

The Magnetic Field of the Milky Way from Faraday Rotation of Pulsars and Extragalactic Sources

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Received: 14 December 2010 / Accepted: 18 November 2011 / Published online: 10 December 2011
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Abstract Faraday rotation towards polarised pulsars and extragalactic sources is the best observable for determining the configuration of the magnetic field of the Galaxy in its plane and also at high latitudes. The Galactic magnetic field plays an important role in numerous astrophysical processes, including star formation and propagation of ultrahigh-energy cosmic rays; it is also an important component in measurements of the cosmological microwave background. This review article provides a brief overview of the latest advancements in the field, from an observer's point of view. The most recent results based on pulsar rotation measures are discussed, which show that we have begun to confidently resolve the main features of the Galactic magnetic field on kiloparsec scales, both in the Solar neighbourhood and at larger distances. As we are currently in great anticipation of polarisation observations with new, state-of-the-art telescopes and hardware, a brief overview of how much this field of research will benefit from the upcoming pulsar surveys is also given.

Keywords Milky Way: magnetic fields · Pulsars: observations · Polarisation

1 Introduction

The properties of the Galactic magnetic field (GMF) have been in the centre of scientific attention since the birth of radio astronomy, in the 1930s. The GMF has been understood to play a role in numerous astrophysical processes: on kpc-scales, it is believed that the GMF contributes to the stability of the interstellar medium (hereafter ISM; Boulares and Cox 1990), and it has even been claimed that it plays a role in the dynamical behaviour of the Galactic disc (Battaner and Florido 2007); also, at smaller scales, the compressed magnetic fields in molecular clouds play an important role in star formation (Heiles and Crutcher 2005)—it is believed that these magnetic fields preserve information related to the large-scale field (Li et al. 2006); last but not least, large-scale fields in the Galaxy, and especially the component of the GMF that is dominant in the Galactic halo, generate pathways for the

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highest-energy cosmic rays from extragalactic sources (Tinyakov and Tkachev 2002; Prouza and Šmída 2003); therefore, understanding the halo fields is crucial in tracing the sources of the most energetic particles in the Universe. Recently, Page et al. (2007) reviewed and modelled the contribution of the Galactic polarised radio foreground to the CMB measurements of WMAP. The polarisation of the Galactic radio emission arises from synchrotron-emitting electrons streaming along the GMF lines but also from the thermal emission of dust particles aligned with the GMF. It is therefore becoming clear that the GMF is an important agent not only for local astrophysical processes, but also for extragalactic astronomy and even cosmology.

2 Tracers of the GMF

2.1 Starlight Polarisation

Starlight can become polarised by scattering or absorption through the ISM, when interstellar dust grains are preferentially aligned along local magnetic field lines. Starlight polarisation can provide the sky-projected component of the magnetic field averaged over the integrated size of the scattering screen between the star and the observer; therefore the measured magnetic fields via this method are weighted by the amount of intervening dust—which is usually unknown. Unfortunately, it is very difficult to detect magnetic fields beyond 2–3 kpc, with this method. Despite this limitation, maps of the magnetic field from starlight polarisation towards several thousands of stars have been produced, which show that the GMF is generally oriented parallel to the Galactic plane (Heiles 2000; Fosalba et al. 2002).

2.2 Polarised Thermal Dust Emission

Magnetically aligned grains can also produce polarised thermal emission in dense regions (e.g. Giant Molecular Clouds or GMCs). The polarised emission is detectable in the mm, sub-mm and far-infrared bands, each band probing a different part of the distribution of dust-particle sizes. As with starlight polarisation, this method gives the sky-projected component of the magnetic field permeating those dense dust regions: typically fields coherent over $\sim 1\text{--}10$ pc can be detected. Currently, the only regions of the ISM that are dense and bright enough to be detectable via this method are molecular clouds. Therefore, the obvious link to observations of the large-scale GMF with this method is the central molecular ring of the Galaxy. However, it has been recently shown with sub-mm observations of GMCs that the field direction surrounding the clouds during their formation tends to be preserved through their volume (Li et al. 2006); and hence such observations could help us bring the direction of the large-scale field to light in certain regions.

2.3 Zeeman Splitting

Zeeman splitting of spectral lines of astrophysical origin generally requires relatively strong magnetic fields (\sim mG), whereas the typical strength of the large-scale GMF is \sim μ G. Therefore, Zeeman splitting can be measurable in molecular clouds and masers but is undetectable over larger scales. Hence, this method is very useful for determining the line-of-sight (LOS) component of localised magnetic fields but can directly tell us very little about the large-scale configuration of the GMF. However, observations of Zeeman splitting in molecular clouds and OH masers, spread across the Galactic plane, have resulted in trends in the overall direction of the detected fields, as a function of distance and longitude, that resemble

the structure of the large-scale field deduced from other methods (e.g. pulsar rotation measures, hereafter RMs—see below; Han and Zhang 2007). In addition, high-resolution Very Long Baseline Interferometric (VLBI) measurements of Zeeman splitting of OH masers in massive star-forming regions indicate that the field orientation before and after collapse is preserved (Fish and Reid 2006). This implies that the field is decoupled during the collapse of the cloud, and therefore a mechanism like *ambipolar diffusion* is perhaps in operation (Hezareh et al. 2010). In conclusion, it seems that—as in the case of polarised starlight and thermal emission—the magnetic field direction of the large-scale fields is preserved across regions that are as dense as e.g. hydroxyl masers ($\rho \sim 10^7 \text{ cm}^{-3}$; Reid et al. 1987; Fish et al. 2003).

2.4 Diffuse Synchrotron Emission

The large-scale magnetic field can also be estimated from polarisation observations of the synchrotron emission from the Galactic population of cosmic-ray (relativistic) electrons (see review by Reich 2006). This method provides the sky-projected, transverse component of the field, and like all such methods it can only tell us the orientation but not the direction of the magnetic field. In addition, measurements of the Galactic synchrotron flux, assuming energy equipartition between the cosmic rays and the total magnetic field, can provide an estimate of the ordered field's strength: i.e. the strength of the regular field, possibly arising from a large-scale dynamo, plus any compressed or sheared fields that are generated from the turbulent ISM. The typical estimates of the large-scale field strength from this method tend to be higher than from other methods: a likely reason is that the GMF also consists of the above-mentioned small-scale, turbulent component—of equal or even higher strength—that contributes to the observed polarised emission. Another caveat to this method is the Faraday depolarisation (i.e. the reduction of polarised flux) that occurs as the observer measures the sum of all polarised emission from different emitting regions along the LOS. A remedy to this deleterious effect is to observe at high frequencies (e.g. at 6 cm; note that accessing the Galactic centre requires $\lambda < 1 \text{ cm}$), as the Faraday effect scales with λ^2 . Also, high-frequency observations allow us to resolve the local regions of synchrotron emission, which distort the large-scale picture of the GMF: such observations have revealed a plethora of foreground sources, like e.g. the North Polar Spur (Wolleben et al. 2006).

The development of high frequency resolution backends combined with low-frequency frontends, like LOFAR and the WSRT, have recently made possible to resolve multiple, synchrotron-emitting Faraday screens towards different LOS (Schnitzeler et al. 2009). A crucial, missing component that has been technically unattainable until recently is the application of Faraday-tomography techniques, such as *Rotation Measure Synthesis* and *wavelet tomography*. RM Synthesis can be applied to polarisation data obtained at high frequency resolution. (A description of the method and its application to astrophysical context can be found in Brentjens and de Bruyn 2005.) In this method, the Fourier transform of the observed sum of polarised intensity across the observing band, $P(\lambda^2)$, provides the Faraday dispersion function, $F(\phi) \propto \int_{-\infty}^{+\infty} P(\lambda) \exp(-2i\phi\lambda^2) d\lambda^2$ —where ϕ is equivalent to RM—which is the polarised brightness profile of all sources along the LOS, in RM space. Hence, a complex region of polarised emission and Faraday rotation is revealed as a number of separate components at different RMs. A recent improvement on the RM Synthesis method comes from the introduction of wavelets, which allow one to decompose $F(\phi)$ —and thus $P(\lambda^2)$ —into different RM structures, for different spatial scales; this is beneficial when dealing with complicated Faraday structures along the LOS, involving several regions of polarised emission, but it also helps filter out the 'noisy' small-scale structure (Frick et al. 2010, 2011).

A main advantage of studying the Faraday rotation of the diffuse, polarised emission is that it is observable almost everywhere in the Galactic foreground (although polarisation voids and canals have also been identified; de Bruyn et al. 2006; Haverkorn et al. 2000). Coupled with modern, wavelet-based, Faraday-tomography techniques such observations are potentially a powerful tracer of the GMF on both small and large scales.

The reader is referred to a more detailed review on magnetic fields in the diffuse ISM by Landecker (2011).

2.5 Faraday Rotation of Pulsars and Extragalactic Sources

Faraday rotation of pulsars and of extragalactic point sources is the best available method for mapping the large-scale GMF in the plane but also at high latitudes. Faraday rotation of the plane of the linearly polarised emission occurs when polarised radio waves traverse the ionised component of the magnetised ISM: the warm, ionised ISM (WIM; $T_{\text{WIM}} \sim 10,000$ K) and, to a lesser degree, the hot, ionised ISM (HIM; $T_{\text{HIM}} \sim 10^6$ K) constitute the principal free-electron populations causing Faraday rotation in the Milky Way; the ultra-relativistic population of cosmic rays has a negligible cross-section for this effect. The magnitude of the Faraday rotation is proportional to the square of the emission wavelength and the RM; the latter is equal to the line integral of the magnetic field, B , along the LOS to the polarised source, weighted by the electron density: i.e. $\text{RM} = 0.812 \int_{\text{PSR}}^{\oplus} (n_e/\text{cm}^{-3})(B/\mu\text{G}) \cdot (ds/\text{pc})$, expressed in rad m^{-2} . Hence, long waves are rotated the most and high-frequency waves remain practically unaffected. The amount of Faraday rotation measured across the observing band, $\lambda_1 - \lambda_2$, is thus given by $\Delta\text{PA} = \text{RM} \cdot \Delta(\lambda^2)$.

The majority of pulsars are significantly linearly polarised, which allows us to easily determine RMs along numerous LOS throughout the Galactic volume: at present, there are roughly 750 pulsar RMs available in the literature (Manchester et al. 2005). Around 85% of the known pulsars are found within a kpc of the Galactic plane and, as expected from the higher stellar density, there is an appreciable concentration of pulsars in the spiral arms. Those pulsars are beneficial for the study of the disc field of the large-scale GMF. The significantly fewer pulsars found at high latitudes are, still, very useful in studies of the halo-field component: e.g. as was done in investigations of the large-scale field's symmetry by Han et al. (1997), using the RMs of high-latitude pulsars ($|b| > 8^\circ$). Thus, the local pulsar population will allow us to completely map the vertical distribution of the GMF in our neighbourhood; furthermore, the high-latitude pulsars accessible to LOFAR will be studied together with remote pulsars in the Galactic disc, from higher-frequency surveys, to investigate whether such a distribution holds elsewhere in the Galaxy.

Moreover, pulsars are compact radio sources and are thus devoid of internal Faraday rotation—which is typically the case for the extended external galaxies—and this allows us to solely sample the magnetic field of the ISM between the source and the observer. An exception is pulsars in supernova shells, whose RMs exhibit variations over monthly timescales due to the magnetised filamentary structure of the shells (Rankin et al. 1988; Moffett and Hankins 1999); but those variations are typically of the order of a few rad m^{-2} and hence hardly affect the overall picture of the magnetic field in that direction. Indeed, there are LOS which pass through numerous, magnetised, local regions, e.g. H_{II} regions, and those should be avoided in studies of the large-scale GMF with pulsars (Mitra et al. 2003; Nota and Katgert 2010).

Last but not least, the beamed, pulsed emission of pulsars means that the amount of dispersive ISM along the LOS (i.e. the 'warm', 8,000 K electrons) is easily measurable by the delay of the pulses across the observing band: $\Delta t = (4.5 \times 10^6 \text{ ms}) \text{DM} \cdot \Delta(\lambda^2)$,

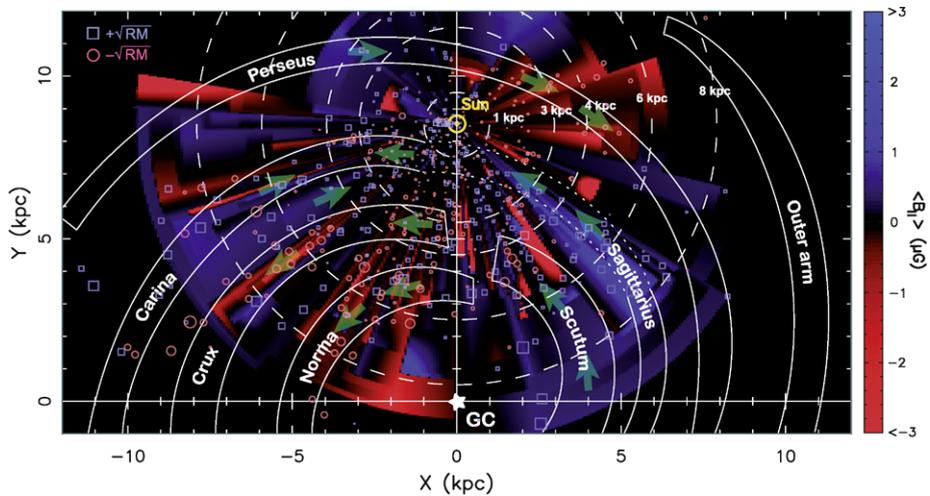


Fig. 1 (Produced by the author) Plan-view map of the large-scale Galactic magnetic field in the plane, within 8 kpc from the Sun (yellow circle), from 622 pulsar rotation measures. Blue-graduated regions denote magnetic fields directed towards the Sun (yellow circle) and red-graduated regions contain fields directed away from the Sun. The field strengths in this map have been interpolated in both the radial and azimuthal directions, in order to fill the empty regions between pulsars. Field strengths $|\langle B_{\parallel} \rangle| > 3 \mu\text{G}$ are represented with the maximum colour saturation on the colour scale

where DM is the dispersion measure, equivalent to the average number of electrons in a unit column between the pulsar and the observer, i.e. $\text{DM} = \int_{\text{PSR}}^{\oplus} n_e ds$ (usually given in pc cm^{-3}). This information can be used to estimate pulsar distances by using a model of the free-electron distribution of the ISM (e.g. NE2001—Cordes and Lazio 2002); moreover, when combined with the RM, it gives us an estimate of the LOS component of the magnetic field, averaged along the LOS between the pulsar and the observer, weighted by the free-electron density: i.e. $\langle B_{\parallel} \rangle = 1.232 (\text{RM}/\text{DM}) \mu\text{G}$. Unlike RMs of extragalactic sources, which provide the magnetic field averaged over practically infinite length, pulsar RMs are unique in that respect, as they reveal the average magnetic field only to the finite pulsar distance; using a large number of pulsars, this allows one to map the field as a function of distance (e.g. see Fig. 1).

3 Analysis Techniques

The first attempts to map the large-scale GMF used a few tens of pulsar RMs, most of them from pulsars within 2 kpc of the Sun, to make maps of the strength and direction of the magnetic field as a function of longitude (Manchester 1972, 1974). Later analyses included hundreds of pulsar RMs, as well as extragalactic RMs, which made it possible to track more closely the variation of the field: by plotting the pulsar RM as a function of DM, sub-kpc scale variations in the magnetic field became evident (Lyne and Smith 1989). The scatter in the RM data revealed the small-scale structure of the magnetic field. Moreover, the change in the sign of the RM between local pulsars and those further out suggested that the magnetic field reverses direction. Those early studies of the GMF simply used the RM/DM ratios towards different pulsars, to calculate the LOS magnetic field averaged over the entire distance between the pulsar and the observer. Later work took advantage of denser pulsar

regions (mainly the first Galactic quadrant, Q1) and provided estimates of the field variations along different LOS by using the RM–DM gradients between pulsar pairs with small angular separations (i.e. a few degrees): the magnetic field averaged between those pulsar pairs, at distances r_1 and r_2 , was then given by $\langle B_{\parallel} \rangle = [\text{RM}(r_2) - \text{RM}(r_1)] / [\text{DM}(r_2) - \text{DM}(r_1)]$.

In the recent years, the advancement of backend technology together with the development of broadband receivers has motivated pulsar-polarisation censuses (e.g. Noutsos et al. 2008; Han et al. 2009). As a result, it has become possible to confront various theoretical models of the large-scale GMF with multi-parametric fits to the rapidly increasing number of pulsar RMs. The different field geometries typically tested are primarily motivated by the corresponding galactic-dynamo modes: e.g. axisymmetric (ASS; Brown et al. 2007), bisymmetric (BSS; Prouza and Šmída 2003) and quadrisymmetric (QSS; Stepanov et al. 2008) spiral-field geometries are predicted from the different dynamo modes, $m = 1, 2, 3$, respectively.

The most advanced methodology of reconstructing the GMF from RMs uses Fourier deconvolution of the spatial distribution of the RMs, by means of a wavelet function that filters out the unwanted small scales of the field: the method is known as wavelet transform (Grossman and Morlet 1984; Farge 1992; Holschneider 1995) and was recently introduced in GMF mapping by Frick et al. (2001) and Stepanov et al. (2002). For the time being, this method can be applied to non-uniformly distributed RM data scattered throughout a volume but requires that the pulsar separation is at most ~ 0.5 kpc (Stepanov et al. 2002). This condition is easily satisfied within about 3 kpc from the Sun, towards the inner Galaxy, but fails elsewhere. For the purposes of large-scale field modelling, one can apply the wavelet transform to a set of measured RMs but also to the RMs predicted by a model: performing both allows one to then fit the model transform to that of the data and, because of the filtered-out small-scale noise, vastly improve the quality of the fits (Frick et al. 2001).

4 The Turbulent ISM

4.1 WIM and Pulsar Distances

A significant obstacle in modelling the large-scale GMF is the unknown distribution of the free-electron density that impacts on the pulsar distances. Early estimates of pulsar distances based on the measured DM assumed a constant electron density (e.g. Thomson and Nelson 1980; Han and Qiao 1994). Later, Taylor and Cordes (1993) made the first effort to model the WIM in their TC93 model; but that model systematically overestimated pulsar distances—due to the underestimated average value of n_e . Nowadays, the most commonly used density model is the NE2001 model of Cordes and Lazio (2002). Although a clear improvement over the TC93, NE2001 is still typically 20% in error for DM-derived distances in the Galactic disc: precision VLBI parallax measurements of pulsars has shown that the distance to individual pulsars from DM can be wrong by as much as a factor of a few (e.g. Deller et al. 2009); as was shown by Gaensler et al. (2008), the problem is accentuated at high latitudes, where much less information about the ISM is available. Despite follow-up work for an improved model of the ISM (e.g. BMM06; Berkhuijsen et al. 2006; Berkhuijsen and Müller 2008) there is still no reliable model that can accurately reproduce all pulsar distances. The limitations of current ISM modelling were recently highlighted by Van Eck et al. (2011) in their attempt to model the large-scale disc field using pulsar and extragalactic RMs: amongst other reasons, they stated that an improvement to their model is unlikely unless a more detailed model of the Galactic free electrons becomes available.

A key ingredient that is missing from all current ISM models is the information on the small-scale structure. The turbulent, small-scale ISM has a significant impact on both DM and RM measurements. This can be easily seen in maps of the reconstructed GMF from pulsar RM and DM gradients, where small-scale fluctuations are largely responsible for the observed incoherent picture (Fig. 1): the magnitude of the turbulent ISM fields is typically estimated to be from roughly of the same order of magnitude up to twice that of the ordered fields, leading to strong RM fluctuations towards most LOS (Noutsos et al. 2008); in addition, a simple differentiation of RM and DM data along a given LOS amplifies the small-scale noise, as was shown by Ruzmaikin (cf. Ruzmaikin et al. 1988, p. 34); finally, depending on the nature of the ISM turbulence, n_e and B fluctuations can be positively or negatively correlated, which results in over- or underestimation of the magnetic-field strengths from pulsar RMs, as the latter calculation assumes that the above quantities are independent (Beck et al. 2003). It is clear, then, that a model of the small scales needs to be included in future modelling.

The next free-electron density model (NE20—) is already being planned and will be the amalgamation of all available observational data: i.e. dispersion, scattering and rotation measures, $H\alpha$ maps, synchrotron diffuse emission, astrometric and timing parallaxes, etc. (see e.g. Jaffe et al. 2010). Many of these data have become available from recent all-sky surveys: e.g. the Parkes multi-beam and High Time Resolution Universe (HTRU) northern and southern surveys (Manchester et al. 2001; Keith et al. 2010; Barr 2011). A much better coverage of the sky with pulsar RMs and scattering measures is also expected soon from the LOFAR and Effelsberg all-sky surveys (van Leeuwen and Stappers 2010). All of the above data will be incorporated in multi-parametric fits that will provide more stringent boundary conditions than before, in order to reach a self-consistent solution for the ionised matter and magnetic field distribution simultaneously.

4.2 RM Scatter in Measurements of the Regular Field

Many investigators have noted the large RM scatter in plots of the spatial RM distribution of pulsars and extragalactic sources (e.g. Mitra et al. 2003; Han et al. 2006). As was noted by Noutsos et al. (2008) and later by Nota and Katgert (2010) and Mao et al. (2010), the observed scatter is neither due to measurement errors nor due to polarisation ambiguities in RM measurements. The main contributing factor is the small-scale ($\sim 1\text{--}100$ pc) magnetic-field fluctuations, which manifest themselves in plots of RM versus longitude or latitude, or distance along the LOS to pulsars and extragalactic sources (Mitra et al. 2003; Han et al. 2006; Noutsos et al. 2008; Nota and Katgert 2010).

In an attempt to describe the effects of the turbulent ISM on polarised emission, Gaensler et al. (2001) modelled a region of reduced linearly polarised intensity ('void'; centred on $l = 332^\circ.4$, $b = 1^\circ.4$) on maps of Q4 from the Southern Galactic Plane Survey (SGPS; McClure-Griffiths et al. 2005; Haverkorn et al. 2006). Given the degree of depolarisation seen in the observations of the above test region, it was possible to estimate the RM fluctuations towards the region ($\sigma_{\text{RM}} \sim 35\text{--}50 \text{ rad m}^{-2}$) and combine it with an *upper* limit on the emission measure ($\text{EM} = \int n_e^2 ds < 7000 \text{ pc cm}^{-6}$), in order to place a *lower* limit on the magnitude of the random fields. The estimated strength of those fields was $B_r \gtrsim 1.3 \mu\text{G}$.

A different approach to determining the influence of the small scales on RM was followed by Mitra et al. (2003), who measured the variation in DM and RM of pulsars behind the H_{II} region S205 (Sharpless 1959). Given the region's extent (≈ 30 pc) and distance ($\approx 900 \pm 300$ pc), the measurements could be used to estimate the magnitude of the magnetic field in S205. The resulting value for the magnetic field was $5.7 \mu\text{G}$, which is consistent

with alternate estimates of the strength of the small-scale fields (Rand and Kulkarni 1989; Ohno and Shibata 1993; Beck et al. 1996; but see Mao et al. 2010, who derived $B_r \sim 1 \mu\text{G}$ for the halo, from equipartition).

5 The Large-Scale GMF

5.1 Field Structure

The large-scale, regular GMF is coherent over kpc-scales and permeates the entire Galactic volume. It is so defined as to separate it from the small-scale, turbulent fields ($\lesssim 100 \text{ pc}$), where a steepening of the magnetic-energy spectrum is observed due to the dissipation of magnetic energy from larger to smaller scales (Han 2004; e.g. Bowers and Li 2007). The large-scale field is associated with the entire Galaxy as whole, thus implying that it was either already present at the Galaxy's formation—and has been later amplified by dynamo action (e.g. Beck et al. 1996; Shukurov 2005; Hanasz et al. 2009)—or was formed in the early stages of Galactic evolution (e.g. Rees 1987, 2006) and has been stretched across the plane by the Galactic rotation, throughout the Galaxy's history.

After the pioneering observations of the Galactic synchrotron emission at 408 MHz by Haslam et al. (1981, 1982) and the subsequent modelling of the emission as the sum of a thin- and a thick-disc component by Beuermann et al. (1985), it has become common practice to treat the large-scale field of the Galaxy in a similar fashion: i.e. as having a thin-disc component of a few hundred pc scale-height, embedded in a thick-disc component of $\approx 2 \text{ kpc}$ scale-height—similar to that observed in edge-on galaxies (Krause 2009) and also to the scale-height of the free-electron distribution of the ISM (see e.g., Kachelrieβ et al. 2007). The value for the latter has been recently revised to 1.8 kpc, based on pulsars with reliable distance estimates (Gaensler et al. 2008), from its earlier value of $\sim 1 \text{ kpc}$ in the NE2001 free-electron density model of Cordes and Lazio (2002).

Various geometries for the large-scale structure of the GMF have been fitted to pulsar and extragalactic-source RM data (Brown et al. 2007; Noutsos et al. 2008; Sun et al. 2008; Men et al. 2008). However, it is becoming clear that the most likely geometry of the disc field is that of a logarithmic spiral (e.g. Nota and Katgert 2010), similar to those observed in external galaxies (e.g. M51—Fletcher et al. 2011; NGC6946—Beck 2007). Nevertheless, it is interesting to note that, although much effort has gone into modelling the spiral field—with various pitch angles and arm widths tested against the data—the latest research shows that the overall profile of the magnetic field as a function of distance (probed along different lines-of-sight) is insensitive to the details of the spiral field (Nota and Katgert 2010). The principal reasons for our inability to distinguish different geometries, especially in the case of pulsars, are: (a) the sparse sample of pulsar RMs available in the Galactic volume, which leads to noise amplification in maps of the magnetic field from RM–DM gradients; and (b) the absence of adequate modelling of the small-scale component of the magnetic field (and electron density) in the models; this small-scale component can be as much as a factor of a few stronger than the large-scale component, introducing huge uncertainties in the models. A direct consequence of these shortcomings, and a limiting factor in itself, is the uncertainty in pulsar distances, which effectively adds confusion to the reconstructed maps (e.g. see Sect. 5 of Van Eck et al. 2011).

On the bright side, it is worth noting the recent simulations of the regular and turbulent Galactic magnetic field and the free-electron distribution, based on a grid of extragalactic RMs observable with the SKA (Sun and Reich 2009). The simulations predict that

arcsecond-resolution RM maps will be possible; these maps show fluctuations of the RM similar to those seen in GMF maps from pulsar RMs. This is a promising result that we need not only expect from the SKA: LOFAR will soon embark on an all-sky polarisation survey at 150 MHz, which is certain to produce an RM grid from Galactic and extragalactic sources that can be used to test the above models.

Beyond the disc field, the dominant component is the halo field. Due to the lack of available polarised sources in its volume, there is little known information about the size of the halo field. In principle, the halo field's extent is observationally limited by the amount of detectable Faraday Rotation through its volume. Alternatively, one can indirectly estimate the scale-height of the halo field by using the vertical distribution of the observed synchrotron emissivity and assume equipartition between the cosmic rays and the magnetic field (Cox 2005): such methods have led to scale-heights of 5–6 kpc for the halo field. Furthermore, the recent surveys of the polarised synchrotron emission, e.g. the Parkes Galactic Meridian Survey (PGMS; Carretti et al. 2009a), are partly aimed at probing the Galactic magnetism of the halo; a detailed discussion of the results from such efforts is presented herein, in Haverkorn and Heesen (2011).

In addition to the planar field in the disc, there are recent measurements of the strength of the vertical component of the magnetic field at the solar radius, towards the north and south Galactic poles, from RMs of polarised extragalactic sources (Mao et al. 2010). These measurements show an incoherent field at the Sun's position, with the field being consistent with zero towards the North Galactic Pole and significantly different from zero ($\sim 0.3 \mu\text{G}$) towards the South Galactic Pole. If these values for the GMF reflect the large-scale field and are not heavily affected by the fields in the local bubble and/or magnetised clouds in the local ISM, then these new results are inconsistent with pure-dipole or quadrupole geometries at the solar radius (see e.g. Han 2007; Sun et al. 2008). It should be stressed, however, that these observations cannot probe the field geometry elsewhere in the Galaxy, as different field configurations may exist in the inner and outer Galaxy (as was suggested, for example, by Van Eck et al. 2011; see Sect. 5.3).

5.2 Field Magnitude

The original polarisation observations of only a few tens of pulsars, as early as the 1970s, revealed a large-scale azimuthal magnetic-field ($l \sim 90^\circ$) within a kpc of the Sun, with a magnitude of the order of $2 \mu\text{G}$ (Manchester 1974). Follow-up attempts to model the typical magnitude of the random fields consistently resulted in estimates of a factor of a few or higher than that of the regular field (Thomson and Nelson 1980; Lyne and Smith 1989).

The contemporary consensus about the field strength at the solar circle is that direct measurement of Faraday Rotation of polarised pulsars, having a range of longitudes and latitudes, yields an average strength of the large-scale field of $\sim 2 \mu\text{G}$, with a clockwise direction, as seen from the North Galactic Pole (Han 2001; Mitra et al. 2003). Moreover, from starlight polarisation, Heiles (1996) found that this local field is directed towards $l = 83^\circ \pm 4^\circ$. Further out, in Q4, towards the Carina, Crux and Norma arms, Nota and Katgert (2010) used pulsars and extragalactic sources with reliable RM measurements (excluding those behind regions of high n_e fluctuations) and showed that the large-scale field maintains a strength of a few μG independently of galactocentric distance; most previous studies of the GMF either assumed or found a radial dependence of the field strength, with the field magnitude increasing towards the Galactic centre (Han et al. 2006; Brown et al. 2007).

At the same time, the various estimates of the magnitude of the large-scale, regular magnetic field from Faraday rotation of pulsars and extragalactic sources are systematically

lower than those from energy-equipartition arguments based on the surface brightness of the polarised Galactic diffuse synchrotron emission: the former typically result in strengths of $\approx 1\text{--}2\ \mu\text{G}$, whereas the equipartition strength is roughly twice that, i.e. $\approx 4\ \mu\text{G}$ (Frick et al. 2001; Mitra et al. 2003; Nota and Katgert 2010). Given that energy-equipartition from the polarised intensity of the Galactic diffuse emission yields the ordered (regular + anisotropic) fields, the higher magnetic field value perhaps implies that a significant fraction of the local, Galactic ordered fields are anisotropic and turbulent. However, as was shown by Beck et al. (2003), the fluctuations of the magnetic field in a turbulent medium are correlated with those of the electron density. Since the measured values of $\langle B_{\parallel} \rangle$ are based on the weighted average of the magnetic field by the electron density, which requires that δn_e and δB vary independently, there is an additional systematic error on the estimates of the regular field both from RMs and from equipartition: if these quantities are anti-correlated, the regular component of the field from RMs is underestimated, whereas positive correlation leads to overestimation of the ordered field from the polarised synchrotron emission.

5.3 Field Reversals

Several investigators have reported a number of large-scale reversals in the magnetic field direction between the optical arms of the Galaxy (Han et al. 2006; Brown et al. 2007; Noutsos et al. 2008; Nota and Katgert 2010; Van Eck et al. 2011). Although there is a certain degree of confusion as to which of these reversals are true features of the large-scale GMF and not local fluctuations of the significantly stronger turbulent field, the ‘smoke’ is beginning to clear: a number of recent publications have confirmed earlier results (Thomson and Nelson 1980; Han and Qiao 1994; Rand and Lyne 1994) indicating a reversal in Q1, between the Orion and the Carina–Sagittarius arm, within 1–2 kpc of the Sun (Weisberg et al. 2004; Han et al. 2006; Noutsos et al. 2008); the reversal changes the clockwise (CW) field of the Orion arm to counter-clockwise (CCW).

For the rest of the Galaxy, the number of reversals has been significantly revised over the recent years. Earlier publications suggested that the Galaxy possesses a field that reverses in every arm–interarm region (Han et al. 2006). More recently, a number of publications claimed a reversal between the Carina–Sagittarius and the Crux arms in Q4 (Brown et al. 2007; Noutsos et al. 2008). However, it has been known that measurements through the Carina region in Q4 show anomalous deviations that disrupt the smoothness of the RM distributions with longitude (e.g. Han et al. 2006; Noutsos et al. 2008; Haverkorn et al. 2008). Nota and Katgert (2010) showed that removal of RMs from pulsars in the direction of the Carina arm alleviates the unusually sharp RM fluctuations and, furthermore, it eliminates the requirement for a reversal between the Carina and Crux arms. It was also stressed that measurements in that direction should be regarded with caution: it is very likely that the Carina–Sagittarius arm possesses an number of H_{II} regions that corrupt the RM measurements—Mitra et al. (2003) showed that an H_{II} region with a 2° angular size and 30-pc linear size can produce a $\Delta\text{RM} \sim 250\ \text{rad m}^{-2}$ across its volume. Moreover, pulsars behind supernova remnants can potentially also distort a smooth RM variation that is expected from a coherent large-scale field.

The latest developments in mapping the orientation of the large-scale magnetic field in the disc and halo come from a combination of a large number of extragalactic RMs and pulsar RMs or diffuse synchrotron emission. Using $> 1,000$ extragalactic RMs from the CGPS, SGPS and VLA Galactic plane surveys and combining them with 557 pulsar RMs from the literature, Van Eck et al. (2011) tested a number of popular large-scale, axisymmetric, bisymmetric and concentric-ring configurations (e.g. Brown et al. 2003, 2007; Weisberg et

al. 2004; Han et al. 2006; Noutsos et al. 2008). This work concluded that the disc field is predominantly clockwise (as seen from the North), with the data being consistent with an axisymmetric spiral for the inner Galaxy, with only one large-scale reversal that appears to “spiral out” from the Galactic centre (see Fig. 2). Towards the outer Galaxy, the authors concluded that the pitch angle of the spiral field diminishes to resemble predominantly concentric rings.

The symmetry and structure of the halo magnetic fields is a long-standing question. Amongst the earliest work suggesting a coherent, large-scale structure in the halo RM sky was that by Han et al. (1997), who combined the few available pulsar RMs above 8° Galactic latitude with RMs of extragalactic sources to investigate the large-scale symmetry of the GMF in the halo. That work hinted at an anti-symmetric high-latitude sky, having azimuthal fields (of $\sim 1 \mu\text{G}$) above and below the Galactic plane with an opposite sense to each other. More recently, a similar conclusion was drawn from the work of Sun et al. (2008) and Sun and Reich (2009), who constructed 3D models of the Galactic total and polarised synchrotron emission from fits to the observed synchrotron maps and extragalactic RMs. The authors concluded that the best fit to the observations yielded a strong toroidal halo field ($\lesssim 10 \mu\text{G}$) that reverses its sense on opposite sides of the Galactic plane.

Despite the convincing evidence for an antisymmetric, large-scale Faraday sky at high latitudes, it has recently emerged from the work of Wolleben et al. (2010b) that the observed antisymmetry may largely be caused by a northern-sky, local H I bubble, at a distance of ~ 100 pc. The strong, compressed magnetic fields in the shell of that local structure were found to be $\sim 20\text{--}34 \mu\text{G}$ and are plausibly strong to cause the apparent antisymmetry in the measured RMs. The influence of such foreground structures can be revealed, as was done in the above work, with high-resolution spectro-polarimetry and the application of RM Synthesis on the diffuse component of the Galactic emission.

In conclusion, it is becoming clear that only a small number, perhaps only one large-scale reversal is indeed present in the configuration of the disc field. In the view of the large number of reversals having been reported in precursor work, it is important to highlight the significance of the distortion to the picture of the large-scale GMF which the small-scale structure can induce. Equally important is the fact that the careful analysis, e.g. by eliminating unreliable data (as was done in recent work), and the combined use of large RM samples and other polarisation information can lead to the true form of the large-scale field.

5.4 Magnetic Fields in the Galactic Centre

The Galactic centre (GC) is particularly challenging observationally, as scattering and depolarisation are deleteriously diminishing the sensitivity of our searches for pulsars and, generally, polarised emission. The steep synchrotron spectra of pulsars are constraining in terms of how high in frequency we can observe before the flux becomes undetectable (Maron et al. 2000); on the other hand, scattering and depolarisation are quadratic and even quartic functions of λ , meaning that high-frequency observations (< 1 cm) are necessary in order to avoid smearing out the signal completely. So, understandably, there are only a few pulsar detections near the GC and, in fact, no Faraday rotation has been measured from them, yet (Deneva et al. 2009). In addition, only a few tens of polarised, extragalactic sources can be seen within a few degrees of Sgr A* (e.g. Roy et al. 2003).

One way of battling the effect of depolarisation in the direction to the GC is to conduct radio observations at high frequencies. This approach was followed in early observations of the GC region, with the Effelsberg telescope at 32 GHz (Reich 1990), in which a ≈ 400 -pc long, highly-polarised filamentary structure (the “Arc”) was found very near

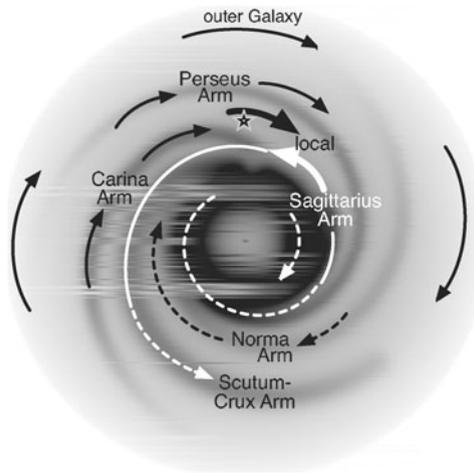


Fig. 2 (From Van Eck et al. 2011) Sketch of the large-scale field orientation of the Galactic magnetic field in the Milky Way disc, according to the contemporary view, overlaid on the NE2001 free-electron density model of Cordes and Lazio (2002). The *star* symbol corresponds to the Sun's position. The *thick, white arrow* indicates the only generally accepted large-scale reversal in Q1. The *thin, white arrow* indicates the large-scale reversal believed to spiral out from the Galactic centre. The *dashed arrows* in this figure correspond to poorly sampled regions, therefore corresponding to field directions that are uncertain

Sgr A* (≈ 30 pc away). The Arc, being nearly perpendicularly to the Galactic plane, was found to contain magnetic fields in the mG range, running almost parallel to its filamentary structure (Yusef-Zadeh and Morris 1987a, 1987b). It is worth noting that the Arc, given its extent and magnetic properties, is indeed a remarkable structure but not a unique one: further such filamentary structures near the GC have been discovered since (e.g. Reich 2003).

At γ -ray energies, the emission is practically unaffected by the aforementioned interstellar propagation effects that impact on radio waves; the recent work of Crocker et al. (2010) took advantage of this fact and placed a lower limit of $50 \mu\text{G}$ on the magnetic field strength (over 400-pc scales) near the GC, based on the observed EGRET γ -ray flux from that region. However, it should be stressed that stronger fields near the GC may be attributed to the increased synchrotron flux in the central regions of the Galaxy and therefore to stronger equipartition-field requirements—but this is not necessarily connected with the large-scale configuration of the GMF.

A very recent study of the central kpc of the inner Galaxy, using the Faraday rotation of the diffuse polarised emission, has revealed a poloidal magnetic field organised on 150-pc scales, directed from south to north (Law et al. 2011). It is also worth mentioning that the RM structure of the central 2° of the GC, as was measured in the above work, indicates an axial symmetry of the magnetic-field structure that is shifted by 50 pc to the west with respect to the dynamical centre of the Milky Way; the location of this axis of symmetry is consistent with, and possibly due to, the presence of a starburst outflow in the central 2° of the GC (Bland-Hawthorn and Cohen 2003). Meanwhile, optical polarimetry of dust grains has been used to bring to light the magnetic structure of the very central part of the Milky Way ($|b| < 0^\circ.4$; Nishiyama et al. 2010): a smooth transition from a toroidal to a poloidal magnetic field has been observed as one moves to higher latitudes, i.e. $|b| > 0^\circ.4$.

In conclusion, it appears that the efforts to uncover the large-scale magnetic-field structure of the GC, utilising different observables, have been dominated by magnetised filamen-

tary structures, organised on a few 100-pc scales. However, there has been little evidence towards linking the magnetic field of those localised structures to a global form of the Galactic magnetic field, as would be e.g. a poloidal field predicted by some dynamo models.

A more focused review on magnetic fields near the GC can be found in Ferrière (2011).

6 Future Instrumentation and Prospects

The field of research dealing with the magnetic field of the Galaxy has gone through an initial phase of a few, promising—mainly qualitative—results (1970s, 1980s); in the 90s, after the pioneering measurements and before the large-scale pulsar surveys that followed, there was a relative paucity of data accumulation, but it meant that the theoretical investigations could flourish. A large part of the last decade saw the relative abundance of pulsar and extragalactic-source RMs (mainly due to a number of pulsar surveys, e.g. Parkes, GBT), but this led more often than not to confusing—or at least inconclusive—results from the respective analyses: as was well pointed out by Nota and Katgert (2010), “The various analyses of the large-scale Galactic magnetic field are often based on identical or very similar datasets. Still, they have led to different or even contradictory conclusions.” However, during the last few years the dust has begun to settle and we are making confident conclusions about the strength and the direction of the large-scale GMF in a number of regions in the Galaxy. Moreover, we are beginning to understand the role of the turbulent ISM in our measurements and have even quantified—to some extent—the relative contribution of small-scale magnetic fields. This is not to say, of course, that we are close to a full description of the GMF. A number of exciting problems await resolution: the extent of the large-scale GMF in the halo has not been determined; how many large-scale reversals are there in total in the Galaxy? None of the external galaxies observed so far shows radial large-scale reversals: is our Galaxy unique in that respect? Also, a number of external galaxies (e.g. IC 342, NGC 6946) show the presence of magnetic arms between the optical arms (Beck 2011), where the field is stronger: is this also true for the Milky Way? What is the large-scale geometry of the GMF and how was it formed? At the moment, there are almost as many proposed models for the spiral field of the Galaxy as supporting publications for each of them. And last but not least, how do the small-scale turbulent fields affect our measurements? We need to characterise the observed fluctuations of the field: are these fluctuations positively or negatively correlated with the electron density?

6.1 Long-wavelength Phased Arrays

In the recent years, the revival of long-wavelength astronomy with the introduction of new, large-area phased arrays promises to be the next big leap in the field of Galactic—and not only—magnetic field studies. These arrays are composed of omnidirectional antennas, typically covering frequencies from a few tens to a few hundreds of MHz. Multiple of those antennas are arranged into stations that are spread across a large geographic area. The individual antennas observe the entire sky and directional beams can be formed by combining the signal from several antennas, and several stations, using powerful computer clusters.

Apart from the clear scientific value of these instruments, a driving force for their fast development has been the Square Kilometre Array (SKA), to which the long-wavelength arrays are considered pathfinder projects. In Europe, the Low Frequency Array (LOFAR; Stappers et al. 2011) is composed of 40 stations in the Netherlands and 12 international stations spread throughout Europe (i.e. Germany, France, UK, Sweden, Poland; more are

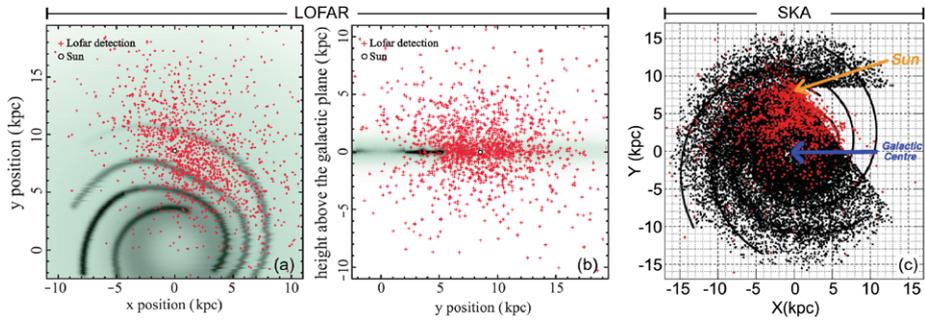


Fig. 3 (a, b) (From van Leeuwen and Stappers 2010) 1,100 simulated pulsar detections from a Galactic survey with LOFAR (1 h pointings). (c) (From M. Kramer, private communication) Simulated detections of pulsars from an SKA survey (*black points*); the *red points* correspond to the positions of all known pulsars

being funded). Each station is split between the Low Band Antennas (LBAs), covering frequencies of 10–80 MHz, and the High Band Antennas (HBAs), covering frequencies from 120–240 MHz. In Australia and the United States, the Murchinson Widefield Array (MWA; Lonsdale et al. 2009) and the Long Wavelength Array (LWA; Kassim et al. 2005), respectively, are similar projects that will consist of thousands of dipoles sensitive to frequencies from 80 to 300 MHz, with several thousands of m^2 of collecting area.

Many pulsars' flux spectra show a turnover at ~ 100 MHz, which means that observing in the high band with LOFAR we expect to detect a new population of pulsars that are difficult to detect at higher frequencies, where they appear much weaker. Simulations by van Leeuwen and Stappers (2010) showed that a 2-month, all-sky survey with LOFAR, at 150 MHz, can produce an excess of 1,000 new, nearby and high-latitude pulsars (see Fig. 3a, b). An important conclusion from those simulations was that LOFAR will detect all the pulsars within 2 kpc from the Sun. Many of these pulsars may not have high polarisation, which will prevent us from using them to map the GMF. However, based on current statistics, 40% of the detected sample of pulsars have enough polarisation for RM determination (Men et al. 2008). This means that at least 400–500 new directions through the Galaxy will be sampled, which will greatly increase the detail of the GMF maps. But LOFAR has an additional advantage in that half of the pulsars found in the northern hemisphere are seen to increase their degree of linear polarisation towards low frequencies (Gould and Lyne 1998). Hence, we expect that a seemingly unpolarised or weakly polarised population of pulsars may appear very strongly polarised at 100 MHz.

Naturally, the advent of the SKA will give us the opportunity, with its unprecedented sensitivity, to discover all Galactic pulsars (Fig. 3c). It will then be truly possible to map the GMF across its entirety: from kiloparsec scales down to a few parsecs; from the central kiloparsec out to the halo.

6.2 Single Dishes

At higher frequencies, single dishes complement the low-frequency arrays in filling the RM sky. Ongoing surveys at 21 cm, with the Effelsberg 100-m telescope in the Northern hemisphere and the Parkes 64-m telescope in the southern hemisphere, promise to return hundreds of new pulsars; and because these observations are at a much higher frequency, scattering is less of a problem and those searches will uncover many undiscovered pulsars buried deep in the Galactic plane. Less severe scattering also means that millisecond pulsars

are not be prohibitively scattered, which is the case at low frequencies; and exotic systems, like relativistic-binary pulsars, are more likely to be found in the Galactic plane, towards the denser Galactic centre. In addition, polarisation surveys of the Galactic diffuse emission are being carried out with Parkes at 2 GHz (S-PASS; Carretti et al. 2009b) and the 26-m Dominion Radio Astrophysical Observatory (DRAO; Wolleben et al. 2010a). In the future, a global project is planned at 300–1800 MHz, with DRAO, Effelsberg, Parkes and other single-dish telescopes, to map the diffuse synchrotron emission over the entire sky and hence provide invaluable information on the magneto-ionic medium of the Milky Way.

In conclusion, surveys with single dishes probe the lateral distribution of bright pulsars, limited off the plane by their collecting area, whereas phased arrays probe the vertical distribution of faint pulsars, limited in the plane by ISM scattering.

6.3 High Energies

The advent of γ -ray satellites with wide fields-of-view, like *Fermi* and *AGILE*, as well as the high sensitivities of ground-based Cherenkov arrays, like HESS, MAGIC and—in the future—the CTA, have opened new possibilities of either directly discovering new pulsars and pulsar wind nebulae (PWNs) or pointing to the right direction for follow-up work with radio telescopes. The *Fermi* γ -ray Space Telescope has already discovered tens of pulsars in blind searches and a much higher number of unidentified γ -ray sources. The latter are being searched with radio telescopes like Effelsberg, GBT and Parkes for radio emission. Searches such as these have led to the discovery of radio pulsars, which will be followed up with polarisation measurements and provide further RMs. In addition, Cherenkov arrays have conducted surveys of the γ -ray sky; their products, which may or may not be associated with radio pulsars, may still prove to be invaluable polarised radio sources themselves, which can be used with RM Synthesis to fill in the RM space between pulsars.

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