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The Large-Scale Magnetic Field Structure of Our Galaxy: Efficiently Deduced from Pulsar Rotation Measures

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Abstract. In this review, I will first introduce possible methods to probe the large-scale magnetic fields in our Galaxy and discuss their limitations. The magnetic fields in the Galactic halo, mainly revealed by the sky distribution of rotation measures of extragalactic radio sources, probably have a global structure of a twisted dipole field. The large-scale field structure in the Galactic disk has been most efficiently deduced from pulsar rotation measures (RMs). There has been a lot of progress since the 1980s when the magnetic field in the local area of our Galaxy was first traced by a very small sample of local pulsars. Now we have pulsars distributed in about one third of the whole Galactic disk of the interstellar medium, which shows that the large-scale magnetic fields go along the spiral arms and that the field directions reverse from arm to arm. The RMs of newly discovered pulsars in the very inner Galaxy have been used to show the coherent magnetic field in the Norma arm. The magnetic fields in the Galactic disk most probably have a bisymmetric spiral structure.

1 Introduction

The origin of magnetic fields in the universe is a long-standing problem. It is clear today that magnetic fields play a crucial role in the evolution of molecular clouds and star formation (e.g. Rees 1987). The diffuse magnetic fields are the physical means to confine the cosmic rays (e.g. Strong et al. 2000). The magnetic fields in galactic disks also have a significant contribution to the hydrostatic balance in the interstellar medium (Boulares & Cox 1990). However, it is not clear whether magnetic fields exist in the very early universe, e.g. the recombination phase, and whether the fields affect the structure formation and galaxy formation afterward.

To understand the magnetic fields, the first step is to correctly and properly describe their properties based on reliable observations. Magnetic fields of galactic scales ($\sim$ 10 kpc) are the most important connection between the magnetic fields at cosmological scales and the fields in currently observable objects. In the last two decades, there have been many observations on magnetic fields in galaxies (see references in reviews by Beck et al. 1996; Han & Wielebinski 2002). Theoretically the magnetic fields in galaxies are believed to be re-generated and maintained by dynamo actions in the interstellar medium (e.g. Ruzmaikin et al. 1988; Kulsrud 1999). The helical turbulence (the α-effect) and differential rotation (the Ω-effect) are two key ingredients for dynamos in galaxies (e.g. Krause & Rädler 1980).

Our Galaxy is the unique case for detailed studies of magnetic fields, as I will show in this review.

It is certainly desirable to know the structure of our Galaxy and to compare it with the magnetic structures. However, as we live near the edge of the disk of the Milky Way, it is impossible for us to get a clear bird-view of the global structure of the whole Galaxy. As has been shown by various tracers, our Galaxy obviously has a few spiral arms with a pitch angle of about 10°. But there is no consensus on the number of spiral arms in our Galaxy and whether and how these arms are connected in the opposite side. Apart from the thin disk, there is a thick disk or halo, filled by low-density gas and possibly weak magnetic fields.

Pulsars are the best probes for the large-scale magnetic fields in our Galaxy. At present, many new pulsars have been discovered up to distances further than the Galactic center (e.g. Manchester et al. 2001; Morris et al. 2002; Kramer et al. 2003), which can be used to probe the large-scale magnetic fields in about half of the Galactic disk. The magnetic field may further give us some hints to the global structure of our Galaxy. Hundreds of pulsars discovered at high Galactic latitudes (e.g. Edwards et al. 2001) can be used to study the magnetic fields in the Galactic halo.

1.1 Comments on definitions of useful terms

Before we start to discuss observational results of magnetic fields, it is worth to clarify the definition of some useful terms.

Large scale vs. small scale:
How large is the "*large scale*"? Obviously it should be a scale, relatively much larger than some kind of standard. For example, the large-scale magnetic field of the Sun refers to the global-scale field or the field with a scale-length comparable to the size of Sun, up to 10^9 m, rather than small-scale magnetic fields in the solar surface. For the magnetic fields of our Galaxy, we should define the *large scale* as being a *scale larger than the separation between spiral arms*. That is to say, large scale means a scale larger than 2 or 3 kpc.

Note that in the literature, *large scale* is sometimes used for large *angular* scale when discussing the structures or prominent features *in the sky plane*, e.g., the large-scale features in radio continuum radio surveys. These *large angular-scale* features are often very localized phenomena, and not very large in linear scale.

Ordered vs. random fields:
Whether a magnetic field is ordered or random depends on the scales concerned. A uniform field at a 1-kpc scale could be part of random fields at a 10-kpc scale, while it is of a very large scale relative to the pc-scale magnetic fields in molecular clouds.

Uniform fields are *ordered fields. Regularly ordered fields* can coherently change their *directions*, so they may not be *uniform fields.* Deviations from *regular fields* or *orderd fields* are taken as *random fields.* The fluctuations of fields at scales 10 times smaller than a concerned scale are oftern taken as *random fields.*

Note also that in the literature the measurements of so-called *polarization vectors* only give the *orientations* rather than *directions* of magnetic fields, so they are not real vectors.

Azimuthal and toroidal fields:
Often the magnetic fields in our Galaxy are expressed in cylindrical coordinates (θ, r, z). The *azimuthal component*, B_θ, of magnetic fields dominates in the Galactic disk, where the *radial and vertical components*, B_r and B_z, are generally weak. The *toroidal component* refers to the structures (without B_z components) confined to a plane parallel to the Galactic plane, while the *poloidal component* refers to the axisymmetrical field structure around z, such as dipole fields (without B_θ component).

Concerning measurements relative to the line of sight, only one field component, either *perpendicular* or *parallel* to the line of sight, can be detected by one method (see below).

The above terms are artificially designed for convenience when studying magnetic fields. Real magnetic fields would be all connected in space, with all components everywhere.

1.2 Observational tracers of magnetic fields

Zeeman splitting:
It measures the *parallel component* of magnetic fields in an emission or absorption region by using the the splitting of spectral lines.

Up to now, measurements of magnetic fields *in situ* of masers (e.g. Fish et al. 2003) and molecular clouds (e.g. Bourke et al. 2001) are available. The relationship between the field strength and gas density has been supported by observational data (e.g. Crutcher 1999). Despite strong efforts it failed to relate the magnetic fields in situ and the large-scale fields (see Fish et al. 2003), as suggested by Davies (1974) and later promoted by Reid & Silverstain (1990).

Polarization at infrared, sub-mm and mm wavebands:
Dust particles are preferentially orientated due to the ambient magnetic fields. The thermal emission

of dust then naturally has linear polarization. Infrared, mm, submm instruments are the best to detect thermal emission. Polarization shows directly magnetic fields projected in the sky plane. Due to the short wavelengths, such a polarized emission does not suffer from any Faraday rotation when passing through the interstellar space.

The recent advance in technology has made it possible to make direct polarization mapping at infrared, sub-mm and mm wavebands (e.g. Hildebrand et al. 1998; Novak et al. 2003). At present, measurements can only be made for bright objects, mostly of molecular clouds. But in future it could be more sensitive and powerful to measure even nearby galaxies. A combination of polarization mapping for the perpendicular component of magnetic fields with the parallel components measured from Zeeman splitting will give a 3-D information of magnetic fields in molecular clouds (or galaxies in future), which is certainly crucial to study the role of magnetic fields in the star-formation process.

The available measurement, which is really related to large-scale magnetic fields, is the polarization mapping of the central molecular zone by Novak et al. (2003). The results revealed possible toroidal fields parallel to the Galactic disk. This field is probably part of an A0 dynamo field in the Galactic halo, complimented to the poloidal fields traced by vertical filaments in the Galactic center (e.g. Sofue et al. 1987; Yusef-Zadeh & Morris 1987).

Polarization of starlight:
The starlight is scattered by interstellar dust when traveling from a star to the earth. The dust particles are preferentially orientated along the interstellar magnetic fields, which induce the polarization of the scattered star light: more scattering, more polarization.

Starlight polarization was the start for the studies of the large-scale magnetic field. Apparently, the starlight can trace prominent magnetic features on large angular scales, over all the sky! Directly from the measurements in the Galactic pole regions, we can easily see the direction of the local magnetic fields in our Galaxy. However, because the measured stars are mostly within 1 or 2 kpc from the Sun, it is not possible to trace magnetic fields further away. Polarization measurements of stars near the Galactic plane give us only the information that the magnetic fields in the Galactic disk are mainly orientated parallel to the Galactic plane.

Synchrotron radiation:
Synchrotron radiation from relativistic electrons shows the *orientation* of magnetic fields in the emission region. Assuming energy equipartition, one may estimate the field strength from the emission flux. Furthermore, from polarized intensity, the energy in the "uniform field" together with that of anisotropic random fields can be estimated.

Many nearby galaxies have been observed in polarized radio emission. The emission suffers from Faraday rotatation within the medium of the galaxy and from the Milky Way. After correcting the foreground RMs, one can obtain a map of intrinsic *orientations* of the *transverse component* of magnetic fields, though it is often called the "vector" map of the magnetic field. The anisotropic random magnetic fields, such as compressed random fields by large-scale density waves, can also produce such an observed polarization map. So, with a polarization map with a coherent "vector" pattern, one cannot claim the large-scale magnetic field. However, a map of the RM distribution with a regular pattern, especially for the inclined galaxies, provides strong evidence for the large-scale magnetic fields in the halo or the thick disk of a galaxy (see Krause, this volume).

As we will show below, the pulsar RM distribution indeed shows large-scale magnetic fields in our Galaxy, with coherent field *directions* going along the spiral arms. This indirectly proves that the polarization maps of nearby galaxies can be at least partially due to the large-scale magnetic field. The strength of "regular fields" calculated from the polarization percentage may be overestimated, however, as one cannot quantify the contributions from anisotropic random magnetic fields (see Beck et al. 2003).

Faraday rotation of polarized sources:
Faraday rotation occurs when radio waves travel through the magnetized medium. The RM, which is measured as being the rate of polarization-angle change against the square of wavelength, is an integration of magnetic field strength together with electron density along the line of sight from the source to the observer, i.e., $RM = a \int_{\rm source}^{\rm observer} n_e\, B_{||}\, dl$. Here a is a constant, n_e the electron density,

dl is a unit length of the line of sight. Obviously, RMs measure the average diffuse magnetic field if the electron density is known.

In the following I will concentrate on how the RMs of pulsars and extragalactic radio sources can be used to probe the large-scale magnetic fields in our Galaxy. Considering various difficulties in other methods, we are really lucky that we can use the RMs of an increasing number of pulsars to probe the large-scale magnetic field in the Galactic disk. It is very hard to conduct observations of Zeeman splitting, and afterwards it is not possible to relate these measurements to the large-scale magnetic fields. Starlight polarization does measure the diffuse magnetic field, but it is not possible to give any other information than the averaged orientation of the field in just 1 or 2 kpc. Diffuse radio emission from our Galaxy can only show the polarized emission from local regions on large *angular* scales, but not on large linear scales in the Galactic disk.

2 The magnetic field in the Galactic halo: based on the RM sky distribution

In the sky the Milky Way is the largest edge-on Galaxy. This gives us the unique chance to study the magnetic fields in a galactic halo in detail, which is not possible at all for nearby extragalaxies. There is a huge number of extragalactic radio sources as well as hundreds of pulsars, which can be potentially used to probe the magnetic fields in the Galactic halo and in the Galactic disk.

The RM of an extragalactic radio source consists of a RM contribution intrinsic to the source, the RM from the intergalactic space from the source to the Galaxy, and the RM within the Galaxy. The first term should be random and hence reasonably small on average, because a source can be randomly orientated in space with any possible field configuration. We observe a random quantity. The second term is ignorable on average. Intergalactic magnetic fields are too weak to be detectable now. A source can be at any possible location in the universe. Even if there is a weak field in the intergalactic space, an integration over the path-length of the intergalactic magnetic fields with random directions together with extremely thin gas should give a quite small combination. Therefore, the common contribution to RMs of extragalactic radio sources is from our Galaxy. So, the *averaged* sky distribution of RMs of extragalactic sources (see Fig. 1) should be the best presentation for the Galactic magnetic field in the Galactic halo.

Though there are many distinguished characteristics related to specific regions in the RM sky, we noticed that the most prominent feature is the antisymmetry in the inner Galactic quadrants (i.e. $|l| < 90°$). The positive RMs in the regions of $(0° < l < 90°,\ b > 0°)$ and $(270° < l < 360°,\ b < 0°)$ indicate that the magnetic fields point towards us, while the negative RMs in the regions of $(0 < l < 90°,\ b < 0°)$ and $(270 < l < 360°,\ b > 0°)$ indicate that the magnetic fields point away from us. Such a high symmetry to the Galactic plane as the Galactic meridian through the Galactic center cannot simply be caused by localized features as previously thought. The antisymmetric pattern is very consistent with the magnetic field configuration of an A0 dynamo, which provides such toroidal fields with reversed directions above and below the Galactic plane (Fig. 1). The toroidal fields possibly extend to the inner Galaxy, even towards the central molecular zone (Novak et al. 2003).

This magnetic field model is also supported by the nonthermal radio filaments observed in the Galactic center region for a long time, which have been thought to be indications for the poloidal field in dipole form (Yusef-Zadeh & Morris 1987; Sofue et al. 1987).

We noticed that the antisymmetric RM sky is also shown by pulsar RMs at high Galactic latitudes ($|b| > 8°$). This implies that the magnetic fields responsible for the antisymmetry pattern could be nearer than the pulsars. Indeed, the fields nearer than the pulsars contribute to the RMs, but this is not the only contribution. If it is only a local effect, then there would be no symmetric RM distribution beyond the pulsars. We made computer simulations, which show that large-scale magnetic field structures further away than the pulsars (i.e. the more inner Galaxy) should result in a strong antisymmetry of RM sky within 50° from the Galactic center, and that the magnitudes of RMs are systematically increasing towards the Galactic plane and the Galactic center.

To judge if antisymmetry is produced by a large-scale magnetic field, it would be necessary to subtract the foreground pulsar RMs induced by local magnetic fields from the RMs of extragalactic

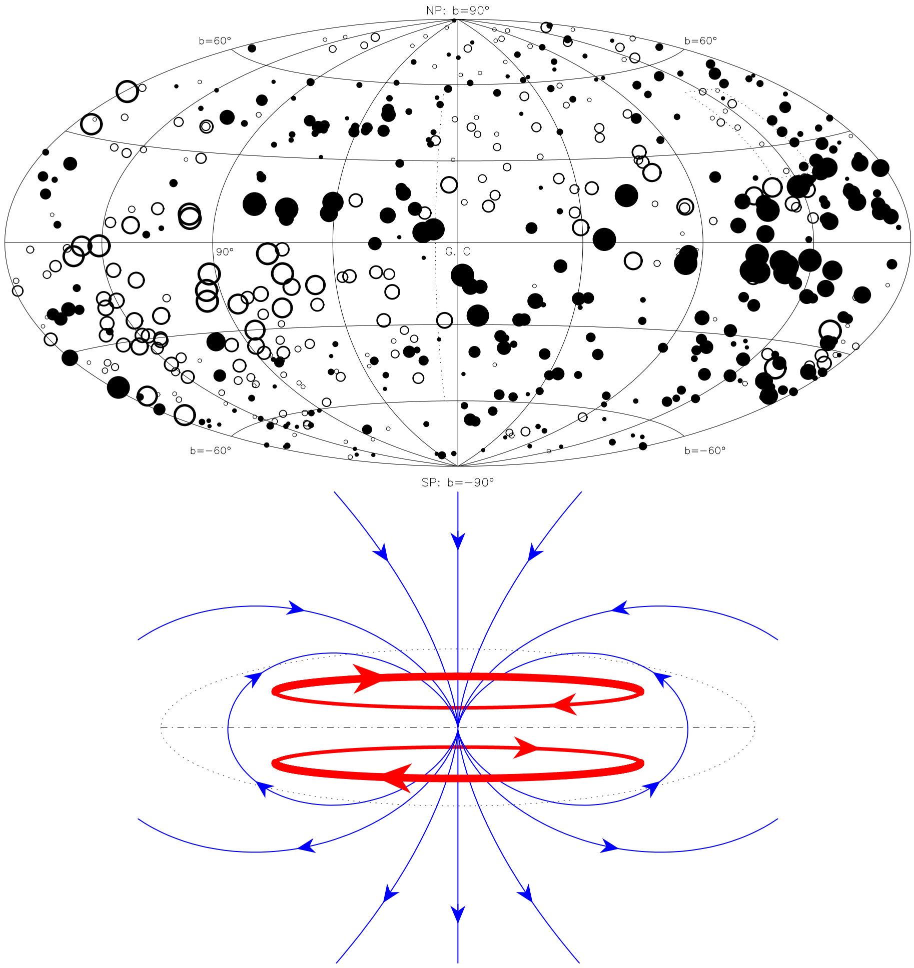

Fig. 1. The sky distribution of RMs of extragalactic radio sources and the magnetic field model in the Galactic halo, as discussed by Han et al. (1997).

radio sources and then check the antisymmetry of the residual RM map. If there is antisymmetry in the residual RM map, then it is large-scale, otherwise it is local. However, both the RM data of pulsars and extragalactic radio sources are so sparse that such a subtraction cannot give a clear result at the moment. We checked the magnitude distribution of RMs of extragalactic radio sources, which is indeed systematically larger than those of pulsars, as expected from the large-scale halo field (Fig.2).

More RM data of both pulsars and extragalactic radio sources towards medium Galactic latitudes in the inner Galaxy are desired to check this crucial issue of Galactic dynamo.

If such a large-scale magnetic field model is confirmed by more data, then our Galaxy is the first galaxy in which the dynamo signature is clearly identified. In other words, it is the first time to identify a dynamo at a galactic scale. This is very difficult for other galaxies. We studied all possible RM data for M31, and got some evidence for the magnetic field configuration of a possible S0 dynamo (Han et al. 1998).

3 Magnetic fields in the Galactic disk: based on pulsar RMs

Pulsars are the best probes for Galactic magnetic fields. First of all, pulsars are highly polarized in general. So their RMs are relatively easy to measure, in contrast to the great difficulties to do Zeeman splitting measurements. Second, pulsars do not have any intrinsic RM. So, what one gets from RMs is just the contribution from the interstellar medium, an integration of diffuse magnetic fields along the

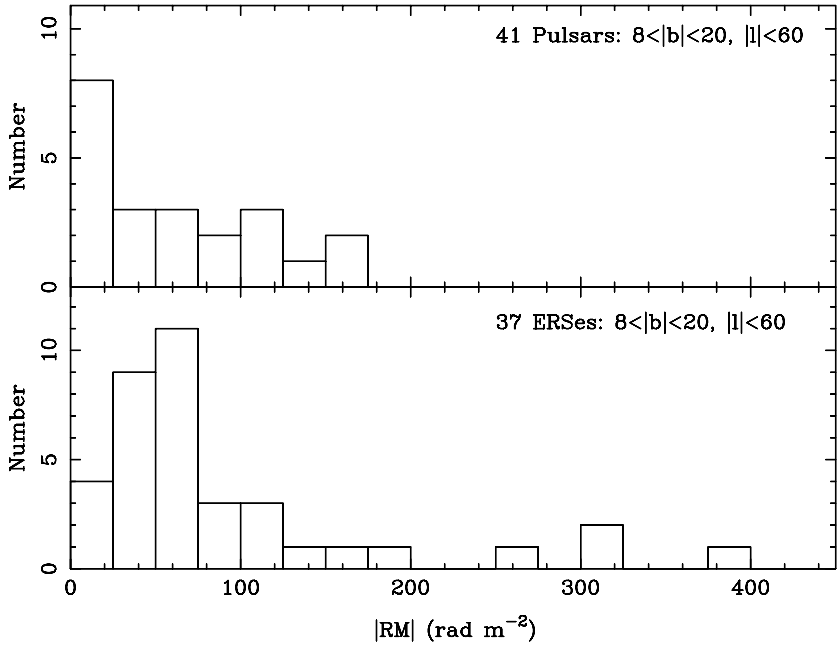

Fig. 2. The RM amplitudes of extragalactic radio sources in the very inner Galaxy are systematically larger than those of pulsars, indicating that the antisymmetric fields extended towards the Galactic center, far beyond the pulsars.

path from a pulsar to the observer, rather than *in situ* measurements in emission regions. Third, the total amount of the electron density between a pulsar and an observer can be measured independently by the pulsar dispersion measure, $DM = \int_{\rm psr}^{\rm obs} n_e \, dl$. This leads to a direct measure of the averaged magnetic field along the line of sight by using $\langle B_{||} \rangle = 1.232 RM/DM$. There have been many pulsars discovered, which are widely spread in our Galaxy. After measuring their RMs, it will not be very hard to find a 3-D magnetic field structure in our Galaxy.

3.1 Historical landmarks of using the pulsar RMs for the large-scale magnetic fields

A close look at the historical landmarks of using pulsar RMs to study the Galactic magnetic fields will show the progress in the last two or three decades.

Soon after the pulsars were discovered, Lyne & Smith (1969) detected their linear polarization. They noted that this "opens up the possibility of measuring the Faraday rotation in the interstellar medium" which "gives a very direct measure of the interstellar magnetic field", because $\int_{\rm obs}^{\rm obj} n_e dl$ can be measured by DM so that $\langle B_{||} \rangle$ can be directly obtained from the ratio RM/DM. Manchester (1972, 1974) first systematically measured a number of pulsar RMs for Galactic magnetic fields and concluded that the local field (within 2 kpc!) is directed toward about $l \sim 90°$. Thomson & Nelson (1980) modeled the pulsar RMs mostly within 2 kpc and found the *first* field reversal near the Carina-Sagittarius arm. The largest pulsar RM dataset was published by Hamilton & Lyne (1987), mostly for pulsars at about 5 kpc and some up to 10 kpc. Then Lyne & Smith (1989) used pulsar RMs to further study the Galactic magnetic field. They confirmed the first field reversal in the inner Galaxy and found evidence for the field reversal in the outer Galaxy by a comparison of pulsar RMs with those of extragalactic radio sources. Rand & Kulkarni (1989) analyzed 185 pulsar RM data and proposed the ring model for the Galactic magnetic field. Rand & Lyne (1994) observed more RMs of distant pulsars and found evidence for the clock-wise field near the Crux-Scutum arm (at about 5 kpc). Han & Qiao (1994) and Indrani & Deshpande (1998) reanalyzed the pulsar RM data and found that the RM data are more consistent with the bisymmetric spiral model than with the ring model.

Han et al. (1997) first noticed that the RM distribution of high-latitude pulsars is dominated by the azimuthal field in the halo. Afterwards, any analysis of pulsar RMs for the disk field was limited

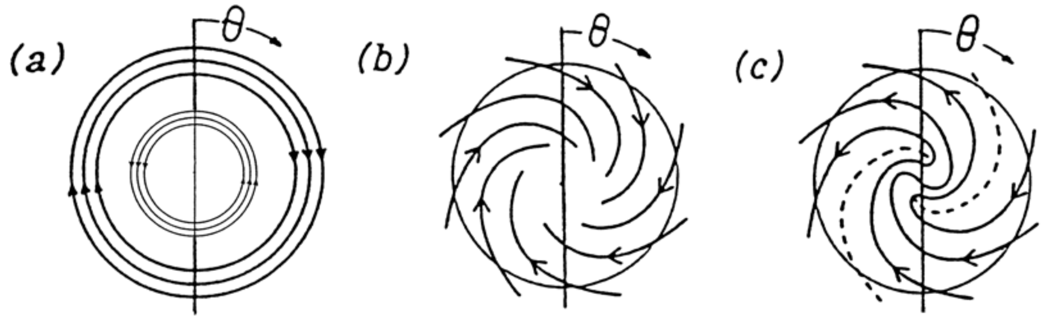

Fig. 3. A sketch of three models for Galactic magnetic fields, namely, (a) the concentric ring model, (b) the axisymmetric spiral model, and (c) the bisymmetric spiral model.

to pulsars at lower Galactic latitudes ($|b| < 8°$). Han et al. (1999) then observed 63 pulsar RMs and divided all known pulsar RMs into those lying within higher and lower latitude ranges for studies of the halo and disk field, respectively, and they confirmed the bisymmetric field structure and refined estimates of the vertical field component.

3.2 The large-scale magnetic field models

There have been three models to describe the global magnetic field structure of our Galaxy. In the early stage, Simard-Normandin & Kronberg (1980) showed that the RMs of extragalactic radio sources and pulsars are consistent with the bisymmetric spiral model. This was later confirmed by Sofue & Fujimoto (1983). The currently available pulsar RM data are mostly consistent with a bisymmetric spiral model as we will discuss below. While Vallée (1991, 1995) has argued for an axisymmetric spiral model. In this model, the field reversal occurs only in the range of Galactic radii from 5 to 8 kpc (Vallée 1996). No field reversals are allowed beyond 8 kpc or within 5 kpc from the Galactic Center. This is in contrast to the field reversals suggested beyond the solar circle and detected interior to the Crux-Scutum arm (e.g. Han et al. 1999, 2002). We noticed that recent arguments favour no field reversal outside the Perseus arm (e.g. Brown et al. 2003), which need more RM data of pulsars in the Perseus arm to check. Extragalactic radio source data are not enough to make a solid conclusion. The concentric ring model, proposed by Rand & Kulkarni (1989) and Rand & Lyne (1994), has a pitch angle of zero, but the observed pitch angle of fields of $-8°$ favours a spiral form of the field structure. Both the ring model and axisymmetric spiral model show that the magnetic field lines go across the spiral arms, which seems not to be physically possible.

3.3 Current status and future directions

Up to now, among about ∼1450 known pulsars, 535 pulsars have measured values of RM and 373 of them are located at lower latitudes ($|b| < 8°$). This includes 200 RM data from Parkes observations, which will be published soon (Han et al. in prep.). Significant progress has been made in the last decade on the magnetic fields in the Galactic disk, mainly because many pulsars have been discovered in the nearby half of the whole Galactic disk (e.g. Manchester et al. 1996; Lyne et al. 1998; Manchester et al. 2001) and extensive observations of pulsar RMs (e.g. Hamilton & Lyne 1987; Rand & Lyne 1994; Han et al. 1999) were conducted.

Analysis of pulsar RMs needs to consider three important factors for the diagnosis of the large-scale field structure. First, one normally assumes that the azimuthal field component B_ϕ is greater than the vertical and radial components B_z or B_r. This is reasonable and has been justified (Han & Qiao 1994; Han et al. 1999). Second, it is *the gradient of the average or general tendency of RM variations* versus pulsar DMs that traces the large-scale field. The scatter of the data about this general tendency is probably mostly due to the effect of smaller scale interstellar structure. Finally, the large-scale field structure should produce a coherence in the gradients for many independent lines of sight (see e.g. $l = \pm 20°$ near the Norma arm in Fig. 4).

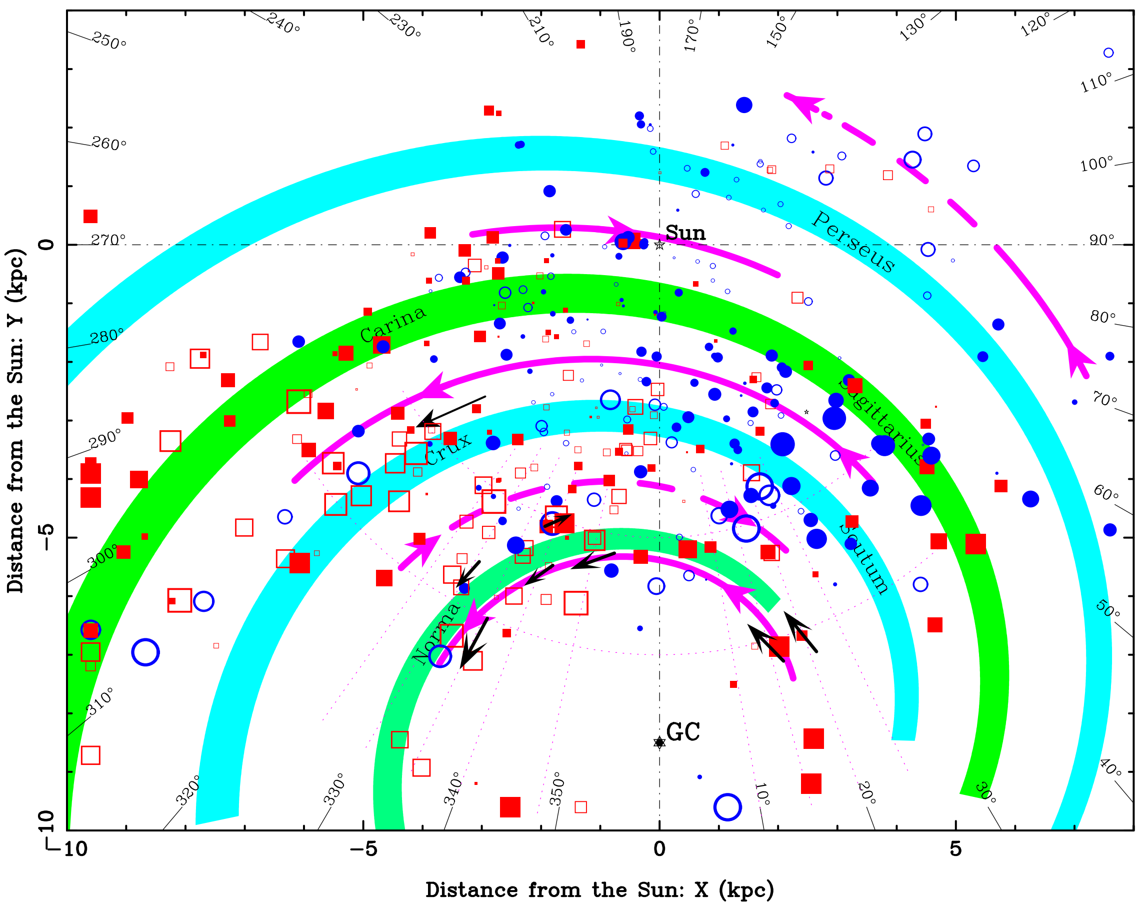

Fig. 4. The RM distribution of pulsars projected onto the Galactic plane. Red data (squares) are newly observed, and blue (circles) are previously published. Filled symbols stand for positive RMs and open ones for negative RMs. The large-scale magnetic fields are drawn by arrows, which was inferred from RM data. Solid-line arrows stand for confirmed field structures, while dashed-line arrows stand for proposed field structures in controversy and to be confirmed. The pulsar distances were estimated by a new electron density model (NE2001: Cordes & Lazio 2002). The magnetic fields are very probably going along the spiral arms, with *coherent directions* over more than 10 kpc interior to Carina-Sagittarius arm.

From the most updated RM distribution (see Fig. 4), we can conclude that magnetic fields between the Perseus arm and Carina-Sagittarius arm have a clock-wise direction when looking from the Northern galactic pole. Apparently this at least holds for about 5 kpc along the spiral arms. Between the Carina-Sagittarius arm and the Crux-Scutum arm, the positive RMs near $l \sim 50°$ and negative RMs near $l \sim 315°$ show the coherently counter-clockwise magnetic field along the spiral arm over more than 10 kpc! From the RMs of pulsars discovered by the Parkes multibeam survey, the counter-clockwise magnetic field along the Norma arm (i.e. the 3-kpc arm) has been clearly identified (Han et al. 2002). There have been some indications for clockwise magnetic fields between the Crux-Scutum arm and the Norma arm, while more RM data are obviously desired for a definite conclusion.

In the outer Galaxy the magnetic fields directions in or outside the Perseus arm have been in controversy recently. The magnetic field reversals suggested by Lyne & Smith (1989) have been confirmed by Han et al. (1999) and Weisberg et al. (2004) using available pulsar RMs mostly near $l \sim 70°$. While Mitra et al. (2003) and Brown et al. (2003) have argued for no reversal near or outside the Perseus arm from the RM data of pulsars and extragalactic radio sources in the region of $145° < l < 105°$. The average of RM values seems not to be significantly different for the foreground pulsar RMs near the Perseus arm and to the background extragalactic radio sources. This fact probably indicates two field reversals outside the Perseus arm which cancels their RM contributions. It is necesary to compare RM data of pulsars in the Perseus arm and background extragalactic radio sources between $45° < l < 110°$ for that purpose. A solid conclusion about the magnetic field configurations in this region would come out soon after many more pulsars in this region will be discovered in a future Arecibo L-band multibeam pulsar survey.

3.4 Discussions

Beside the large-scale magnetic field, naturally there are small-scale magnetic fields in our Galaxy. The strength of the large-scale magnetic field has been estimated to be $1.8 \pm 0.5\ \mu$G (Han & Qiao 1994; Indrani & Deshpande 1998), while the total field strength estimated from cosmic-rays or using the equipartition assumptions is about 6μG. We have composed the energy spectrum of Galactic magnetic fields at different scales, from 0.5 kpc to 15 kpc (Han et al. 2003). Based on this spectrum, we estimate the fluctuations of magnetic fields have an rms field strength about 6 μG, which is very consistent with estimates for the total field strength by other methods. This confirms that the magnetic field strengths estimated from pulsar rotation measures are statistically fine for the diffuse interstellar medium. The field strength of regular magnetic fields estimated from the percentage of polarized continuum emission of nearby galaxies then probably has been two or three times overestimated.

Recently, Mitra et al. (2003) have shown that two or three pulsar RMs are affected by H II regions as these pulsars can be easily identified by their large DMs. In fact, the large DM should lead to an overestimated distance for the pulsar in a given electron density model. However, only a very small number of pulsars can be affected by chance, according to simulations made by Cordes & Lazio (2002).

The coherent variation of RMs versus DMs in different directions not only provides the information about the large-scale magnetic fields, but also indicates that the data scattering from the general tendency of variation due to small-scale regions does not influence the analysis of RMs for the large-scale magnetic fields.

4 Conclusions

Pulsars provide unique probes for the *large-scale* interstellar magnetic field in the Galactic disk. Other methods seem to have many difficulties for that purpose. The increasing number of RMs, especially of newly discovered distant pulsars, enables us for the first time to explore the magnetic field in nearly one third of the Galactic disk. The fields are found to be *coherent in directions* over a linear scale of more than ~ 10 kpc between the Carina-Sagittarius and Crux-Scutum arms from $l \sim 45°$ to $l \sim 305°$ and more than 5 kpc along the Norma arm. The magnetic fields reverse their directions from arm to arm. The coherent spiral structures and field direction reversals, including the newly determined counter-clockwise field near the Norma arm, are consistent with a bisymmetric spiral model for the disk field.

At high latitudes, the antisymmetric RM sky is most probably produced by the toroidal field in the Galactic halo. Together with the dipole field in the Galactic center, it strongly suggests that an A0 dynamo is operating in the halo of our Galaxy.

Acknowledgments

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References

Beck R., Brandenburg A., Moss D., Shukurov A., Sokoloff D. (1996) *Annnu. Rev. Astron. Astrophys.* **34**, 155.
Beck R., Shukurov A., Sokoloff D., Wielebinski R. (2003) *Astron. Astrophys.* **411**, 99.

Boulares A., Cox D.P. (1990) *Astrophys. J.* **365**, 544.
Bourke T.L., Myers P.C., Robinson G., Hyland A. R. (2001) *Astrophys. J.* **552**, 916.
Brown J. C., Taylor A. R., Wielebinski R., Mueller P. (2003) *Astrophys. J.* **592**, L29.
Cordes J.M., Lazio T.J.W. (2002) *Astrophys. J.*, submitted.
Crutcher R.M. (1999) *Astrophys. J.* **520**, 706.
Davies R.D. (1974) *IAU Simp.* **60**, 275.
Edwards R.T., Bailes M., van Straten W., Britton M.C. (2001) *Mon. Not. R. Astron. Soc.* **326**, 358.
Fish V., Reid M.J., Argon A.L., Menten K.M. (2003) *Astrophys. J.* **596**, 328.
Hamilton P.A., Lyne A.G. (1987) *Mon. Not. R. Astron. Soc.* **224**, 1073.
Han J.L., Beck R., Berkhuijsen E.M. (1998) *Astron. Astrophys.* **335**, 1117.
Han J.L., Ferriere K., Manchester R.N. (2003) *Astrophys. J.*, submitted.
Han J.L., Manchester R.N., Lyne A.G., Qiao G.J. (2002) *Astrophys. J.* **570**, L17.
Han J.L., Qiao G.J. (1994) *Astron. Astrophys.* **288**, 759.
Han J.L., Manchester R.N., Berkhuijsen E.M., Beck R. (1997) *Astron. Astrophys.* **322**, 98.
Han J.L., Manchester R.N., Qiao G.J. (1999) *Mon. Not. R. Astron. Soc.* **306**, 371.
Han J.L., Wielebinski R. (2002) *Chinese Journal of A&A* **2**, 293.
Hildebrand R.H., Davidson J.A., Dotson J.L., Dowell C.D., Novak G., Vaillancourt J. (2000) *Publ. Astron. Soc. Pac.* **112**, 1215.
Indrani C., Deshpande A.A. (1998) *New Astronomy* **4**, 33.
Kramer M., Bell J.F., Manchester R.N. et al. (2003) *Mon. Not. R. Astron. Soc.* **342**, 1299.
Krause F., Raedler K.H. 1980, *Mean-field Magnetohydrodynamics and Dynamo Theory* (Oxford: Pergamon Press).
Kulsrud R.M. (1999) *Annnu. Rev. Astron. Astrophys.* **37**, 37.
Lyne A.G., Smith F.G. (1968) *Nature* **218**, 124.
Lyne A.G., Smith F.G. (1989) *Mon. Not. R. Astron. Soc.* **237**, 533.
Lyne A.G., Manchester R.N., Lorimer D.R., Bailes M., D'Amico N., Tauris T.M., Johnston S., Bell J.F., Nicastro L. (1998) *Mon. Not. R. Astron. Soc.* **295**, 743.
Manchester R.N. (1972) *Astrophys. J.* **172**, 43.
Manchester R.N. (1974) *Astrophys. J.* **188**, 637.
Manchester R.N., Lyne A.G., Camilo F. et al. (2001) *Mon. Not. R. Astron. Soc.* **328**, 17.
Manchester R.N., Lyne A.G., D'Amico N., Bailes M., Johnston S., Lorimer D.R., Harrison P.A., Nicastro L., Bell J.F. (1996) *Mon. Not. R. Astron. Soc.* **279**, 1235.
Mitra D., Wielebinski R., Kramer M., Jessner A. (2003) *Astron. Astrophys.* **398**, 993.
Morris D.J., Hobbs G., Lyne A.G. et al. (2002) *Mon. Not. R. Astron. Soc.* **335**, 275.
Novak G., Chuss D.T., Renbarger T., Griffin G.S., Newcomb M.G., Peterson J.B., Loewenstein R.F., Pernic D., Dotson J.L. (2003) *Astrophys. J.* **583**, L83.
Rand R.J., Kulkarni S.R. (1989) *Astrophys. J.* **343**, 760.
Rand R.J., Lyne A.G. (1994) *Mon. Not. R. Astron. Soc.* **268**, 497.
Rees M. (1987) *Qua.J. R. Astron. Soc.* **28**, 197.
Reid M.J., Silverstein E.M. (1990) *Astrophys. J.* **361**, 483R.
Ruzmaikin A.A., Sokolov D.D., Shukurov A.M. (1988) *Magnetic Fields of Galaxies* (Dordrecht: Kluwer).
Simard-Normandin M., Kronberg P.P. (1980) *Astrophys. J.* **242**, 74.
Sofue Y., Fujinmoto M. (1983) *Astrophys. J.* **265**, 722.
Sofue Y., Reich W., Inoue M., Seiradakis J.H. (1987) *Publ. Astron. Soc. Japan* **39**, 95.
Strong A.W., Moskalenko I.V., Reimer O. (2000) *Astrophys. J.* **537**, 763.
Thomson R.C., Nelson A.H. (1980) *Mon. Not. R. Astron. Soc.* **191**, 863.
Vallée J.P. (1991) *Astrophys. J.* **366**, 450.
Vallée J.P. (1995) *Astrophys. J.* **454**, 119.
Vallée J.P. (1996) *Astron. Astrophys.* **308**, 433.
Weisberg J.M., Cordes J.M., Kuan B., Devine K.E., Green J.T., Backer D.C. (2004) *Astrophys. J.*, in press.
Yusef-Zadeh F., Morris M. (1987) *Astrophys. J.* **320**, 545.

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Statistical Analysis of Extra-galactic Rotation Measures

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Abstract. We have performed a statistical analysis of a sample of 1100 extra-galactic rotation measures (RMs) obtained from the literature. Using a subsample of approximately 800 reliable RMs we compute a rotation measure sky and determine reliable large scale features for the line of sight Galactic magnetic field. We find that the influence of the Milky Way can be seen up to roughly 30° on either side of the Galactic plane. Furthermore we observe an excess of RM on spatial scales between 30° and 50° in the region of the Galactic Plane. Additionally, the support for a bisymmetric spiral Galactic magnetic field is significantly reduced in our analysis.

1 Introduction

Magnetic fields are assumed to be pervasive throughout the Universe on all scales, from the fields surrounding planets right up to fields in the intracluster and intergalactic media. In recent years the role of magnetic fields in both galactic and extra-galactic regimes has gained increased attention across many astrophysical disciplines. For example, the magnetic field is a key factor in studies of large-scale structure formation, galaxy and star formation, and cosmic ray generation. In particular, the Galactic magnetic field has been studied since the late seventies with a variety of techniques. While it is clear that magnetic field research has progressed considerably in this time, the mostly indirect measurement techniques have meant that it has been difficult to address many basic issues. Questions as to how strong the Galactic magnetic field is, how uniform it is, what the seeding and amplification mechanisms are, and, most importantly, what the contribution is to the energy density of the galactic medium remain topics of animated debate.

One of the ways in which the Galactic magnetic field can be examined is through analysis of the rotation measures obtained for background extra-galactic sources. This gives information on the line-of-sight Galactic magnetic field and is complementary to results obtained from other techniques such as pulsar dispersion measures and mapping of the diffuse polarised emission of the Galaxy.

We present a statistical analysis of the RM sky as derived from a sample of extra-galactic RMs given in the literature and use these data to generate an interpolated map of the RM sky to give some insight into properties of the large-scale Galactic magnetic field.

2 RM Sample and Interpolated All-sky Mapping

Over 1000 extra-galactic RMs taken from several catalogues (Tabara & Inoue, 1980; Simard-Normandin et al., 1981; Broten et al., 1988; Hennessey et al., 1989; Rudnick & Jones, 1983; Lawler & Dennison, 1982) were initially examined. Only those with a reliable RM fit over at least three wavelengths were selected. In the case of sources appearing in more than one reference, the more reliable fit was used. This produced a final catalogue of 820 sources which was utilised in a two-stage process.

First, RMs projected through lines of sight through galaxy clusters were removed as it has been shown that they would be contaminated by passage through the cluster magnetic field (Clarke, 2000; Johnston-Hollitt, 2003). Next a culling algorithm removed sources for which there was a three-sigma deviation from the local median modulus RM. This was similar to previous small-scale Galactic

RM estimation techniques (Hennessey et al., 1989; Athreya et al., 1997) but rather than using a defined radius about an individual point the algorithm tests the population of at least the nine nearest neighbours. Moreover, unlike previous techniques, we estimate sigma from the median modulus value rather than simply the mean. The effect of the culling was to remove 19 sources of extremely high intrinsic RM. The estimation of line-of-sight RMs across the entire sky was then performed by obtaining a convergent solution to the 2-dimensional Poisson's equation. Unfortunately the source density of this dataset is approximately 0.013 sources per square degree and so the resolution of the resultant map was set to be no finer than one pixel per square degree. Figure 1 shows the resultant estimated all-sky RM map in Galactic coordinates. This clearly shows the strong correlation between RM and distance from the Galactic plane.

3 Structure Analysis

With such a dataset and all-sky RM map it is possible to statistically determine properties of the RM sky, such as the region in which our Galaxy significantly affects RM measurements. We investigated the data in several ways including a Fourier analysis of the RM sky at various Galactic latitudes and the source distribution for extra-galactic RMs beyond the region of Galactic influence.

3.1 Fourier Analysis

A Fourier analysis of the power at different spatial scales in the interpolated RM map was performed within different strips along the Galactic plane with increasing latitude. The power spectra within increasing intervals from the Galactic plane were examined starting from $\pm 15°$ and increasing to $\pm 60°$ in steps of 15°. An excess of RM power was seen at 30°, 46° and 50° in the small interval of $\pm 15°$ about the plane. In this region closest to the Galactic plane there was also marginal evidence for an excess at around 80°. In the interval $\pm 30°$ about the plane an excess was seen on spatial scales of 30° and 50°. In the intervals above 30° there was only very marginal evidence for some excess at around 50° in the $\pm 45°$ interval.

These results show that the Galactic magnetic field significantly influences RMs of extra-galactic sources that lie within an area roughly 30° either side of the Galactic plane. A comparative study of excess RM above and below the Galactic plane was also conducted. From this second analysis we obtain marginal evidence that the area of influence of the Galaxy extends further in the south. However, as there are much fewer actual RM measurements in this region of the sky this could well be the affect of poor and uneven sampling (as compared to the rest of the sky).

Reassuringly, results from this method are consistent with the large-scale positive and negative RM regions seen in the wavelet analysis study of Frick et al. (2001), which makes use of a similar dataset but does not make any attempt to remove RM values that are dubious or where a source has more than one value. In comparison to Frick et al. (2001) who obtain structures on spatial scales of roughly 30°–45° and 76°, we find excess RM power on scales between 30° and 50° within a region of 30° either side of the Galactic plane. Moreover, we find weak evidence of an excess at a scale of around 80°.

3.2 Global Field Examination

Comparison of the large-scale RM features with the position of the spiral arms as deduced from electron density models (Taylor & Cordes, 1993) demonstrates that these features are likely to be correlated with the magnetic field in the interarm region between the Perseus and Sagittarius spiral arms. The number and position of field reversals in the Milky Way are critical to distinguish the global field as either axisymmetric or bisymmetric (Vallée, 1996) and proponents of various models often have widely varying interpretations of the global direction of each arm and its associated interarm regions (Vallée, 1991; Clegg et al., 1992; Han et al., 1994; Rand et al., 1994; Vallée, 1996). It is generally agreed that the field rotates in a clockwise direction in the interarm region between the Perseus and Sagittarius–Carina arms and in an anti-clockwise direction in the region between the Sagittarius–Carina and

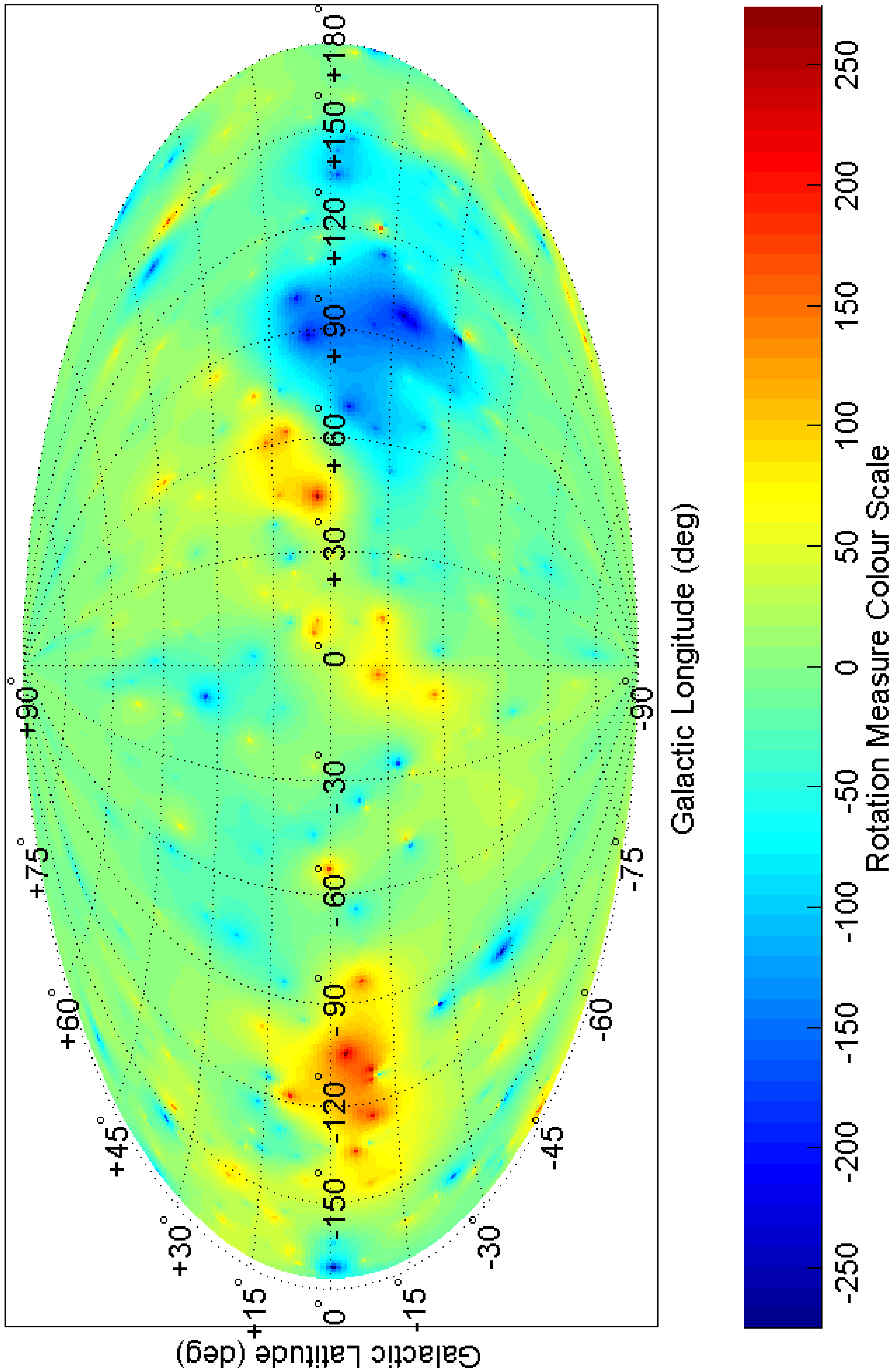

Fig. 1. Interpolated All-sky Rotation Measure Map, created from over 800 published RM values calculated for extra-galactic sources. The resolution is one pixel per square degree.

Scutum–Crux arms. In addition, the weight of the literature supports a clockwise rotation in the interarm region between the Scutum-Crux and Norma arms. However, the field direction between the other spiral arms in the outer and inner parts of the galaxy is an area of contention.

The interpolated data appear consistent with a clockwise field direction beyond the Perseus spiral arm, in the region between the Perseus and Perseus +I arm, however, this is inconsistent with pulsar dispersion measures (Han et al., 1994) but agrees with models including other RM data (Vallée, 1996).

The interpolated data are not conclusive for other regions. In the regions corresponding to both the Perseus/Sagittarius–Carina interarm region the interpolated data show both positive and negative features. In the area between the Sagittarius–Carina and Scutum–Crux arms these data show only a positive RM region. One notable feature in the interpolated map from the new dataset is the lack of the alternating positive-negative-positive-negative RM average in the four quadrants of the sky which had been claimed in previous work (Han et al., 1997). As the alternating positive-negative signature is believed to give evidence for a bisymmetric field structure in our Galaxy, the lack of the expected positive average RM in the region between $0^\circ \leq l \leq 180^\circ$ and $0^\circ \leq b \leq 90^\circ$ puts the bisymmetric model in some doubt. We note that Frick et al. (2001) also find only marginal evidence for this signature. This suggests this feature is highly sensitive to even small changes in the dataset used and more RMs will be required to settle this point.

3.3 Source Statistics

In order to investigate the statistical behaviour of the RM distribution, subsets of the data at various distances from the Galactic plane were examined prior to removing the high intrinsic RM sources. In particular, the region greater than 30° from the Galactic plane was heavily investigated as this had previously been shown to be beyond the influence of the Galactic field (see Section 3.1). The standard deviation of 474 extra-galactic RMs at greater than 30° from the Galactic plane was found to be 10 rad m^{-2} which is consistent with more localised calculations taken at such high Galactic latitudes (Athreya et al., 1997; Clarke, 2000). Furthermore, it was discovered that at high galactic latitudes the source distribution follows an exponential. This result is both interesting and unexpected as at these latitudes one expects little or no contribution to the RM from the magnetic field of the Galaxy, suggesting that the exponential distribution must either be a product of internal rotation in the extra-galactic sources or propagation through different magnetized cells in the interstellar medium. It was previously thought that this distribution would be Gaussian. This is an interesting and important result which implies that the occurrence of intrinsically high RMs is currently being underestimated. Figure 2 shows the distribution of RM at $|b| \geq 30^\circ$ for the Galactic plane overlaid with an exponential fit to the data. Figure 3 shows the same data but with a log–linear plot. Chi-squared testing shows this data to be exponential of the form Number of occurrences = A $\exp(-0.037 \times \mathrm{RM})$ (where A is a scaling constant in this case A=289) to greater than the 99.9% confidence level. In comparison, the distribution obtained from all data, i.e. including those RMs seen on lines of sight through the Galaxy shows a marked deviation from the exponential fit, especially for sources with modulus RMs greater than 50 rad m^{-2}.

4 Conclusions

We have presented an analysis of the currently available reliable population of extra-galactic rotation measures. From this we find that the influence of the Galactic magnetic field is statistically significant out to ±30° from the Galactic plane and that it has excess power on spatial scales of 30°, 46° and 50°. This agrees well with alternative analyses. We further find that the current data do not suggest the alternating positive-negative average RM values in each Galactic quadrant required to support a bisymmetric magnetic field for the Milky Way. Furthermore, we show that the population of high Galactic RMs presumed to be unaffected by the magnetic field of our Galaxy follows an exponential distribution to above 99.9% confidence.

With the completion, or near completion, of major polarimetric surveys such as the Southern Galactic Plane Survey and the Canadian Galactic Plane Survey, a wealth of new information on the

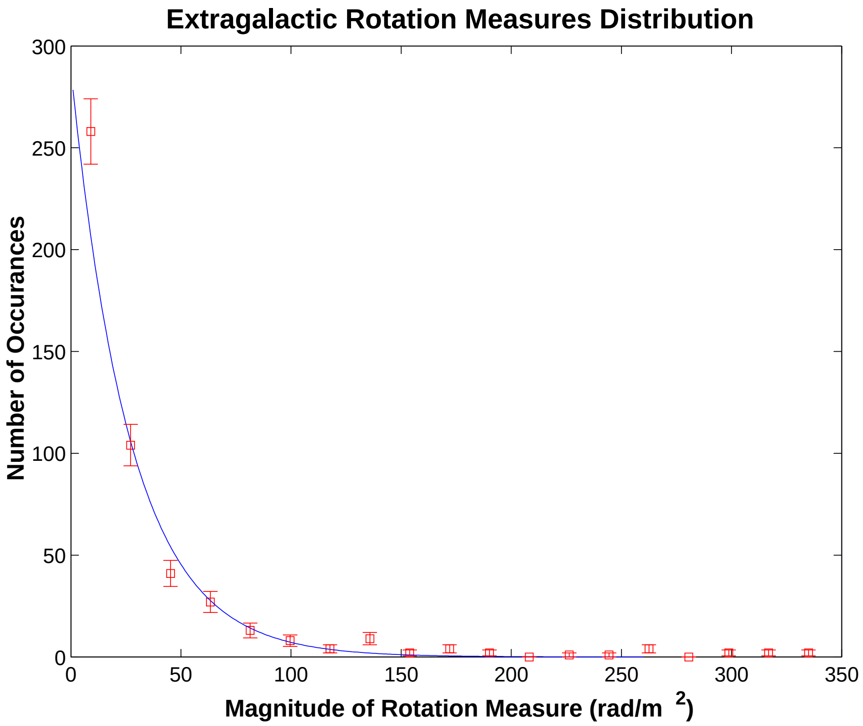

Fig. 2. Plot of the extra-galactic RM distribution for sources greater than 30° from the Galactic plane. The boxes represent the data, while the line is the chi-squared fit to the data.

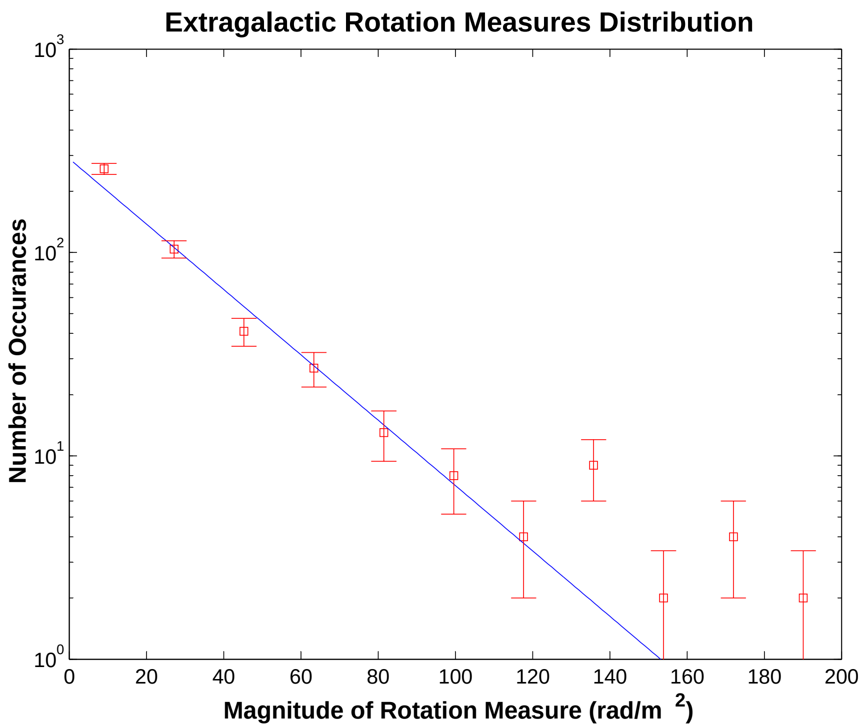

Fig. 3. Plot of the extra-galactic RM distribution for sources greater than 30° from the Galactic plane shown as a log–linear plot. The boxes represent the data, while the line is the chi-squared fit to the data.

magnetic field structure of our galaxy will soon become available. The expected boost in available data for this work is a factor of 5–10. Tantalising preliminary results have recently appeared, giving new insight into both the RM structure of the sky as seen through the Galaxy and the role of the magnetic field in diffuse Galactic plasma (Gaensler et al., 2001; Brown et al., 2001). As these new data become available, better modelling and possibly even subtraction of the effect of the local field will be possible. With new instruments such as the SKA it may even be possible to completely disentangle the propagation effects on RM data and see, for the first time, the 3D magnetic structure of the Universe. Thus, the interpolated technique presented here should continue to be useful in evaluating the rotation measure sky.

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References

Athreya R.M., Kapahi V.K., McCarthy P.J., van Breugel W. (1997) *Astron. Astrophys.* **329**, 809.
Broten N.W., MacLeod J.M., Vallée J.P. (1988) *Astrophys. Space. Sci.* **141**, 303.
Brown J.C, Taylor A.R. (2001) *Astrophys. J.* **563**, L31.
Clarke T.E. (2000) *Probing Magnetic Fields in Clusters of Galaxies* (Ph.D. Thesis, University of Toronto).
Clegg A.W., Cordes J.M., Simonetti J.H., Kulkami S.R. (1992) *Astrophys. J.* **386**, 143.
Frick P., Stepanov R., Shukurov A., Sokoloff D. (2001) *Mon. Not. R. Astron. Soc.* **325**, 649.
Gaensler B.M., Dickey J.M., McClure-Griffiths N.M., Green A.J., Wieringa M.H., Haynes R.F. (2001) *Astrophys. J.* **549**, 959.
Han J.-L., Qiao G.J. (1994) *Astron. Astrophys.* **288**, 759.
Han J.-L., Manchester R.N., Berkhuijsen E.M., Beck R. (1997) *Astron. Astrophys.* **322**, 98.
Hennessey G.S., Owen F., Eilek J. (1989) *Astrophys. J.* **347**, 144.
Johnston-Hollitt M. (2003) *Detection of Magnetic Fields and Diffuse Radio Emission in Abell 3667 and other Rich Southern Clusters of Galaxies* (Ph.D. Thesis, University of Adelaide).
Lawler J.M., Dennison B. (1982) *Astrophys. J.* **252**, 81.
Rand R.J., Lyne A.G. (1994) *Mon. Not. R. Astron. Soc.* **268**, 497.
Rudnick L., Jones T. (1983) *Astron. J.* **88**, 518.
Simard-Normandin M., Kronberg P.P., Button S. (1981) *Astrophys. J. Suppl.* **45**, 97.
Tabara H., Inoue, M. (1980) *Astron. Astrophys. Suppl.* **39**, 379.
Taylor J.H., Cordes J.M. (1993) *Astrophys. J.* **411**, 674.
Vallée J.P. (1991) *Astrophys. J.* **366**, 450.
Vallée J.P. (1996) *Astron. Astrophys.* **308**, 433.

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A Re-examination of Data on Magnetic Fields in the Galaxy*

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Abstract. The Milky Way was shown to be a spiral galaxy first by mapping the H I gas, then through studying H II regions and more recently by CO observations. The existence of magnetic fields in the Milky Way was first deduced from optical starlight polarization observations although earlier radio continuum observations have been made, that required magnetic fields to be present. Definitive proof of the existence of magnetic fields in our Galaxy came from radio polarization observations. Zeeman effect detection in molecular clouds followed. Additional methods of studying of magnetic fields is to use extragalactic sources and pulsars as probes of the interstellar Faraday effect. The combination of all these data should allow us to determine the magnetic field morphology. We examine some recent observations of pulsars and extragalactic radio sources in the Galactic plane as well as radio polarization data to point out problems and limitations of these data in giving us information about the morphology of the magnetic field in the Galaxy.

1 Introduction

The delineation of the spiral structure of the Milky Way is one of the great results of radio astronomy. The mapping of the neutral hydrogen (H I) line at 1.427 GHz gave us the basic data on the distribution of neutral gas in the Milky Way (e.g. Nakanishi & Sofue, 2002). The study of H II regions (e.g. Georgelin & Georgelin, 1976; Paladini, 2003) allowed us to delineate spiral arms. From these results we know that the Sun is on the inside edge of the Perseus spiral arm at a distance of $\sim$ 8.5 kpc from the Galactic center. The Carina-Sagittarius arm is inside, followed by the Crux-Scutum spiral arm. The Norma spiral arm is nearest to the Galactic center. Recent studies suggested several irregular features joining the individual spiral arms, like spokes of a wheel, an observational feature also seen in other nearby galaxies.

The radio continuum observed by Karl Jansky 70 years ago was a signature of magnetic fields in the Milky Way. It took 20 years to give the correct interpretation of this startling discovery. The final interpretation was that the synchrotron emission process is responsible for this radio emission. Synchrotron emission is emitted as linearly polarized wave with the **B** vector normal to the magnetic field orientation, i.e. $\mathbf{B}_\perp$. The concept of equipartition between magnetic fields and cosmic rays suggest that Galactic magnetic fields are of the order of 3–10 μG in magnitude. Both optical and radio continuum polarization has been detected in 1949 and 1962 respectively towards the nearby Perseus spiral arm, notably towards the 'fan region' ($l = 140°,\ b = 10°$). Both the optical and radio observations suggested that the magnetic field is oriented along the azimuth of the Galactic plane, since the 'E' vectors are seen perpendicular to the plane of the Galaxy. The observed Faraday rotation of the 'fan region' suggested in addition a loop-like local magnetic field structure with RMs of opposite sign on either side of the neutral point. Radio Zeeman effect gives us information about magnetic fields in molecular clouds. Extragalactic radio sources (EGRS) that probe the line of sight magnetic fields ($\mathbf{B}_{||}$) have been studied by e.g. Simard-Normandin & Kronberg (1980) suggesting a large-scale magnetic field alignment. Even more important are observations of pulsars which allow the absolute determination of the magnetic fields intensity as well as the direction in the line of sight. We refer to Han et al. (2002), Han & Wielebinski (2002) and to the contribution by Han (this volume) for some of the historical references. In the published papers it has been suggested that the magnetic field of the Galaxy has a very well organized bi-symmetric structure, i.e. the direction of the magnetic field changes (reverses) from one spiral arm to the next.

*Based on observations with the Effelsberg 100-m telescope operated by the Max-Planck-Institut für Radioastronomie (MPIfR), Bonn, Germany

We re-examine these data in the quest for understanding the morphology of the magnetic field in our Galaxy. In fact some of the assumptions made by workers in the field do not hold in view of recent results.

(a) The fact that magnetic fields are concentrated to a thin plane, as seen in the polarized intensity of the 2.3 GHz Parkes and 2.7 GHz Effelsberg Galactic plane surveys, implies that we must probe preferably regions with $b = \pm 5^{\circ}$.

(b) The realization that rotation measure due to the H II (Hα) regions in our Galaxy is much higher than previously published means we must correct for foreground H II (Hα) regions. Here the new Hα surveys are a great help.

(c) We must understand the methods as how magnetic fields couple to interstellar matter. Progress seems to have been achieved in this direction both by theory and by observations.

In the following we summarize the recent developments and point out how they effect the established knowledge.

2 Optical polarization

Techniques to observe the polarization of starlight came in to use in 1949. Later optical surface polarimetry was successfully used to delineate the optical polarization, especially of nearby galaxies. Since a viable interpretation was given for the action of magnetic fields in aligning dust grains in 1951 this method could be applied to observe magnetic fields in the Milky Way and in nearby galaxies. The optical community remained skeptical, since polarization could be produced by other mechanisms, as well as by aligned dust grains. In retrospect, after radio polarization observations became available, we can say that the method was sound and gave us correct information in most cases. The milestones in our information about the Milky Way was a collection of northern hemisphere and southern hemisphere data by Mathewson & Ford (1970) who showed that the magnetic fields are aligned along the Galactic plane with some local features, like the North Polar Spur, showing vertical orientations. The limitation of this method is to the local magnetic field with $d < 1$ kpc. A more recent catalogue of $\sim$10,000 stars by Heiles (2000) and the review by Fosabla et al. (2002) emphasize this limitation.

3 Radio continuum surveys

Radio continuum surveys have been made over a wide frequency range. The lowest frequency of an all-sky survey is 30 MHz. Data at 45, 150, 408, and 1420 MHz also being available with degree resolution. Most recently excellent surveys have been made in the WMAP satellite project, giving us all-sky data at 22.8, 33.0, 40.7, 60.8 and 95.5 GHz. These are total intensity data. Early surveys of linear polarization, made in the 1960's gave us the first look at the distribution of polarization across the sky. All-sky polarization data will become available at 1.4 GHz as a result of surveys by Testori et al. (this volume) of the southern sky and Wolleben et al. (this volume) of the northern sky. Polarization surveys of the Galactic plane are more numerous but usually cover only a very limited Galactic latitude range (e.g Duncan et al., 1997, 1999). The Canadian Galactic Plane Survey (CGPS, Taylor et al., 2003) gives us polarization data of the northern plane with arcminute resolution. The Effelsberg Medium Latitude Survey (EMLS) will give us polarization data with $9'$ resolution for $b = \pm 20^{\circ}$ (Reich et al., this volume). This survey will also be used to add the diffuse structure in the CGPS interferometer data. In a preliminary result for selected EMLS fields Uyanıker et al. (1999) showed that there are considerable polarized intensity fluctuations. This implies significant rotation measure variations in the local interstellar medium. All these data must be considered to understand the morphology of the Galactic magnetic field. Also studies at 1.6 GHz (Wolleben, this volume) have shown that rotation measure towards local molecular clouds can be as high as RM $\sim$ 30–50 rad m^{-2}. Also the southern survey at 1.4 GHz by Gaensler et al. (2001) showed coherent RM values of ± 200 rad m^{-2} on scales of $10'$ towards the inner Galaxy. The results published by Spoelstra (1986) were derived from undersampled maps made with $\sim 2^{\circ}$ resolution and hence gave very low RM values.

4 Pulsars and extragalactic sources

Pulsars ideally probe the Galactic magnetic fields since once both dispersion measure and rotation measure have been observed the value of mean magnetic field intensity can be determined. Pulsars are found well concentrated to the Galactic plane and hence should be ideal as probes. However of the $\sim$ 1400 pulsars known only some 350 have observed RM. These are also preferentially seen towards the Galactic center. We (Mitra et al., 2003) have added new RM observations for 25 pulsars in the direction of the Perseus spiral arm. This was aimed to improve the statistics in this direction and to advance compatibility with EGRS observations described below. In the course of this work we have discovered that pulsars seen in the direction of extended H II regions show an increase in DM and RM as well as sometimes a change in the field direction. In particular in the direction of $l = 149°,\ b = -1.^\circ 0$, the H II region Sharpless S205 suggests that interaction leads to a magnetic field reversal.

We have added the observed sources from our work to the published results (e.g. Han et al., 2002) and show this in Figure 1. We suggest that there is a well established clockwise magnetic field along the Perseus arm. The claim by Han et al. (2002a) that a reversal is seen beyond the Perseus arm cannot be substantiated, based on pulsar and EGRS data. The situation in the Carina-Sagittarius arm is very complicated. In the Sagittarius section of the spiral arm the direction of the magnetic field observations is predominantly anti-clockwise. However in the Carina section there is a mixture of observed directions. In the inner Galaxy the situation is most complicated. There are numerous H II/Hα regions between the Sun and the Galactic Center requiring careful analysis. More work on RM observations of weak and distant pulsars is needed before a conclusive result can be claimed.

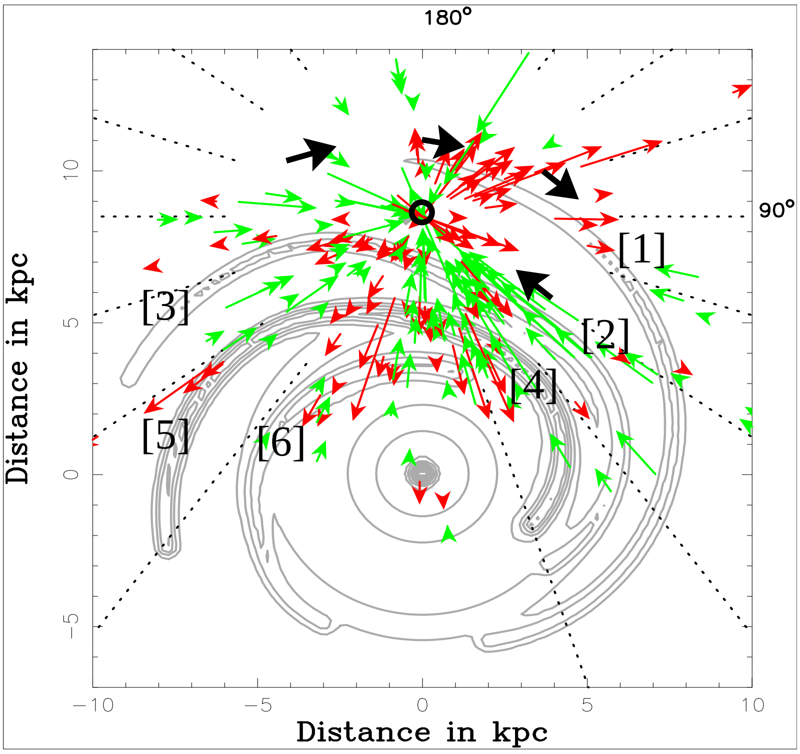

Fig. 1. The grey contours represents the electron density distribution of the top view of our Galaxy as given by the Taylor & Cordes (1993) electron density model. Numbers correspond to spiral arms named as [1] Perseus, [2] Sagittarius, [3] Carina, [4] Scutum, [5] Crux and [6] Norma. The dark open circle is the location of the Sun. Red and green arrows are negative and positive RM of pulsars with pulsars located at the center of these arrows and the size of the arrows corresponding to the magnitude of RM. The dark arrows correspond to the direction of the average magnetic field towards the Perseus and the Sagittarius arms. Note that these are only two directions where such coherent direction of the field can be inferred from the pulsar data. Other directions are limited by statistics and insignificant pattern in pulsar RM distribution.

The rotation measure of $\sim$ 500 EGRS (e.g. Simard-Normandin & Kronberg, 1980) has been traditionally used to determine the ‘Magnetic Field of the Galaxy’. The number of sources is relatively small for the whole sky and thus does not sample the magnetic field very well. Also since this data does not have many sources in the Galactic plane we consider this to be only a signature of a very local Galactic magnetic field. In the CGPS, using four frequency channels, a large number of sources have been observed in the inner $b = \pm 5°$ and $150° > l > 70°$ of the Galactic plane (Brown et al., 2003b). Papers by Brown & Taylor (2001) and Brown et al. (2003a) have analyzed these data, pointing out that no reversals of the magnetic field are seen in the outer Galaxy (Perseus arm). Many local reversals are seen, which are mainly correlated with H II regions.

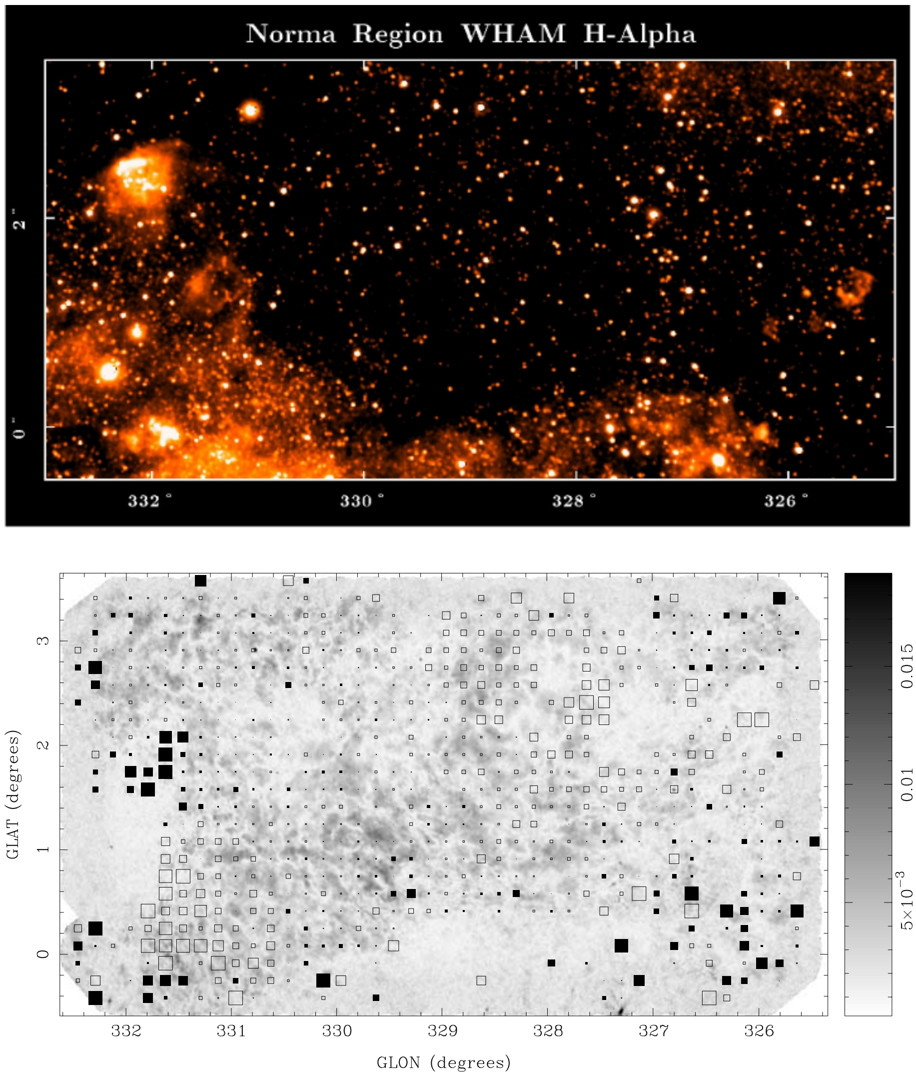

Fig. 2. The RM picture from Gaensler et al. (2001) and the WHAM Hα suvey showing the association of field reversals and Hα regions

5 Additional information

The Zeeman effect has been detected in several spectral lines at radio frequencies. The first detection was in the H I line which was followed by OH, H_2O, H30α recombination line, CN and CCS lines. (see Troland and Crutcher, this volume). In view of the small number of observations it is not really possible to determine a large-scale structure of the Galactic magnetic field. The only more extended catalogue of OH observations by Fish et al. (2003) gives data on 100 Zeeman pairs in 50 massive star-forming regions. The authors say that the data does not support a uniform, Galactic scale magnetic field direction, nor is there any strong correlation within the spiral arms. The one conclusion is that the magnetic field outside the solar circle is oriented clockwise while inside the solar circle it is oriented anti-clockwise.

Several additional observations confirm the complicated picture of the magnetic field orientations in our Galaxy. The observations of the RM of the Galactic emission by Gaensler et al. (2001) in the direction of the Norma arm shows considerable fluctuations of RM on scales of arcminutes. In fact values of $200\,\mathrm{rad\,m^{-2}} > \mathrm{RM} > -200\,\mathrm{rad\,m^{-2}}$ have been observed. When correlation with the WHAM Hα survey is made various RM reversals occur near H II regions, as in the northern sky. This is shown in Figure 2.

Observations of SNRs can be used to determine the direction of the magnetic field also (Fürst & Reich, this volume). By probing the RM of background sources near a SNR Kim et al. (1988) studied the magnetic field around this object. Similar studies were done for CTB 104A by Uyanıker et al. (2002). The results of this study do not agree with the direction of the global magnetic field as claimed by Han et al. (2002) but it does agree with an anomaly in RM distribution in this direction. Theoretical work, which favours the dynamo process for the amplification of magnetic fields, suggests a much more complex structure of the magnetic field, with many vertical components that are needed to maintain the dynamo process.

6 Conclusions

We believe that it is still too early to claim that we know the morphology of the Galactic magnetic field. The observations of external galaxies, e.g. Beck (2000), Krause (this volume), review the state of knowledge and come to the conclusion that we have hardly any ideal one mode (bi- or axi-symmetric) magnetic field. The real magnetic fields in galaxies are very individual with possible superposition on many modes. Also irregularities are observed in almost every object, once the resolution is sufficient. Vertical fields are observed in some galaxies, especially near the nucleus.

References

Beck, R. (2001) *Space Sci. Rev.* **99**, 243.
Brown, J.C., Taylor, A.R. (2001) *Astrophys. J.* **563**, L31.
Brown, J.C., Taylor, A.R., Wielebinski, R., Müller, P. (2003a) *Astrophys. J.* **592**, L29.
Brown, J.C., Taylor, A.R., Jackel, B.J. (2003b) *Astrophys. J.* **145**, 213.
Duncan, A.R., Haynes, R.F., Jones, K.L., Stewart, R.T. (1997) *Mon. Not. R. Astron. Soc.* **291**, 279.
Duncan, A.R., Reich, P., Reich, W., Fürst, E. (1999) *Astron. Astrophys.* **350**, 447.
Fish, V.L., Reid, M.J., Argon, A.L. et al. (2003) *Astrophys. J.* **596**, 328.
Fosalba, P., Lazarin, L., Prunet, S., Tauber, J.A. (2002) *Astrophys. J.* **564**, 762.
Gaensler, B.M., Dickey, J.M., McClure-Griffiths, N.M. et al. (2001) *Astrophys. J.* **549**, 959.
Georgelin, Y.M., Georgelin, Y.P. (1976) *Astron. Astrophys.* **49**, 57.
Han, J.L., Wielebinski, R. (2002) *Chin. J. Astrophys.* **2**, 293.
Han, J.L., Manchester, R.N., Lyne, A.G., Qiao, G.J. (2002) *Astrophys. J.* **570**, L17.
Heiles, C. (2000) *Astron. J.* **119**, 923.
Kim, K.-T., Kronberg, P.P., Landecker, T.L. (1988) *Astron. J.* **96**, 704.
Mathewson, D.S., Ford V.L. (1970) *Mem. R. Astron. Soc.* **74**, 139.
Mitra, D., Wielebinski, R., Kramer, M., Jessner, A. (2003) *Astron. Astrophys.* **398**, 993.
Nakanishi, H., Sofue, Y. (2003) *Publ. Astron. Soc. Japan* **55**, 191.
Paladini, R. (2003), PhD Thesis, SISSA Trieste.
Simard-Normandin, M., Kronberg, P.P. (1980) *Astrophys. J.* **411**, 674.
Spoelstra, T.A.T. (1984) *Astron. Astrophys.* **135**, 238.
Taylor, J. H., Cordes, J. M. (1993) *Astrophys. J.* **411**, 674
Uyanıker B., Fürst, E., Reich, W. et al. (1999) *Astron. Astrophys. Suppl.* **138**, 31.
Uyanıker, B., Kothes, R., Brunt, C.M. (2002) *Astrophys. J.* **565**, 1022.

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Structure Function Studies for Turbulent Interstellar Medium

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Abstract. We study structure functions of rotation measures in the Canadian Galactic Plane Survey (CGPS) region and the North Galactic Pole (NGP) to extract the interstellar medium (ISM) fluctuation information. The CGPS data are divided into three longitude intervals: $82° < l < 96°$ (CGPS1), $115° < l < 130°$ (CGPS2) and $130° < l < 146°$ (CGPS3). The structure functions of all three regions have large uncertainties when the angular separation is smaller than $\delta\theta \approx 1°$. A power law can fit the structure function well for $\delta\theta > 1°$. The power law indices get smaller from CGPS1 to CGPS3 and the amplitudes decrease. The variations of the large-scale field and the electron density have only negligible effects on the structure function and thus cannot account for the changes, indicating that the turbulent properties of the Galactic ISM are intrinsically longitude-dependent. The Kolmogorov-like fluctuation spectrum of the electron density or the magnetic field should produce a power law structure function with an index of 5/3 or 2/3, neither of which is consistent with our results of small indices in the three sub-CGPS regions. For the NGP region, the structure function is flat, showing that the rotation measures are mostly intrinsic to the extragalactic sources, and the ISM is very random in that part of our Galaxy. It is obvious that the ISM fluctuation is latitude-dependent when comparing the results in the NGP region and the CGPS regions.

1 Introduction

The electron density irregularities have been studied either by refractive scintillation or by diffractive scintillation phenomena as systematically summarized by Armstrong et al. (1995). The fluctuation spectrum from scales of $\sim 10^6$ m to scales of $\sim 10^{13}$ m can be fitted by a single power law with a power index of ~ 3.7, i.e. the Kolmogorov spectrum. This spectrum can be extended up to $\sim 10^{18}$ m. The property of magnetic field fluctuations is not yet clear although they are more important than the electron density fluctuations in some circumstances such as in the solar wind (Armstrong et al. 1995).

The structure function of rotation measures (RMs) contains information on electron density and magnetic field fluctuations (Simonetti et al. 1984). More data are available now allowing a better determination of the structure function and a careful comparison of the turbulent properties of different regions. In this contribution, we show the RM structure functions of extragalactic sources in the Canadian Galactic Plane Survey (Brown et al. 2003, CGPS hereafter) and briefly discuss the results. The detailed report of this work will be given elsewhere.

2 The Theoretical Structure Function

The RM structure function ($D_{\rm RM}$), if assumed as a stationary random process, can be written as

$$D_{\rm RM}(\delta\theta) = \langle[{\rm RM}(\theta_{\mathbf{0}}) - {\rm RM}(\theta_{\mathbf{0}} + \delta\theta)]^2\rangle \ , \tag{1}$$

where $\delta\theta$ is the angular separation of two sources for RMs in degree throughout this paper, and $\langle\cdots\rangle$ denotes the ensemble average over any θ_0 so that the result is independent of θ_0. Both the electron density (n_e) and the magnetic field ($\mathbf{B}$) are assumed to consist of uniform backgrounds (n_0 and $\mathbf{B_0}$) and Gaussian fluctuations (δn and $\delta\mathbf{B}$) with averages of zero, in the form of

$$\begin{aligned} n_e &= n_0 + \delta n \ , \\ \mathbf{B} &= \mathbf{B_0} + \delta\mathbf{B} \ . \end{aligned}$$

The exact spectra of the electron density and magnetic field fluctuations are not known, so it is straightforward to take the power law form as

$$\begin{aligned} P_{\delta n}(q) &= \frac{C_n^2}{[l_{on}^{-2} + q^2]^{\alpha/2}} , \\ P_{\delta B}(q) &= \frac{C_B^2}{[l_{oB}^{-2} + q^2]^{\beta/2}} , \end{aligned}$$

where q is the wave number, C_n^2 and C_B^2 are the fluctuation intensities, l_{on} and l_{oB} are the outer scales, and α and β are the power indices. The structure function can be reduced to the form below when $l_{on} = l_{oB} = l_o = 1/q_o$ (Minter 1995)

$$\begin{aligned} D_{\rm RM}(\delta\theta) &= \Psi_{\rm RM}(\delta\theta) + 2C_{\rm RM}^2 B_{0z}^2 C_n^2 f(\alpha) L^{\alpha-1} \delta\theta^{\alpha-2} + 2C_{\rm RM}^2 n_0^2 C_B^2 g(\beta) L^{\beta-1} \delta\theta^{\beta-2} \\ &\quad + 2C_{\rm RM}^2 C_n^2 C_B^2 h(\alpha,\beta) L^{(\alpha+\beta)/2-1} q_o^{3-(\alpha+\beta)/2} \delta\theta^{(\alpha+\beta)/2-2} , \end{aligned}$$

where $\Psi_{\rm RM}(\delta\theta)$ is the geometrical term attributed to the variation of the large-scale electron density and the magnetic field, L is the path length, $f(\alpha)$, $g(\beta)$ and $h(\alpha,\beta)$ are constants containing Γ-functions. As $\delta\theta \ll 1$ rad, the geometrical term can be approximated as

$$\Psi_{\rm RM}(\delta\theta) \approx C_{\rm RM}^2 n_0^2 B_0^2 L^2 \delta\theta^2 \approx 3 \times 10^{-4} \langle {\rm RM} \rangle^2 \delta\theta^2 ,$$

here $\delta\theta$ is in degree. If both the electron density and the magnetic field fluctuations follow a Kolmogorov spectrum, the structure function has a simple form as below,

$$D_{\rm RM}(\delta\theta) = \Psi_{\rm RM}(\delta\theta) + C\delta\theta^{5/3} ,$$

where C is a constant related to the intensities in the regular and fluctuating components.

3 Analysis of Data

In principle, two methods can be employed to extract the fluctuation information of the ISM from RMs: the autocorrelation function and the structure function. The autocorrelation function is the Fourier transform of the power spectrum density according to the *Wiener-Khinchin theorem*, so the direct way is to derive the autocorrelation function. But this can cause problems when the data are irregularly spaced (Spangler et al. 1989). Regardless of the data sampling, it is easy to obtain the structure function, however. So we will take the structure function approach below.

Given a sample of RM data, the logarithm of angular separations of RM pairs are set to bins with equal lags. In each bin the differences of RM pairs are squared and then averaged to obtain the structure function. The standard deviations are taken as the uncertainty of each function value.

Around each source we can derive the local RM average and dispersion. If a RM value is different from the average by three times larger than the dispersion, it is defined as "anomalous". We will illustrate by simulation that such an anomalous RM can significantly affect the structure function.

Let the RMs distribute in the region $0^\circ \le x \le 2^\circ$ and $0^\circ \le y \le 2^\circ$ uniformly with grid intervals of 0.1°. Two samples of random RM values following Gaussian distributions with an average of zero and a dispersion σ of 30 and 50 rad m^{-2}, respectively, are generated with the Monte-Carlo method. Note that the average value does not affect the results. Theoretically the structure function should be flat with an amplitude $2\sigma^2$ and an index 0. The structure functions from simulations are displayed in Fig. 1. We then fitted the structure functions with $D_{\rm RM}(\delta\theta) = A\delta\theta^\alpha$ and found that the results are consistent with theoretical expectations.

As is obvious in Fig. 2, an anomalous RM value (1000 rad m^{-2}, indicated by a cross) can distort the real structure function to a different extent. With regard to actual RM data, such a RM can be either due to an enhanced local medium or it is intrinsic to the extragalactic source. One should pick

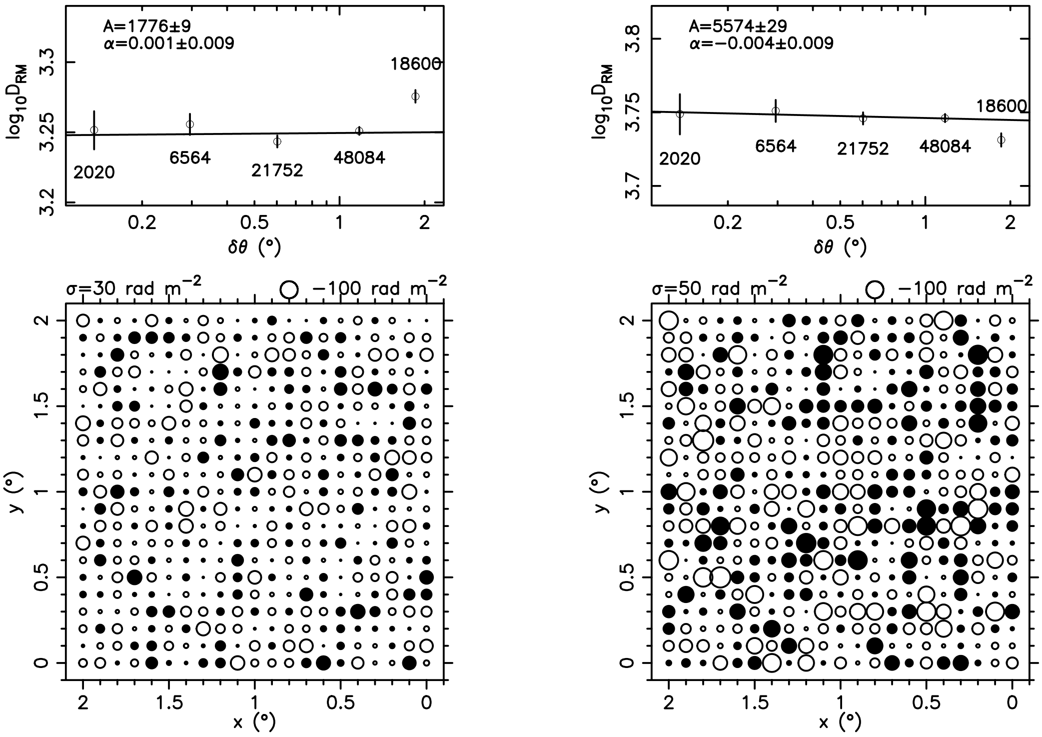

Fig. 1. Simulated RM distributions are shown in the lower panels, with filled and open circles representing positive and negative values, respectively. The sizes of symbols are proportional to the square-root of RM values. The structure functions are plotted in the upper panels with the number of pairs in each bin marked.

Table 1. Fitting parameters of the structure functions in the CGPS regions and the NGP region.

Region	Range	⟨RM⟩	$\sigma_{\rm RM}$	A	α
CGPS1	$82\overset{\circ}{.}42 < l < 96\overset{\circ}{.}23$	−237	306	118630±6901	0.28 ±0.03
CGPS2	$115\overset{\circ}{.}01 < l < 129\overset{\circ}{.}99$	−147	117	23016±1241	0.10 ±0.03
CGPS3	$130\overset{\circ}{.}12 < l < 146\overset{\circ}{.}51$	−106	94	17756± 958	−0.003±0.027
North Galactic Pole	$(b > 70°)$	−3	15	548± 215	−0.06 ±0.12

up such RMs for further identification. Below we will only show the results of real observed RM data after discarding these anomalous RMs, as identifications have not yet been made.

We took the RMs of the extragalactic sources (EGSs) in the CGPS region but excluded sources containing separate or unresolved components (marked by a, b and c in the catalog of Brown et al. 2003). The data are divided into three longitude intervals: $82° < l < 96°$ (CGPS1), $115° < l < 130°$ (CGPS2) and $130° < l < 146°$ (CGPS3). We also collected the RMs of EGSs in the North Galactic Pole (NGP) region with latitudes larger than 70°. Then we calculated the structure functions for these four regions, as shown in Figs. 3, 4, 5, and 6. The fitting results using $D_{\rm RM}(\delta\theta) = A\delta\theta^{\alpha}$ are listed in Table 1, where Column 1 refers to the region, Columns 2 and 3 to the average and dispersion of the RMs. The amplitude and power index of each power law structure function are listed in Columns 4 and 5.

4 Discussion

The electron density fluctuations are better known than the magnetic field fluctuations. Armstrong et al. (1995) have shown that the electron density fluctuation spectrum is Kolmogorov-like, but the

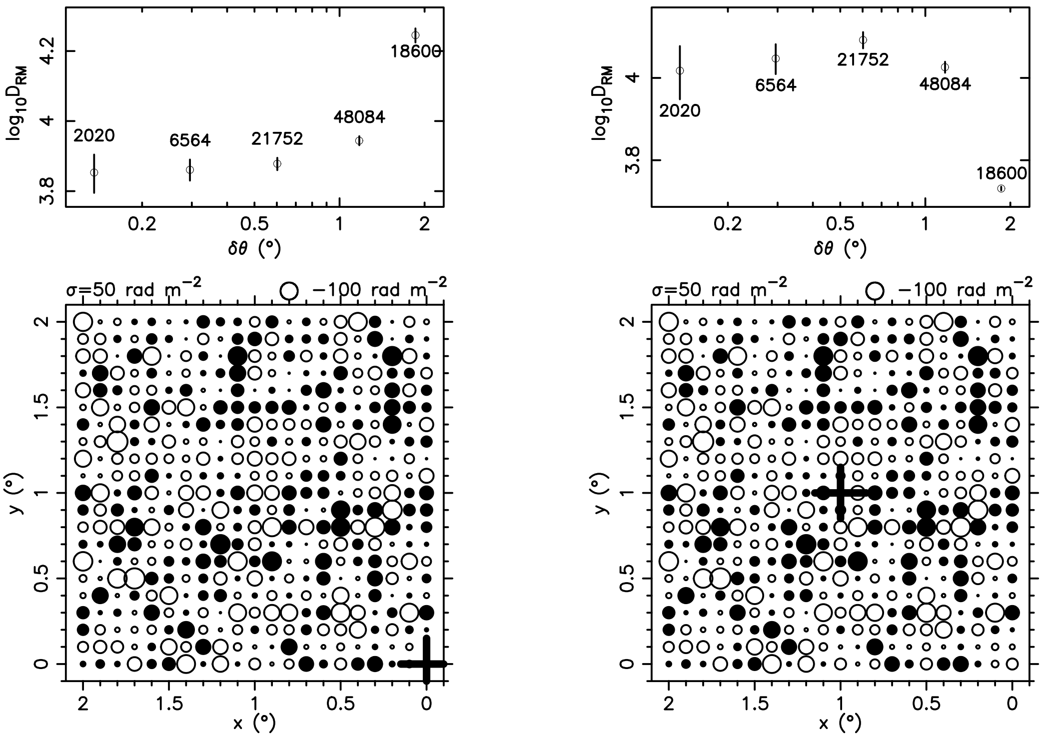

Fig. 2. Same as Fig. 1 for σ = 50 rad m^{-2} but with an anomalous RM of 1000 rad m^{-2} in the corner and in the center as indicated by a cross.

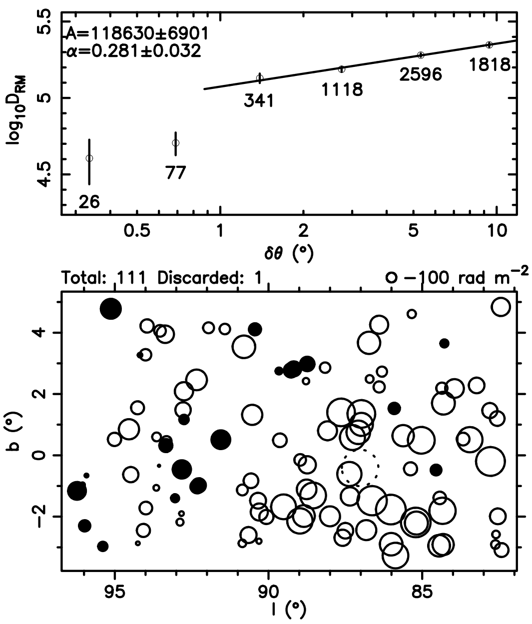

Fig. 3. The RM distribution in the CGPS1 region (lower panel) and the calculated structure function (upper panel). The symbols are plotted as in Fig. 1, but anomalous RMs are plotted as hatched circles when positive or dotted circles when negative.

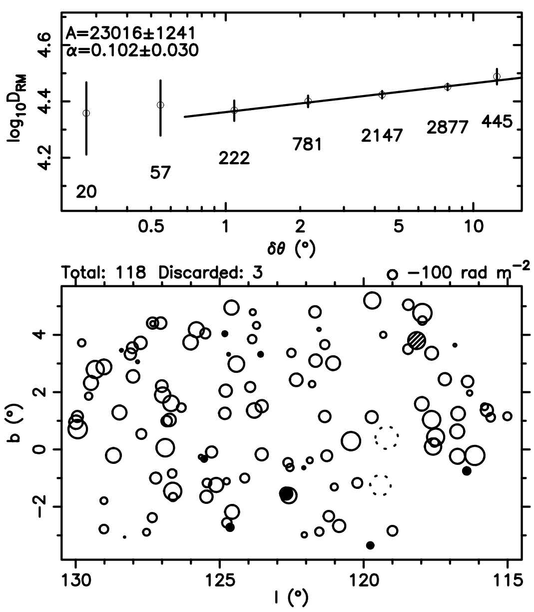

Fig. 4. Same as Fig. 3 but for the CGPS2 region.

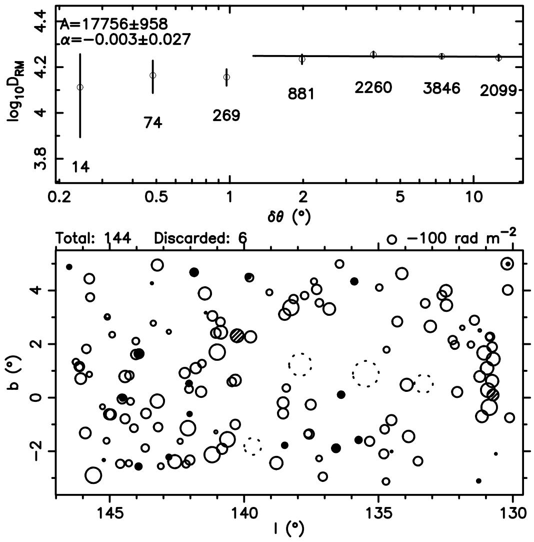

Fig. 5. Same as Fig. 3 but for the CGPS3 region.

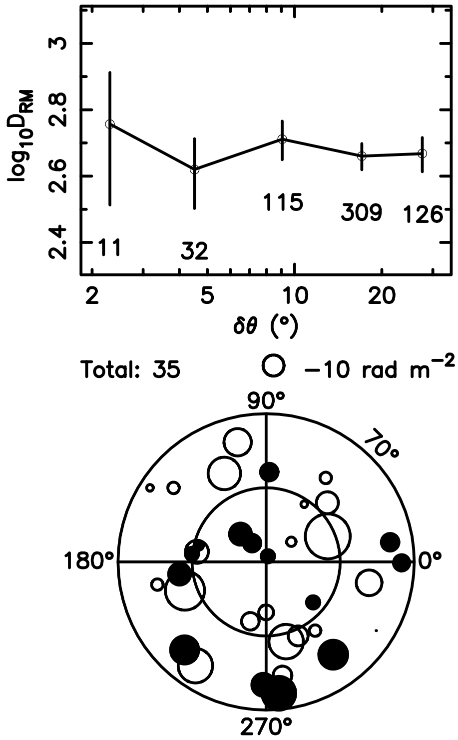

Fig. 6. Same as Fig. 3 but for the NGP region.

magnetic field fluctuation remains mysterious and totally unclear as mentioned above. We know that many physical processes in the ISM affect the electron density and the magnetic field at the same time, such as supernova explosions. The magnetic field is often assumed to be frozen into the interstellar medium. So we can assume that there is no distinct discrepancy between the fluctuations of the electron density and the magnetic field. In this case the structure function can be written as $D_{\rm RM}(\delta\theta) = \Psi(\delta\theta) + C\delta\theta^{\alpha-2}$ where C is a constant.

In the three sub-CGPS regions, the average rotation measures $\langle{\rm RM}\rangle = -237$, -147 and -106 rad m^{-2}, respectively, corresponding to the geometrical term contributions $\Psi_{\rm RM}(\delta\theta) = 17\delta\theta^2$, $6\delta\theta^2$ and $3\delta\theta^2$, which are definitely negligible when compared to the obtained amplitudes (A) of the structure functions in these regions. In fact, the indices from our results are much smaller than 2, which also means that the geometrical term plays a minor role in the structure function. Therefore the structure function can be simplified as $D_{\rm RM}(\delta\theta) \approx C\delta\theta^{\alpha-2}$.

The structure function $D_{\rm RM}(\delta\theta) \approx C\delta\theta^{5/3}$ holds for 3D Kolmogorov fluctuations and $D_{\rm RM}(\delta\theta) \approx C\delta\theta^{2/3}$ for 2D Kolmogorov fluctuations (Minter & Spangler 1996). *It is clear that the Kolmogorov spectrum cannot account for our results.* Actually, the indices of the structure functions in the three sub-CGPS regions are very small, close to zero. Let us try to discuss the nearly flat structure functions we got.

From the results (Table 1) it is evident that the amplitudes of the structure function A decrease from CGPS1 to CGPS3. This is probably caused by the extent of the ISM in our Galaxy. From our simulation, we know that $A \sim 2\sigma_{RM}^2$, where σ_{RM} is the dispersion of RM along the line of sight. Assuming that there are many fluctuation cells with typical scale l and a RM dispersion σ_l along the line of sight, the total RM dispersion can be represented by $\sigma_{RM}^2 = \frac{L}{l}\sigma_l^2$; where L is the path length to the edge of our Galaxy. Because L decreases from CGPS1 to CGPS3, it is understandable that the fluctuation intensity gets smaller.

Due to the disk structure of the Galactic electron distribution and the Sun's location at 8 kpc distance from the Galactic center, the RMs of EGSs near the pole region are little affected by the

Galactic interstellar medium, so that the structure function for the EGSs in the pole region should be very flat. Our result in Fig. 6 and the fitting parameters in Table 1 are consistent with Simonetti et al. (1984) and strengthen the fact that the RMs of EGSs in the pole region are very random, indeed mainly of intrinsic origin. We can also see that the fluctuation intensity in the NGP region is much smaller than that in the CGPS region, indicating a trend of a latitude-dependence of the ISM turbulence.

5 Conclusion

We have used the structure function to study ISM fluctuations. Simulation shows that an anomalous RM can significantly influence the structure function, so we suggest that these large RMs should be carefully checked before performing a structure function analysis, or otherwise should be used with caution. The structure functions of the RMs of EGSs in the CGPS region have been calculated. The structure functions at $\delta\theta > 1^\circ$ can be fitted by a power law. The power indices are all nearly zero which cannot be interpreted by Kolmogorov-like ISM fluctuations. The fluctuation intensity is longitude-dependent. The flat structure function in the NGP region shows that the RMs in this region are almost intrinsic to EGSs.

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References

Armstrong J. W., Rickett B. J., Spangler S. R. (1995) *Astrophys. J.* **443**, 209.
Brown J. C., Taylor A. R., Jackel B. J. (2003) *Astrophys. J. Suppl.* **145**, 213.
Minter A. H. (1995) *Ph.D. Thesis*, University of Iowa.
Minter A. H., Spangler S. R. (1996) *Astrophys. J.* **458**, 194.
Simonetti J. H., Cordes J. M., Spangler S. R. (1984) *Astrophys. J.* **284**, 126.
Spangler S. R., Fanti R., Gregorini L., Padrielli L. (1989) *Astron. Astrophys.* **209**, 315.