Cosmic Magnetic Fields:
From Planets, to Stars and Galaxies
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Measuring ISM fields using Pulsars

Aristeidis Noutsos†

University of Manchester, Jodrell Bank Centre for Astrophysics, Alan Turing Building, Manchester M13 9PL.
email: aristeidis.noutsos@manchester.ac.uk

Abstract. The sample of available Galactic pulsar rotation measures has proven an invaluable tool for measuring the direction and magnitude of the interstellar magnetic fields of our Galaxy. In this review, I present highlights of recent efforts to measure and map the Galactic magnetic field using pulsars. I give an overview of the analysis methods that were used by previous authors and underline the key results that have given us a clear picture of the magnetic field in certain regions of the Galaxy. This review also lays out the limitations of the present analysis methods and the observational difficulties that have so far hindered the study of the Galactic magnetic field with pulsars. Despite these difficulties, the continuous discovery of new pulsars in more and more sensitive surveys offer a continuous improvement on the existing knowledge of the Galactic magnetic field.

Keywords. Galaxy: structure – ISM: magnetic fields – pulsars: general – techniques: polarimetric

1. Introduction

The shape and strength of the Galactic magnetic field (GMF) has been the subject of research since the birth of radio astronomy, in the 1930s. There are many interesting astrophysical processes that are connected with the GMF: e.g star formation, the deflection of ultra-high energy cosmic rays, etc. However, despite the many efforts to produce a clear picture of the GMF – both in the field of radio astronomy, but also by studying the optical and infrared radiation through the interstellar medium (ISM) – the subject is still under discussion and there is little consensus over most of the field's properties.

1.1. *Sizing up the Galactic Magnetic Field*

Many of the previous studies of the GMF have tried to distinguish between a large-scale, regular component of the field, with typical scales of ~ 1 kpc, and a smaller-scale, turbulent component, with scales $\sim 10 - 100$ pc. This is, of course, an artificial classification, aimed at simplifying the view of the ISM field, whereas in reality the ISM field everywhere is the inseparable combination of all of its components.

In general, the regular field of the Galaxy is thought to have originated from a primordial field that has been strengthened via dynamo action and shaped by the Galactic gas motions or perhaps by the interaction with a companion galaxy. The turbulent component is usually attributed to the fields of localised structures, like supernova bubbles and ionised HII regions or even to frozen fields in molecular HI clouds. Well known examples of this type are the "North Polar Spur" and the "Gum Nebula", which are parts of supernova features.

† Present address: University of Manchester, Jodrell Bank Centre for Astrophysics, Alan Turing Building, Manchester M13 9PL.

1.2. *The shape and direction of the regular magnetic field*

To date, there is no conclusive evidence for the current shape of the Galactic disc field, and the subject of the field's origin remains open. The spiral shape of the luminous matter of the Galaxy has made the study of spiral forms for the regular component of the GMF an attractive possibility. In addition, observational data — mainly from pulsars — have suggested the existence of large-scale discontinuities in the field direction, known as "field reversals". Beyond the disc field, the Galaxy maintains a thick-disc or halo component with a measured typical scale-height of ~ 1.5 kpc: comparable to that of the free electron distribution (Beuermann *et al.* 1985; Han & Qiao 1994). The Galactic rotation has almost certainly stretched any primordial field across the GP. As a result, the vertical component of the GMF is about an order of magnitude weaker than the planar components.

1.3. *Models of the regular magnetic field*

There are three main classes of model for the regular field of the GMF: the concentric-ring field, the axisymmetric spiral (ASS) and the bisymmetric spiral (BSS).

The concentric-ring models have no radial component, i.e. $B_r = 0$, but their azimuthal component, B_θ, can vary with Galactocentric radius, r (see figure 1a). These models find support in the density-wave theory, which predicts that gas should follow circular orbits around the Galactic centre (GC).

The ASS models are compatible with theories of dynamo action on a primordial field. These models have both radial and azimuthal components, which vary independently only with Galactocentric distance, r, but not with azimuth, θ (see figure 1b). Although pure ASS models do not naturally predict magnetic-field reversals — and those that do usually restrict their location between the Perseus and Crux–Scutum arm — under certain conditions, i.e. that the primordial field exhibits strong reversals, reversals are compatible with the dynamo theory.

BSS models are described by radial and azimuthal components that are sinusoidal functions of θ (figure 1c). They can easily incorporate field reversals in both the radial and azimuthal components.

A property of all the above models is the symmetry of the field with respect to the GP: antisymmetric (odd) field models are oppositely directed either side of the GP, whereas symmetric (even) field models maintain the same direction.

Finally, most of the above models adopt a field-strength variation with r, with B increasing towards the GC. However, the actual function, $B(r)$, has not been conclusively estimated yet.

1.4. *Observational tracers of ISM fields*

The methods that have been employed so far for the detection and measurement of ISM fields are only able to explicitly produce the value of the field component perpendicular or parallel to our line-of-sight (LOS), but not the full, three-dimensional $\boldsymbol{B}$ vector.

Zeeman splitting of the spectral lines measures the parallel component to the LOS. Although this method is successful in measuring the local fields in molecular clouds, etc., it is difficult to relate these measurements with the large-scale magnetic field.

Polarization of dust emission at infrared, mm and sub-mm wavelengths can reveal the perpendicular-to-the-LOS (transverse) component of the magnetic field. Currently, this method only works well with bright molecular clouds. Hence, the only relevant region to the large-scale GMF that can be studied this way is the central molecular ring of the Galaxy.

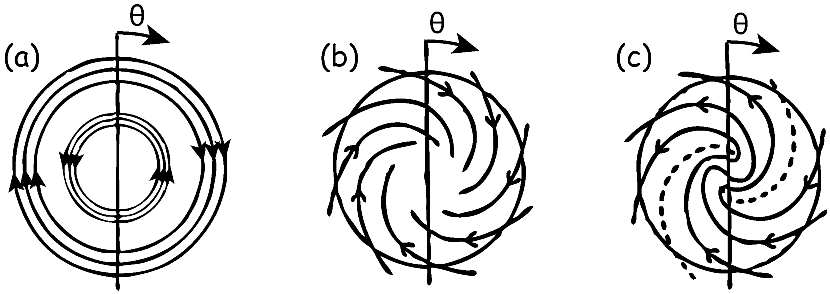

Figure 1. Three classes of regular Galactic magnetic-field model: (a) concentric rings (b) axisymmetric spiral and (c) bisymmetric spiral.

Polarization of starlight is another tracer of the magnetic field that can measure the sky-projected component of the GMF. Unfortunately, since the stars that can be measured this way are at most ∼2 kpc from the Sun, the field further afar cannot be explored with this method.

Maps of the transverse component of the GMF can also be constructed from polarization observations of the synchrotron emission of the Galactic relativistic-electron population. However, the anisotropic, random fields of large-angular-scale features, like the North Polar Spur, also appear in such maps, so that it can be difficult to separate them from the regular GMF.

Finally, Faraday rotation of the polarised emission of pulsars and extragalactic sources (EGRS) can be used to measure the LOS component of the GMF. Since the magnitude of this effect represents the integrated (along the LOS) interaction between the magnetised ISM and the polarised emission, pulsars at different distances can reveal the field's strength and direction across different depths through the Galaxy.

2. Pulsars as probes of the Galactic Magnetic Field

Soon after the discovery of pulsars, in 1967, it was realized that their polarized emission can be used to retrieve spatial information about the strength and direction of the GMF. The linearly polarized pulsar emission on its way to the observer interacts with the magnetized ISM, which causes the rotation of the plane of linear polarization ($\Delta\Psi$): the well-known Faraday effect. The magnitude of this effect is a quadratic function of the emission wavelength (λ) and proportional to the Rotation Measure (RM): the latter is a function of the pulsar distance and the radial profiles of the free-electron density and the interstellar magnetic field along the LOS to the pulsar. I.e.

$$\Delta\Psi = \lambda^2 \cdot 0.812 \int_{\mathrm{PSR}}^{\oplus} n_e(l) B_{\|}(l) dl = \lambda^2 \cdot \mathrm{RM} \tag{2.1}$$

Using a receiver of a known, finite bandwidth, $c/\lambda_1 - c/\lambda_2$, one could measure the difference in the amount of rotation between the edges of the band, $\Delta\Psi(\lambda_2) - \Delta\Psi(\lambda_1)$, and calculate RM. Given a strongly polarized pulsar, this is usually done in any of the two following ways: (a) the recorded Stokes parameters of the polarized signal, Q and U, are combined to calculate $\Psi = 0.5 \arctan(U/Q)$ for each frequency channel across the band, and the rotation of Ψ with frequency is fitted with the quadratic function of Eq. 2.1 to obtain the best value of RM. (b) Alternatively, one can combine Q and U to calculate the linear polarization, $L = (Q^2 + U^2)^{1/2}$, in each frequency channel and then sum the Ls of all channels together by first de-rotating Q and U with a candidate RM. This process can be repeated for a range of candidate RMs and should produce the maximum L at the correct RM. The second method, although evidently more computationally expensive

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than the first, works well for low-s/n pulsars, where the noisy frequency channels cannot produce a reliable fit.

Having measured the pulsar RM, we can combine it with the known dispersion measure (DM) to estimate the average LOS component of the magnetic field between the pulsar and the observer, weighted by the electron density, n_e:

$$\langle B_{\parallel} \rangle = \frac{\int_{\mathrm{PSR}}^{\oplus} n_e(l) B_{\parallel} dl}{\int_{\mathrm{PSR}}^{\oplus} n_e(l) dl} = 1.232 \, \frac{\mathrm{RM}}{\mathrm{DM}} \tag{2.2}$$

2.1. *Advantages*

The efforts to determine the three-dimensional structure of the GMF are hindered by our location being inside the volume we are trying to probe. The use of pulsars in this attempt is however advantageous for a number of reasons: (a) pulsar emission carries, in general, a high degree of linear polarization, which allows us to measure RMs with great accuracy; (b) since pulsar magnetospheres contain ultra-relativistic plasma that has a minor, if any at all, contribution to the measured RMs, the Faraday effect on pulsar emission is a direct consequence of solely the properties of the ISM; (c) the pulsar population is distributed across the entire galactic volume, which allows us to sample the ISM properties over a wide range of Galactic longitudes and distances (figure 2a); (d) last but not least, the pulse dispersion caused by the ISM (given by the pulsar DM), not only allows us to estimate their distances but also, when combined with their RMs, to directly measure the average value of the interstellar magnetic field between the pulsar and the observer.

Most pulsars are found close to the Galactic plane and there is an appreciable concentration of pulsars along the spiral arms. The large sample of pulsars at low latitudes has proven beneficial for the studies of the thin-disc component of the GMF, whereas those that are found at high latitudes allow us to study the magnetic field of the Galactic halo (Han & Qiao 1994).

2.2. *Using Pulsar RMs to reveal the structure of the Galactic Magnetic Field*

The aforementioned advantages of pulsars in studies of the GMF have encouraged many workers to use them to map the large-scale component of the field. The early work by Manchester (1972) and Manchester (1974) used Eq. 2.2 to estimate the field direction, averaged over the entire LOS to the pulsar, as a function of Galactic longitude. Later, Lyne & Smith (1989) were the first to advance this method by exploiting the RM–DM gradients along given LOS. They used pairs of pulsars, close to each other in the sky but at different distances, to estimate the local variations of $B_{\parallel}$ as a function of distance: i.e. $\langle B_{\parallel} \rangle_{d_1-d_2} \propto (RM_2 - RM_1)/(DM_2 - DM_1)$. Using this method for different LOS revealed the field variations in different directions, across nearly 200° of Galactic longitude.

As the number of pulsars with RMs reached nearly 200, the reverse logic could be applied to uncover the structure of the regular field: it became possible to dream up various models of the field's configuration and test their viability by fitting the models' predicted RM values to those observed (e.g Rand & Kulkarni 1989; Rand & Lyne 1994); the model's goodness-of-fit would then be the decisive factor. Such multivariate approaches have been followed by many authors in the recent years (see e.g. Han *et al.* 2006; Brown *et al.* 2007; Noutsos *et al.* 2008; Vallée 2008; Men *et al.* 2008).

The latest methodology in pulsar studies of the GMF is the use of wavelets to analyse the currently hundreds of available pulsar RMs (Frick *et al.* 2001; Stepanov *et al.* 2002). Wavelets are self-similar functions that can be used to describe the spatial and frequency distribution of the RM sample. Using wavelets, one can fit not the RM data themselves

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but the wavelet transform of the RM data to the magnetic-field model. A significant advantage of wavelet analysis over alternative methods of studying the regular GMF is its ability to filter out the smaller scales (due to the turbulent component), thus potentially improving the fits to the large-scale GMF models.

2.3. *Fundamental problems and limitations of analyses using Pulsars*

General: All of the above methods have been successfully used with the sample of RMs that were available to the different workers. However, despite their usefulness, there are shortcomings associated with each one, which limits their reliability.

The simple approach of dividing the pulsar RMs by their DMs to characterize the magnetic field in a certain direction in the sky, for example, assumes implicitly that the average values of n_e and $B_{||}$ are a good representation of their actual profiles along the LOS: that is to say, the electron density and magnetic field are uniform between the observer and the pulsar. We know, of course, that this is far from the truth, as the magnitude of both can change along the LOS; and there is good evidence that the the magnetic field's direction changes as well.

Those methods that used pairs of pulsars, located close to each other in the sky, suffer from the limitation that dominates all pulsar studies of the magnetic field: the number of available RMs is not sufficiently high for those methods to be able to track the fluctuations of the magnetic field along different LOS. Not only does the RM sample not have adequate density for a reliable mapping of the ISM fields to small scales, but the sparseness and irregularity of the pulsar positions results in very noisy maps of the magnetic field, when the latter is calculated from the gradients ΔRM/ΔDM (Ruzmaikin *et al.* 1988; Stepanov *et al.* 2002).

Methods that rely on RM–DM gradients to represent magnetic-field variations are sensitive to the presence of localized structures: e.g. if a magnetized HI cloud lies between a pair of pulsars along our LOS, it will contribute little in DM across its volume but may have a substantial contribution in RM (Manchester 1974). There are certainly observations of neighboring pulsars with very different, and even sometimes opposite RMs (e.g. Han *et al.* 2006).

An added complication comes from the pulsar distances that are derived from their DMs: this requires a model of the free-electron density along the LOS. Earlier work, based on the limited information available at the time, assumed a uniform electron density (e.g. Lyne & Smith 1989), which almost certainly introduced significant errors into their distance measurements. But even nowadays, with the use of the more accurate free-electron density model of Cordes & Lazio (2002), there is still a 10–20% error in the estimation of pulsar distances in the Galactic disc, whereas a much higher error is introduced at high latitudes (Gaensler *et al.* 2008).

The multivariate approach of fitting an ad hoc model to the data may also be influenced by the effects mentioned above, which makes it sometimes impossible to be certain of which model fits the data best. In addition, the a priori restrictions that these models impose on the GMF are not always represented in actuality.

Wavelet transform is certainly an improvement on previous analyses. However, it still requires a sufficiently dense sample of pulsars: the current RM-sample density fails to satisfy this criterion beyond 3 kpc. Application of wavelets on the currently available RM database has produced rather confusing and difficult-to-interpret maps of the local GMF (Stepanov *et al.* 2002).

Finally, caution is required when combining RM data sets from different epochs in order to perform a global fit to magnetic-field models. There are many examples of pulsars whose derived RM is seen to change significantly over a period of years (van

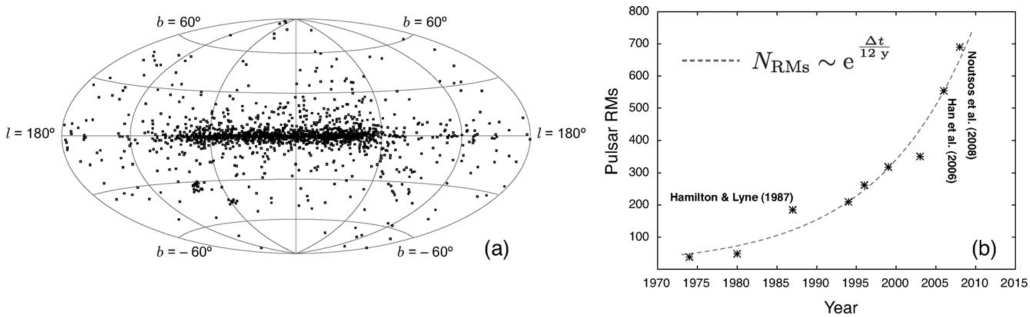

Figure 2. (a) Hammer–Aitoff projection of all discovered pulsars. (b) Measured number of pulsar RMs as a function of time.

Ommen *et al.* 1997; Han *et al.* 1999; Han *et al.* 2006 and Noutsos *et al.* 2008). These changes can occur as a result of magnetic-field or electron-density variations along the LOS — either due to changes in the ISM or due to different LOS as a consequence of pulsar proper motions. Nevertheless, it has been suggested that the changes of several rad m^{-2} observed are most likely because of ISM-field variations (Weisberg *et al.* 2004).

RM variations are also observed at much shorter time scales. Recent work by Ramachandran *et al.* (2004) clearly showed RM variations of tens of rad m^{-2} across the pulse phase, for a number of strong pulsars. It is yet unclear if there is a single reason for these variations, although ISM scattering is thought to play an important role (Karastergiou 2008, *submitted*).

The turbulent field: Any method that tries to map the regular component of the GMF should be capable of identifying the large-scale trends of the field in a forest of small-scale, turbulent fields. The turbulent fields are highly organized in a range of scales, as is observed e.g. for the fields of the North Polar Spur and "Region A": parts of extended supernova remnants (Rand & Kulkarni 1989). The typical strength of such fields has been estimated to be as much as twice that of the regular field: i.e. 3–7 μG (Beck *et al.* 2003). The impact of the turbulent component of the GMF on our RM measurements is significant: for example, its effect is evident in RM–DM plots, where it dominates the RM scatter – by an order of magnitude – over measurement errors.

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 $\langle B_{\|} \rangle$ are based on the weighted average of Eq. 2.2, which requires that σ_{n_e} and $\sigma_{B_{\|}}$ vary independently, there is an additional systematic error on the estimates of the regular field: if these quantities are anticorrelated, the regular component of the field is underestimated, whereas positive correlation leads to overestimation of $\langle B_{\mathrm{reg}} \rangle$.

Finally, the work of Mitra *et al.* (2003) showed that LOS that translate HII regions exhibit anomalous RM and DM fluctuations, which calls for the need to exclude such LOS from any analysis that aims at recovering the regular component of the GMF. However, they point out the value of using pulsars behind such HII regions to study the local value of the turbulent magnetic field. In the recent years, many workers have noticed the effects on RM data from such regions, like e.g. the anomalous RMs obtained in the direction of the Carina arm (e.g. Han *et al.* 2006; Noutsos *et al.* 2008).

3. The current picture of the Galactic Magnetic Field from Pulsars

3.1. *The Pulsar sample*

Pulsar studies of the GMF in the 1970s had to rely on a very poor sample of only a few tens of RMs, most of which were within 2 kpc from the Sun (Manchester 1972; Manchester

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1974; Thomson & Nelson 1980). An important step in this direction was made in the late 1980s with the acquisition of 163 pulsar RMs by Hamilton & Lyne (1987). Up until the end of the last decade, some 320 RMs had been measured (Costa *et al.* 1991; Rand & Lyne 1994; Qiao *et al.* 1995; van Ommen *et al.* 1997; Han *et al.* 1999). To date, a number of recent pulsar-polarization surveys have brought the RM count to 690 (Mitra *et al.* 2003; Weisberg *et al.* 2004; Han *et al.* 2006; Noutsos *et al.* 2008). Figure 2b shows the accumulation of measured pulsar RMs as a function of time.

As was mentioned before, since most pulsars are found near the Galactic disc, naturally most RM measurements correspond to low Galactic latitudes. In addition, the higher pulsar density in the inner Galactic quadrants compared to that beyond the solar radius means that the first (Q1) and fourth quadrant (Q4) of the disc have a richer RM sample than the other two. An observational bias that is caused by enhanced scattering and generally lower detectability at larger distances has resulted in a drop of the density of the RM sample with increasing distance; an exception is the high-latitude pulsars, like e.g. those in the LMC and SMC, which are not obscured by the dense environment of the Galactic disc and can be detected even at large distances.

An additional nuisance factor in RM measurements is that not all pulsars have enough intrinsic polarization to be measurable with the instruments' current sensitivity. It is reasonable to assume that there will always be a fraction of the discovered pulsar sample, whose RMs will not be measurable: at the moment, the fraction of pulsars with a measured RM stands a little over 40%; but, with more sensitive instruments planned for the future (e.g. LOFAR, FAST, SKA), it is bound to increase.

3.2. *What have we learnt so far?*

So far, the majority of pulsar work on the GMF has concluded that the solar neighborhood is permeated by a nearly azimuthal, $\sim 2\ \mu$G field, with a CW direction (as seen from the Galactic north). Initial publications concluded that the local field is directed towards $\ell \sim 90^\circ$ (Manchester 1972; 1974; Thomson & Nelson 1980), advocating for a ring-like configuration of the regular field. Following work, however, noted that those early studies may have been biased by selection effects, mainly due to poor sampling (Han & Qiao 1994), and that the most likely direction of the field lies somewhere between $\ell = 75^\circ - 85^\circ$, i.e. close but perhaps at a significant angle to the Orion spur. Similar values for the direction of the local field are nowadays commonly adopted when spiral models of the field are assumed (Brown *et al.* 2007; Noutsos *et al.* 2008; Sun *et al.* 2008).

Moreover, other methods of measuring the local field (e.g. Zeeman splitting, diffuse synchrotron emission) have resulted in fields of $\sim 4\ \mu$G for the regular component. According to Beck (2008), depending on the properties of the turbulent medium, the pulsar-based result may be an underestimate of the actual field strength, or the other methods may be overestimating that value.

Also, many investigators have provided convincing evidence for a reversal of the local field in Q1, near the Carina–Sagittarius arm, within 1 kpc from the Sun (Lyne & Smith 1989; Rand & Kulkarni 1989; Han & Qiao 1994; Rand & Lyne 1994; Frick *et al.* 2001; Weisberg *et al.* 2004; Han *et al.* 2006; Noutsos *et al.* 2008). The reversal changes the CW direction of the local field to CCW in the Carina–Sagittarius arm.

The current estimate of the the vertical component of the local magnetic field is $B_z \approx 0.4\ \mu$G, with a direction pointing from the South to the North Galactic Pole (Han & Qiao 1994; Han *et al.* 1999). The result was drawn from RMs of high-latitude EGRs ($\mid b \mid > 60^\circ$) and was checked for consistency with 8 pulsars in the north polar region. From modelling, Indrani & Deshpande (1999) found that B_z remains more or less constant in the solar vicinity.

In addition to the local reversal towards the Carina–Sagittarius arm, Brown *et al.* (2007) combined 120 pulsar RMs with 148 EGRS RMs and provided convincing evidence for a second reversal between the Sagittarius–Carina and the Scutum–Crux arm, in Q4 (towards $\ell \sim 312°$). This find was confirmed by Noutsos *et al.* (2008), based on 150 southern-pulsar RMs. The reversal changes the CW field of the Carina–Sagittarius arm, in Q4, to CCW in the Scutum–Crux arm. The total of only two reversals confirmed, contrasts previous pulsar studies that reported reversals in every arm or interarm region, including reversals exterior to the solar circle (Weisberg *et al.* 2004; Han *et al.* 2006).

3.3. *Compelling evidence*

A number of studies of RMs of both EGRS and high-latitude pulsars ($| b |> 8°$) have revealed an antisymmetry in the signs of pulsar RMs, with respect to the Galactic equator, towards the inner Galaxy ($\ell = 270° - 90°$) (Han 2007; Sun *et al.* 2008). Based on such antisymmetry, it has been claimed that the Galactic halo maintains an azimuthal field that is oppositely directed below and above the plane, with an estimated strength of ~ 1 μG (Han *et al.* 1997; Han *et al.* 1999). This is the signature of an A0 dynamo operating in the halo of our Galaxy. If these finds are confirmed by more data, it will be the first time that such a signature is clearly identified.

Previous studies of the regular GMF strength have suggested that it decreases with Galactocentric radius (Rand & Lyne 1994; Han *et al.* 2002; Han *et al.* 2006): e.g. based on pulsar RMs in the Norma arm, Han *et al.* (2002) estimated a field of ~ 4 μG, which is twice as strong as the local field. Despite those clues, the functional form of the field's strength with r remains uncertain: earlier models assumed a $1/r$ and $1/r^2$ dependence on the Galactocentric radius; the more recent work of Han *et al.* (2006) used a larger sample of RMs and tried to parameterize the magnetic-field strength as an exponential function of r.

Many models of the regular GMF assume an exponential suppression of the planar field, $B(x, y)$, with Galactic height, z (see e.g. Thomson & Nelson 1980; Kachelrieß *et al.* 2007). From pulsar work, we have very little, if any at all, information about the field's dependence on z. Under the assumption of a frozen-in GMF in the magneto-ionic slab of the Galaxy, Han & Qiao (1994) concluded that the field should exponentially decrease as a function of Galactic height, with an exponential scale-height similar to that of the free electrons.

3.4. *Controversial results*

In the recent years, the efforts to describe the regular GMF with one of the three aforementioned classes of model has led to controversy. The BSS models have been favored in earlier work, e.g. by Simard-Normandin & Kronberg (1980) and Indrani & Deshpande (1999), and more recently by Han *et al.* (2006). The concentric-ring models, despite having received heavy criticism (e.g. Han *et al.* 2006), have survived the test of time (Rand & Kulkarni 1989; Rand & Lyne 1994; Vallée 2005; Vallée 2008). Even though ASS models follow naturally from the dynamo theory, they have received limited support until now (Vallée 1996). This type of model was challenged by the recent results of Han *et al.* (2006) and Weisberg *et al.* (2004), showing reversals near the GC and exterior to the Perseus arm, since it only allows for reversals between the Crux-Scutum and Perseus arms.

Nevertheless, the most recent work on the large-scale field of the Galactic disc, which utilized a larger and more reliably measured sample of RMs, has rejected any of the three model classes as being a good description of the observed pulsar RMs. Men *et al.* (2008) tried a fit of all three types of model to 482 pulsar RMs and concluded that none of them was acceptable, noting however that a BSS model was the least unacceptable; the authors conceded that the true form of the GMF is much more complex than the

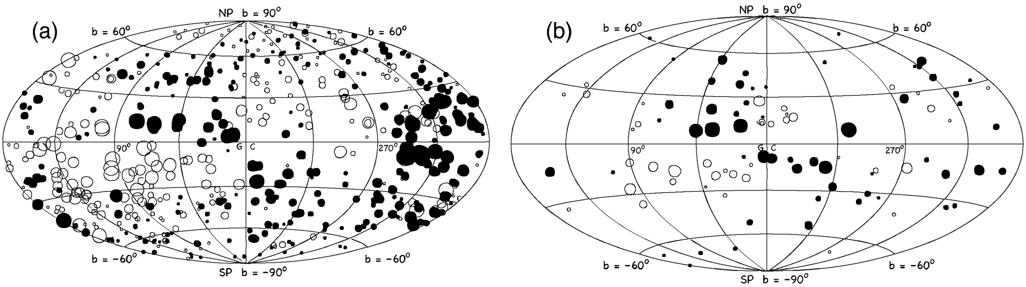

Figure 3. (From Han *et al.* 1997) The antisymmetric patterns with respect to the Galactic plane of the RMs of (a) extragalactic sources and (b) pulsars, seen at high latitudes towards the Galactic centre.

existing models lead us to believe. Moreover, a similar analysis by Noutsos *et al.* (2008), using 150 well-measured southern-pulsar RMs, also rejected any of the three types of BSS model as being significantly better than the rest. On the other hand, Vallée (2008) tried a concentric ring and the ASS model of Brown *et al.* (2007) on 554 pulsar RMs and found them reasonable. On those grounds, he urged future investigators to consider the concentric ring model in their analyses.

So far, current modelling has fallen short of a good description of the GMF, and perhaps a combination of all the above models is required — and with possibly only specific regions of the Galaxy being compatible with any one model.

4. Future studies of ISM fields with Pulsars

In the last decade, most published work on the study of the GMF with pulsars has used data either from the Parkes 64m radio-telescope, in the southern hemisphere, or from northern-hemisphere telescopes, like Effelsberg (100m) and Arecibo (305m). However, experiments planned for the near future, like the LOw-Frequency ARray (LOFAR) in the Netherlands, and those that are expected to be completed in the next decade, like the Square Kilometre Array (SKA), will almost certainly discover a large number of pulsars and subsequently measure their RMs. One of the scientific goals of LOFAR is to perform an all-sky survey of the northern sky at 150 MHz, in search for nearby and high-latitude pulsars. LOFAR will then perform follow-up polarimetric observations on the new pulsar sample and, having the advantage of operating at frequencies where pulsar spectra peak and the ISM Faraday effect is strong, accurately measure new pulsar RMs: some 300–500 new pulsar RMs is currently estimated to emerge from such a survey. The new RM sample, together with the use of novel analysis methods, like the RM synthesis (Brentjens & de Bruyn 2005), will help us probe the local fields with unprecedented resolution, contributing to our knowledge of the small-scale, turbulent component of the GMF; it will also help us map the vertical profile of the field and trace its extent.

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Discussion

Beckman: Have the RM measurements been used to quantify local fields, and if so what were the volumes derived?

Noutsos: Rand & Kulkarni (1989) used the residuals to a pulsar-RM fit to the concentric ring model to estimate the field of local structures (¡ 3kpc). They found $B_r \approx 5\ \mu$G. But they used a *single* coherence scale, which they conclude is not representative of the actual multi-scale turbulent field. Mitra *et al.* (2003) estimated the random field towards $\ell \approx 149°$ from the scatter of pulsar RMs. They give an estimate of 5.7 μG (in agreement with RK89). Both analyses attribute the random fields to HII regions in the directions investigated. The general magnetic spectrum from pulsar data was calculated by Han *et al.* (2001). They investigated scales between 0.5 and 15 kpc. The pulsar RM sample is not dense enough yet to calculate the field of individual structures (HI, HII regions).