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 ±15° and increasing to ±60° in steps of 15°. An excess of RM power was seen at 30°, 46° and 50° in the small interval of ±15° about the plane. In this region closest to the Galactic plane there was also marginal evidence for an excess about 80°. In the interval ±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 ±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 $30^\circ$ 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 $30^\circ$ from the Galactic plane was found to be $10 \text{ rad m}^{-2}$ 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 = $A \exp(-0.037 \times \text{RM})$ (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 $50 \text{ rad m}^{-2}$.

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 $\pm30^\circ$ from the Galactic plane and that it has excess power on spatial scales of $30^\circ$, $46^\circ$ and $50^\circ$. 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.
Broun 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.