of the magnetic field, $B_\parallel$.

A vast body of Zeeman splitting measurements has now built up, both for the 21 cm line of HI (in atomic clouds) and for several centimeter lines of OH and other molecules (in molecular clouds). With appropriate statistical corrections for projection effects, it is found that in atomic clouds, the field strength is typically a few μG (median value $\simeq$ 6 μG), with a slight tendency to increase with increasing density (Troland & Heiles, 1986; Heiles & Troland, 2005), while in molecular clouds, the field strength increases approximately as the square root of density, from $\sim$ 10 μG to $\sim$ 3 000 μG (Crutcher, 1999, 2007).

4. Faraday rotation

In ionized regions of the ISM, the interstellar magnetic field can be probed with Faraday rotation measures of Galactic pulsars and extragalactic sources of linearly polarized radio waves.

Faraday rotation of a linearly polarized radio wave occurs when the wave propagates along the magnetic field of an ionized region, as a result of its interaction with free electrons gyrating about magnetic field lines. The angle by which the direction of polarization rotates is equal to wavelength squared times the so-called rotation measure,

$$\mathrm{RM} \;=\; C \int_0^L n_e \, B_\parallel \, ds \,, \tag{1}$$

where C is a numerical constant, n_e the free-electron density, and L the path length from the source to the observer. In practice, the rotation measure of a given radio source can be determined by measuring the direction of polarization of the incoming radiation at at least two different wavelengths.

Rotation measures have now been derived for about 1 200 Galactic pulsars and almost 40 000 extragalactic radio sources. Used in conjunction either with a model for the spatial distribution of free electrons or, in the case of Galactic pulsars, with their distances and dispersion measures, these numerous rotation measures have made it possible to gather a wealth of information on the strength, direction, and spatial configuration of the interstellar magnetic field, **B**, in ionized regions. Here are the key points that have emerged from Faraday rotation studies.

1) **B** has a regular component, $\mathbf{B}_{\rm reg}$, and a turbulent component, $\mathbf{B}_{\rm turb}$. Near the Sun, $B_{\rm reg} \simeq 1.5\ \mu$G and $B_{\rm turb} \sim 5\ \mu$G (Rand & Kulkarni, 1989). Away from the Sun, $B_{\rm reg}$ increases toward the Galactic center, to $\gtrsim 3\ \mu$G at $R = 3$ kpc (Han et al., 2006), i.e., with an exponential scale length $\lesssim 7.2$ kpc. Moreover, $B_{\rm reg}$ decreases away from the Galactic plane, albeit at a very uncertain rate; for reference, the exponential scale height inferred from the rotation measures of extragalactic radio sources is ~ 1.4 kpc (Inoue & Tabara, 1981).

2) In the Galactic disk, $\mathbf{B}_{\rm reg}$ is nearly horizontal and generally dominated by its azimuthal component. Near the Sun, $\boldsymbol{B}_{\rm reg}$ runs clockwise at an angle $\simeq -8°$ to the azimuthal direction (Han et al., 1999), which is very close to the pitch angle $\simeq -7°$ inferred from starlight polarization. Away from the Sun, $\mathbf{B}_{\rm reg}$ reverses direction at least a couple of times with decreasing Galactic radius, but the exact number and radial locations of the field reversals are still highly controversial (Rand & Lyne, 1994; Han et al., 1999; Vallée, 2005; Han et al., 2006; Brown et al., 2007; Nota & Katgert, 2010). These field reversals have often been interpreted as evidence that $\mathbf{B}_{\rm reg}$ is bisymmetric (azimuthal wavenumber $m = 1$), while an axisymmetric ($m = 0$) field would be expected from dynamo theory. In reality, Men et al. (2008) showed that neither the axisymmetric nor the bisymmetric picture is consistent with the existing pulsar rotation measures, and they concluded that $\mathbf{B}_{\rm reg}$ must have a more complex pattern.

3) In the Galactic halo, $\mathbf{B}_{\rm reg}$ could have a significant vertical component. At the horizontal position of the Sun, Taylor et al. (2009) obtained $(B_{\rm reg})_z \simeq -0.14\ \mu$G above the Galactic midplane ($z > 0$) and $(B_{\rm reg})_z \simeq +0.30\ \mu$G below the midplane ($z < 0$), whereas Mao et al. (2010) obtained $(B_{\rm reg})_z \simeq 0.00\ \mu$G toward the north Galactic pole and $(B_{\rm reg})_z \simeq +0.31\ \mu$G toward the south Galactic pole. In contrast to the situation prevailing in the Galactic disk, the horizontal component of $\mathbf{B}_{\rm reg}$ shows no sign of reversal with decreasing radius.

4) $\mathbf{B}_{\rm reg}$ displays some symmetry properties with respect to the Galactic midplane. At low latitudes (basically, in the disk), $\mathbf{B}_{\rm reg}$ appears to be roughly symmetric in z (Rand & Lyne, 1994; Frick et al., 2001), while at high latitudes (in the halo), the rotation-measure sky exhibits a rather striking antisymmetry/symmetry in z in the inner/outer Galactic quadrants (Oren & Wolfe, 1995; Han et al., 1997, 1999), which suggests that $\mathbf{B}_{\rm reg}$ is roughly antisymmetric/symmetric in z inside/outside the solar circle (Han et al., 1997, 1999, but see also Frick et al., 2001). Finding $\mathbf{B}_{\rm reg}$ to be symmetric in the disk and antisymmetric in the inner halo is consistent with the predictions of dynamo theory and with the results of galactic dynamo calculations (e.g., Ruzmaikin et al., 1988; Moss & Sokoloff, 2008).

5. Synchrotron emission

A global method to map out the interstellar magnetic field in the general ISM, through both neutral and ionized regions, rests on the observed Galactic synchrotron emission.

Synchrotron emission is produced by relativistic electrons spiraling about magnetic field lines. The synchrotron emissivity at frequency ν due to a power-law energy spectrum of relativistic electrons, $f(E) = K_e\, E^{-\gamma}$, is given by

$$\mathcal{E}_\nu \;=\; \mathcal{F}(\gamma)\; K_e\; B_\perp^{\frac{\gamma+1}{2}}\; \nu^{-\frac{\gamma-1}{2}}\;, \qquad (2)$$

where $\mathcal{F}(\gamma)$ is a known function of the electron spectral index and $\mathbf{B}_\perp$ is the total magnetic field projected onto the plane of the sky.

The spatial distribution of the Galactic synchrotron emissivity was modeled by Beuermann et al. (1985), based on an all-sky radio continuum map at 408 MHz. Several authors then used this synchrotron distribution model to derive the magnetic field distribution in our Galaxy. To do so, the vast majority of them resorted to the standard double assumption that (1) relativistic electrons represent a fixed fraction of the cosmic-ray population and (2) cosmic rays and magnetic fields are in (energy or pressure) equipartition. Relying on the cosmic-ray ion and electron spectra directly measured by the *Voyager* spacecraft, Ferriere (1998) verified that, locally, cosmic rays and magnetic fields are indeed close to (pressure) equipartition, with a total magnetic field strength $B \simeq 5\ \mu$G. She also found that the total field strength has a radial scale length $\simeq$ 12 kpc and a vertical scale height near the Sun $\simeq$ 4.5 kpc.

Because synchrotron emission is linearly polarized perpendicular to $\mathbf{B}_\perp$, information can also be gained on the orientation of $\mathbf{B}_\perp$. Evidently, if the observing frequency is too low to avoid Faraday rotation, the received polarized signal must somehow be "de-rotated" in order to recover the true magnetic field orientation. In addition, if the magnetic field has a turbulent component, the contributions from isotropic magnetic fluctuations to the polarized emission cancel out, leaving only the contribution from the ordered (i.e., regular + anisotropic random) magnetic field, $\mathbf{B}_{\rm ord}$.

Thus, while the *total* synchrotron intensity yields the strength of the *total* magnetic field (projected onto the plane of the sky), the *polarized* synchrotron intensity yields the strength and the orientation of the *ordered* magnetic field (again projected onto the plane of the sky).

Near the Sun, the ratio of ordered to total magnetic field strengths turns out to be $\simeq$ 0.6 (Beck, 2001). Together with $B \simeq 5\ \mu$G, this ratio implies an ordered magnetic field strength $B_{\rm ord} \simeq 3\ \mu$G.

Magnetic field orientations are more difficult to determine. Due to the importance of magnetic fluctuations and to the presence of large discrete structures, they can usually not be directly read off radio polarization maps. Instead, radio maps are often used in combination with magnetic field modeling. In this spirit, Sun et al. (2008) and Sun & Reich (2010) developed comprehensive 3D models of the Galactic magnetic field, constrained by observations of the Galactic total and polarized emission over a wide range of radio frequencies together with an all-sky map of extragalactic-source rotation measures. They achieved a good fit to all the data for axisymmetric models where the disk field is purely horizontal, has a constant pitch angle of 12°, reverses inside the solar circle, and is symmetric in z (clockwise near the Sun), while the halo field is purely azimuthal and antisymmetric in z (counterclockwise/clockwise above/below the midplane at all radii). They also came to the conclusion that bisymmetric models are incompatible with rotation measure data.

6. Conclusions

Our current view of interstellar magnetic fields in our Galaxy is still incomplete. While a growing number of magnetic field properties can now be considered as reasonably firmly established, a few crucial pieces of the puzzle are still missing.

In a nutshell, here is what we believe we know about (1) the strength of the Galactic magnetic field and (2) the direction of its regular component, first near the Sun and second in the Galaxy at large.

1) **Magnetic field strength.** Near the Sun, the regular, ordered (regular + anisotropic random), and total magnetic fields have approximately the following strengths: $B_{\rm reg} \simeq 1.5\ \mu$G, $B_{\rm ord} \simeq 3\ \mu$G, and $B \simeq 5\ \mu$G. Although the values of $B_{\rm reg}$ and $B_{\rm ord}$ were estimated with two completely independent methods (Faraday rotation and polarized synchrotron emission, respectively), their significant difference might be real and, therefore, indicative of the presence of anisotropic random magnetic fields. The latter, in turn, could be generated by compression or shearing of turbulent magnetic fields – for instance, at spiral arms (Beck, 2008). Moving away from the Sun, both $B_{\rm reg}$ and B increase toward the Galactic center and decrease toward the halo.

2) **Magnetic field direction.** Near the Sun, the regular magnetic field, $\mathbf{B}_{\rm reg}$, is horizontal and nearly azimuthal, running clockwise with a pitch angle $\simeq -8°$. In the rest of the Galactic disk, $\mathbf{B}_{\rm reg}$ remains approximately horizontal and dominated by its azimuthal component, running clockwise in some regions and counterclockwise in others. In the Galactic halo, $\mathbf{B}_{\rm reg}$ has both horizontal and vertical components; the horizontal component is probably counterclockwise at $z > 0$ and clockwise at $z < 0$ inside the solar circle, while being clockwise at all z outside the solar circle.

Aside from these presumably well-established facts, a number of open questions remain, concerning, in particular, the azimuthal structure of the magnetic field, the number and radial locations of field reversals in the Galactic disk as well as their origin, the magnetic field parity with respect to the Galactic midplane, the possible connection between the magnetic field in the disk, in the halo, and near the Galactic center ... One may hope that with the abundant observational data recently collected by the *Planck* satellite as well as those expected from the LOFAR low-frequency radio telescope, some of these thorny questions will finally find clear and firm answers.

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