The latitude dependence of the rotation measures of NVSS sources

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ABSTRACT

In this Letter I use the variation of the spread in rotation measure (RM) with Galactic latitude to separate the Galactic from the extragalactic contributions to RM. This is possible since the latter does not depend on Galactic latitude. As input data I use RMs from the catalogue by Taylor, Stil, and Sunstrum, supplemented with published values for the spread in RM ($\sigma_{\text{RM}}$) in specific regions on the sky. I test 4 models of the free electron column density (which I will abbreviate to 'DM') of the Milky Way, and the best model builds up DM$_{\odot}$ on a characteristic scale of a few kpc from the Sun. $\sigma_{\text{RM}}$ correlates well with DM$_{\odot}$. The measured $\sigma_{\text{RM}}$ can be modelled as a Galactic contribution, consisting of a term $\sigma_{\text{RM,EG}}$ that is amplified at smaller Galactic latitudes as $1/\sin|\theta|$, in a similar way to DM$_{\odot}$, and an extragalactic contribution, $\sigma_{\text{RM,EG}}$, that is independent of latitude. This model is sensitive to the relative magnitudes of $\sigma_{\text{RM,EG}}$ and $\sigma_{\text{RM,EG}}$, and the best fit is produced by $\sigma_{\text{RM,EG}} \approx 8$ rad/m$^2$ and $\sigma_{\text{RM,EG}} \approx 6$ rad/m$^2$. The 4 published values for $\sigma_{\text{RM}}$ as a function of latitude suggest an even larger $\sigma_{\text{RM,EG}}$ contribution and a smaller $\sigma_{\text{RM,EG}}$. This result from the NVSS RMs and published $\sigma_{\text{RM}}$ shows that the Galactic contribution dominates structure in RM on scales between about 1° to 10° on the sky. I work out which factors contribute to the variation of $\sigma_{\text{RM}}$ with Galactic latitude, and show that the $\sigma_{\text{RM,EG}}$ I derived is an upper limit. Furthermore, to explain the modelled $\sigma_{\text{RM,EG}}$ requires that structure in ($B_\parallel$) has a 1-$\sigma$ spread $\lesssim 0.4$ $\mu$G.

Key words: polarization – Galaxy: general – ISM: magnetic fields – galaxies: magnetic fields

1 INTRODUCTION

In recent years, models of the large-scale Galactic magnetic field have increased greatly in both complexity and breadth of input data and output variables (see e.g. Fauvet et al. 2010, Jaffe et al. 2010, Nota & Katgert 2010, Janssen et al. 2009, Waelkens et al. 2009, Sun & Reich 2009, Men et al. 2008, Sun et al. 2008, Brown et al. 2007). One popular approach to determine magnetic field strengths is to look for Faraday rotation of the polarized emission coming from extragalactic sources (see e.g. Gaensler et al. 2005). The rotation measure (RM) quantifies the amount of Faraday rotation between the source of the emission and us, the observers, and it depends on the free electron density, $n_e$, and the magnetic field component along the line of sight, $B_\parallel$, that the emission encounters along its path:

$$\text{RM} \ [\text{rad/m}^2] = 0.81 \sum_{\text{source}} n_e \ [\text{cm}^{-3}] \ B_\parallel \ [\mu\text{G}] \ dl \ [\text{pc}]$$

where $dl$ an infinitesimal part of the line of sight towards the observer. The RM can tell us about the magnetic field strength along the line of sight, when the electron density contribution to RM is accounted for, for example by determining the free electron column density towards the source of the emission, which is known as the dispersion measure (DM) in the pulsar community.

In this Letter I will focus on one particular observational aspect, which is that the width of the RM distribution ($\sigma_{\text{RM}}$) of extragalactic sources increases closer to the Galactic plane. This increase furthermore closely matches the increase in DM closer to the plane. I will use this, in combination with the fact that the extragalactic RM contribution is independent of Galactic latitude, to separate this component from the Galactic RM contribution. This Letter is organised as follows. First I will describe the NVSS RM catalogue by Taylor, Stil and Sunstrum (2009) that I use for my analysis in Sect. 2 and in Sect. 4 I describe the analysis that led to the observation that $\sigma_{\text{RM}}$ depends on Galactic latitude. In Sect. 4 I determine how well 4 models for the free electron density in the Galaxy predict the observed DM of pulsars at known distances. Finally, in Sect. 5 I will model the Galactic and extragalactic contributions to $\sigma_{\text{RM}}$, and separate the two. Throughout this Letter I have calculated statistics in a way that is robust against outliers.

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2 THE DATA

Taylor, Stil and Sunstrum (2009) determined RMs for 37,543 sources from the NVSS catalogue, which covers declinations $> -40^\circ$. This means that the NVSS sources are separated on average by about 1° on the sky. Even though the accuracy of the individual RMs is limited (the median error in RM is about 11 rad/m$^2$), the sheer size of the NVSS RM catalogue makes it very useful for studying the properties of the Galactic magnetized interstellar medium on large scales. In Fig. 1 I show the distribution of NVSS RMs as a function of Galactic latitude.

Close to the Galactic plane, the RMs are much higher than further away, and this impacts the reliability of NVSS RMs at small Galactic latitudes. First, a large RM will induce a large amount of bandwidth depolarization, which reduces the polarized signal/noise ratio. Also, since the NVSS uses only 2 frequency bands, large RMs will suffer from nr ambiguities due to the periodicity of the polarization angles, and they will show up in the NVSS RMs as small RMs. Taylor et al. have suppressed the latter effect when they fitted RMs by also estimating the amount of bandwidth depolarization that would be expected for large RMs. Because of these reasons, I only use NVSS sources with $|\text{RM}| < 300$ rad/m$^2$ and Galactic latitudes $|b| > 20^\circ$ in my analysis. The NVSS catalogue is not very sensitive to diffuse Galactic structure, which would have introduced further depolarization effects.

3 THE SPREAD IN RM AS A FUNCTION OF LATITUDE

Fig. 1 shows that the spread in the NVSS RM increases for lines of sight closer to the Galactic plane, and in this Letter I will show that this increase very closely follows the increase in the Galactic DM$_e$. Fig. 5 from Taylor, Stil and Sunstrum (2009) also shows this increase in $\sigma_{\text{RM}}$. The NVSS RMs should however be corrected for 2 effects before this conclusion can be drawn.

First, the average RM will vary in a strip along Galactic longitude, an effect which becomes more pronounced close to the Galactic plane, and this increases $\sigma_{\text{RM}}$ when left uncorrected. I divided each strip along Galactic latitude into bins, and determined the average RM for each bin. For latitudes within $77^\circ$ of the plane bins are $5' \times cos(b) \times 4'$ in size ($\Delta l \times \Delta b$). The $\text{cos}(b)$ dependence of the bin width produces bins with a constant surface area on the sky, which guarantees that each bin will contain about 20 NVSS RMs, and that the maximum separation between two points in a bin is constant. Doubling $\Delta l$ does not significantly influence the results from Sect. 5 I divided the cap regions above $|b| = 77^\circ$ into intervals with $\Delta l = 20^\circ$ that converge at $b = \pm 90^\circ$. I then calculated a cubic spline through the bin-averaged RM at the longitudes of the individual NVSS RMs, and subtracted this spline fit from the RMs. This removes structure in RM on scales larger than 10° (Nyquist sampling; for bins with $|b| < 77^\circ$). The resulting RM distribution for each strip along Galactic latitude is much better centred on 0 rad/m$^2$ than the uncorrected measurements, and variations in (RM) that would increase $\sigma_{\text{RM}}$ are strongly reduced.

Second, the $\sigma_{\text{RM}}$ that were determined from the corrected NVSS RMs should be corrected in a statistical sense for the measurement errors of the individual NVSS RMs. I estimate the $\sigma_{\text{RM}}$ that is produced by just the variation in uncertainty in RM of the NVSS sources (errRM) by using a Monte Carlo simulation, which I set up as follows. First, I randomly draw errRM for 1000 lines of sight in the NVSS catalogue, and I then use a random number generator to find a distribution of RM based on these 1000 errRM. I then calculate the $\sigma_{\text{RM}}$ of this distribution, and repeat this process 10$^5$ times. The total number of independently drawn random variables for these 1000 lines of sight therefore does not exceed 10$^8$, the maximum number of independent draws for the random number generator that I used. I repeated this process for 35 sets of 1000 lines of sight, to cover most of the errRM with $|b| > 5^\circ$. An analysis of the $\sigma_{\text{RM}}$ found after each run shows that the spread due to the errors in NVSS RMs gives a $\sigma_{\text{errRM}} = 10.4 \pm 0.4$ rad/m$^2$.

For 2 Gaussians, the widths ($\sigma$) add quadratically, and

\[ \text{Figure 1. Distribution of NVSS RMs as a function of Galactic latitude, which clearly shows the broadening of the RM distribution close to the Galactic plane. The average RM and 1-$\sigma$ spread around the average RM are calculated for 2° bins in Galactic latitude, and are shown as the red line and the blue lines on either side of the red line. Only lines of sight with $|\text{RM}| < 300$ rad/m$^2$ are included in this and the following figures; 3% of the lines of sight have $|\text{RM}| > 150$ rad/m$^2$ and are not shown in this figure.} \]

\footnote{The random generator in IDL, which is similar to the ran1 generator from Sect. 7.1 in Press et al. (1992) }
\[ \sigma_{\text{errRM}} = \sigma_{\text{errRM, uncorrected}} + \sigma_{\text{nature}}. \]

The ‘excess \( \sigma_{\text{RM}} \)' can then be recovered from the \( \sigma_{\text{errRM, uncorrected}} \) measured with NVSS, and the \( \sigma_{\text{errRM}} \) that I simulated with a Monte Carlo process. A second Monte Carlo simulation showed that this relation is not exactly correct due to a slight non-Gaussianity in the distribution of the RM errors in NVSS. This shows up as a 6\% difference between the expected \( \sigma_{\text{RM}} \) excess and the measured \( \sigma_{\text{RM}} \) excess, if the latter is 10 rad/m² (this difference decreases with increasing \( \sigma_{\text{RM}} \) excess). I corrected the \( \sigma_{\text{RM}} \) excess for this effect, and I will use these corrected \( \sigma_{\text{RM}} \) in the remainder of the Letter.

In Figs. 2 and 3 I plot the distribution of the excess \( \sigma_{\text{RM}} \) as a function of Galactic latitude for both positive (solid line) and negative (dashed line) latitudes; in Fig. 4 I will distinguish between positive and negative latitudes in the same way. I also show the \( \sigma_{\text{RM}} \) distribution of the uncorrected NVSS RM data (yellow line). It is striking that there is a gap in the distribution of the uncorrected NVSS RMs (yellow line) and the \( \sigma_{\text{RM}} \) at these latitudes, their \( \sigma_{\text{RM}} \) can be considered as tight upper limits. Since the data sets from \( |b| > 30^\circ \) and \( |b| > 77^\circ \) span a wide range in Galactic latitudes, I plotted these symbols at their surface-area-weighted average Galactic latitude.\textsuperscript{4}

The correction for the variation in (RM) of the NVSS RMs is not perfect, and the RM distribution in the latitude bins often cannot be properly fitted by a Gaussian distribution, which is reflected in the high values for the reduced \( \chi^2 \) (\( \chi^2_{\text{red}} \)) of the Gaussian fits. However, Figs. 2 and 3 show that there is a reasonable agreement between the \( \sigma_{\text{RM}} \) from Table 1 and the excess \( \sigma_{\text{RM}} \) that I calculated, an indication that the corrections that I applied to the \( \sigma_{\text{RM}} \) of the NVSS sources work well. Furthermore, latitude bins with \( \chi^2_{\text{red}} \) between 2 and 4 show the same global behaviour with latitude as the bins with \( \chi^2_{\text{red}} < 4 \). For my analysis in the remainder of this Letter I will therefore use the excess \( \sigma_{\text{RM}} \) of the NVSS sources with \( \chi^2_{\text{red}} < 4 \), and the \( \sigma_{\text{RM}} \) from the literature. I will distinguish excess \( \sigma_{\text{RM}} \) from NVSS with \( \chi^2_{\text{red}} < 2 \) from those with \( \chi^2_{\text{red}} < 4 \) by using filled symbols for the former, and open symbols for the latter.

Table 1. Values of \( \sigma_{\text{RM}} \) compiled from the literature.

| region | \( b \) | \( \sigma_{\text{RM}} \) [rad/m²] | source |
|--------|-------|----------------|--------|
| Centaurus A | 19° | 27±2\textsuperscript{a} | Feain et al. (2009) |
| LMC | -33° | 15±1\textsuperscript{a} | Gaensler et al. (2005) |
| \( |b| > 30^\circ \) | 49\textsuperscript{c} | 10±2 | Johnston-Hollitt et al. (2004) |
| \( |b| > 77^\circ \) | 81\textsuperscript{c} | 9±0.3\textsuperscript{a} | Mao et al. (2010) |

\( \sigma_{\text{RM}} \) : calculated as the standard error in the mean, using the number of sources that the authors listed to lie outside the target object.
\( \sigma_{\text{RM}} \) : and Ann Mao, private communication
\( \sigma_{\text{RM}} \) : \( |b| > 30^\circ \), and they would therefore not increase \( \sigma_{\text{RM}} \). It turns out that there is some variation in Galactic RM even at these latitudes, which means that their \( \sigma_{\text{RM}} \) is an upper limit to the excess \( \sigma_{\text{RM}} \).

4 A MODEL FOR THE FREE ELECTRON DENSITY

Several models have been proposed in the literature to describe the free electron density in the Milky Way. Here I test the accur
racy of the NE2001 model by Cordes & Lazio (2002),
the model by Gaensler et al. (2008), and the model by Berkhuijsen & Müller (2008), by comparing the predicted DM to the measured DM for 65 pulsars of which the distance is known to within 33%. I compiled this sample from the ATNF pulsar catalogue (Manchester et al. 2005), downloaded from this website[4] on 25/05/2009, and the papers by Chatterjee et al. (2009) and Deller et al. (2009). I also fitted a plane-parallel exponential model of the free electron density to this data set, taking into account the uncertainty in the pulsar distances. This model uses a more recent version of the catalogues that Gaensler et al. and Berkhuijsen et al. compiled, it includes also pulsars at latitudes within 40° from the Galactic plane (the model by Gaensler et al. is constrained by pulsars at latitudes |b| > 40°), and it puts a stronger constraint on which pulsars to use (distance errors < 33%, where Berkhuijsen et al. required < 50%). The best fitting model has a mid-plane electron density n_e(0) = 0.02 ± 0.0001 cm^{-3} and scale height h = 1.225 ± 0.007 kpc. (see also Schnitzeler & Katgert, in preparation) The ratios of the predicted DM/observed DM for these four models are 1.22 ± 0.53, 0.8 ± 0.31, 1.05 ± 0.41 and 0.99 ± 0.37 resp. (mean ± 1-σ spread; the error in the mean is smaller by a factor of \sqrt{55} ≈ 8), so I selected the final model to work with. The 65 pulsars that I selected cover a wide range of heights above the Galactic midplane, out to about 10 kpc, so the fitted scale height is well sampled by this pulsar distribution.

The 3 models that use a plane-parallel exponential profile for the free electron density in the Milky Way (Gaensler et al., Berkhuijsen et al., and the model I fitted) differ in mid-plane density and scale height. However, when integrating these models out to infinity (a good approximation for the NVSS sources), all 3 models should show the same asymptotic behaviour for a given Galactic latitude b: DM_∞ = 24.4/sin|b|, DM(b=±90°) = 24.4 cm^{-3}pc is the median DM that I calculated for the 8 pulsars from the sample that lie further than 4 kpc from the Galactic plane. (Berkhuijsen & Müller 2008 find DM_∞(b=±90°) = 21.7 cm^{-3}pc, and Gaensler et al. 2008 find DM_∞(b=±90°) = 25.6 cm^{-3}pc) In Fig. 1 I overplot the DM_∞ predicted by this model. To emphasize how well DM_∞ follows the trend in σ_RM excess, I scaled the DM_∞ by a factor of 0.37, which is the average value of σ_RM × sin|b|/24.4 for NVSS RMs at |b| > 20°. The resulting match in Fig. 2 is not perfect, since the values of σ_RM × sin|b| from Fig. 2 depend on latitude. In Sect. 5 I will show that the match can be improved by taking the b-independent contribution from σ_RM^EG to σ_RM into account.

To determine the characteristic distance over which most of the DM_∞ is built up, I introduce the electron-density weighted average distance along the line of sight, \langle dist(\gamma)\rangle = h/sin|b|.[3] Note that \langle dist(\gamma)\rangle is somewhat larger than the distance over which half the DM_∞ is built up, DM_1/2=ln(2)×h/sin|b|≈ 0.7 \langle dist(\gamma)\rangle . When going from |b|=90° to |b|=20°, \langle dist(\gamma)\rangle increases from 1 to 2 h, or about 1.2 – 2.5 kpc. These distances imply that the structure in DM_∞ (and σ_RM) is neither produced very close to the sun, nor outside the Milky Way or its ionized halo.

For a line of sight at 20° from the Galactic plane, \langle dist(\gamma)\rangle is 2h, or about 2.5 kpc. This is nearby enough that the truncation of the Milky Way disk does not play a significant role in limiting the calculated DM_∞. However, at smaller Galactic latitudes this can no longer be ruled out, at 10° from the plane (\langle dist(\gamma)\rangle is already 4h (5 kpc), and at 5°, \langle dist(\gamma)\rangle = 8h (10 kpc), so the model I use to calculate DM_∞ breaks down close to the Galactic plane. This might be the reason why in Fig. 2 DM_∞ increases much more rapidly at small latitudes than the measured σ_RM.

5 THE RELATIVE CONTRIBUTIONS OF THE MILKY WAY AND EXTRAGALACTIC SOURCES TO σ_RM

Fig. 3 shows σ_RM × sin|b| as a function of Galactic latitude. The data points from Table I are nearly independent of latitude in this figure, which means that these σ_RM closely follow a 1/sin|b| relation; the best-fitting DM_∞ model from Sect. 4 shows the same dependence on Galactic latitude. To explain why σ_RM and DM_∞ might be correlated requires identifying which quantities determine how σ_RM varies with Galactic latitude.

The electron-density weighted line-of-sight component of the magnetic field, \langle B_\| \rangle, is defined as

\[ \langle B_\| \rangle = \frac{\int_{\text{source}} n_e B_\| \, dt}{\int_{\text{source}} n_e \, dl} = \frac{\text{RM}}{0.81 \, \text{DM}_\infty} \]

The total RM of the line of sight can then be written in terms of its Galactic and extragalactic contributions as

\[ \text{RM} = \text{RM}_{\text{MW}} + \text{RM}_{\text{EG}} = 0.81 \langle B_\| \rangle \, \text{DM}_\infty + \text{RM}_{\text{EG}} \]

with variance

\[ \sigma_{\text{RM}}^2 = 0.81^2 \text{DM}_\infty^2 \langle B_\| \rangle^2 + \text{RM}_{\text{EG}}^2 \]

(assuming no correlation between the magnetic field and the free electron density) In this Letter σ_RM is the (average) variance of an ensemble of lines of sight within a single cell used to remove the large-scale variation in (RM) from the NVSS data (Sect. 3) or within the area covered by the data sets from Table I.

A priori only σ_RM^EG is known to be independent of Galactic latitude; the first two terms on the right-hand side of Eqn. 2 can have both a b-dependent and a b-independent part. Although these different contributions to σ_RM could in theory produce a complicated variation with latitude, the data show that this behaviour can be modelled in a simple way, as σ_RM(b) = \sqrt{\text{RM}_{\text{MW}}^2 \langle B_\| \rangle^2 + \text{RM}_{\text{EG}}^2} (I will use ‘\|’ to distinguish the parameters from this model from the standard deviations in Eqn. 2). The model ameliorates σ_RM^MW, which itself does not depend on Galactic latitude, at smaller Galactic latitudes as 1/sin|b| to mimic the increase in DM_∞ at these latitudes, and then combines it with σ_RM^EG to form σ_RM. I show the best fitting models in Fig. 3 as blue lines, and these fits reproduce the global behaviour of σ_RM with Galactic latitude (for |b| > 20°). The parameters that produce these fits at positive (negative) latitudes are σ_RM^MW = 6.8 ± 0.1 (8.4 ± 0.1) rad/m² and σ_RM^EG = 6.5 ± 0.1 (5.9 ± 0.2) rad/m²; the values for the reduced χ^2 of these fits

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are 4.4 and 3.9. I fitted the $\sigma_{\text{RM}}$ at positive and negative latitudes separately because they are off-set in Fig. 2. To illustrate how sensitive the modelled $\sigma_{\text{RM}}$ are to different $\sigma_{\text{RM,LMW}}$, I show for negative latitudes also the best-fitting $\sigma_{\text{RM}}$ models for $\sigma_{\text{RM,LMW}}=9.4$ rad/m$^2$ (top dashed curve) and $\sigma_{\text{RM,LMW}}=7.4$ rad/m$^2$ (bottom dashed curve). Since the values of $\sigma_{\text{RM}} \times \sin|b|$ depend much less on Galactic latitude for the data from table I than for the NVSS RMs, their $\sigma_{\text{RM}}$ can be modelled with a much smaller $\sigma_{\text{RM,LMW}}$ contribution.

Now the $\sigma_{\text{RM,LMW}}$ and $\sigma_{\text{RM,EG}}$ parameters from the model can be identified with the terms in Eqn. 2. The $\sigma_{\text{DM}}$, $\sigma_{(B)}$, and $\sigma_{(B)\alpha}$ terms can both have $b$-independent parts, but since these terms add quadratically to $\sigma_{\text{RM,EG}}$, $\sigma_{\text{RM,EG}} \leq \sigma_{\text{RM,LMW}}$. The $b$-independent part of Eqn. 2 is modelled as $\sigma_{\text{RM,LMW}}/\sin|b|$. When all the structure of the latitude-dependent part would be produced only by $\sigma_{(B)\alpha}$, which is equivalent to setting $\sigma_{\text{DM}}=0$, then $\sigma_{(B)} = \sigma_{\text{RM,LMW}}/(0.81 \times \text{DM}_{\odot}(b=90^\circ))$. $\sigma_{\text{DM}}$ will however not be zero, since it contains a contribution from the variation in modelled $\text{DM}_{\odot}$ over the region of interest, and from local structure in the free electron density that is not included in the smooth $\text{DM}_{\odot}$ model from Sect. 4. This structure in $\text{DM}_{\odot}$ can explain part of the observed structure in $\sigma_{\text{RM}}$, and the calculated $\sigma_{(B)}$ is therefore an upper limit. (again since the $\sigma$ terms add quadratically) Using $\text{DM}_{\odot}(b=90^\circ)=24.4$ cm$^{-3}$pc, and an average value of $\sigma_{\text{RM,LMW}} = 7.6$ rad/m$^2$, then gives $\sigma_{(B)} \lesssim 0.4 \mu G$. The $\sigma_{\text{RM}}$ from Table I gives the same value when calculating $\sigma_{\text{RM}} \times \sin|b|/(0.81 \times 24.4)$. (I ignored the $\sigma_{\text{RM,EG}}$ term in this case – please see the end of the previous paragraph)

The magnitude of the $\sigma_{\text{RM,LMW}}$ term compared to the $\sigma_{\text{RM,EG}}$ term implies that the Milky Way dominates structure in RM on scales between about 1° – 10° is dominated by the Galactic foreground.

Future radio polarimetry surveys will provide accurate rotation measures on a much finer grid on the sky. The analysis I present here can be improved upon with such data sets; in particular they will permit using smaller bins in Galactic longitude and latitude, which can better correct for the variation in RM with Galactic longitude and latitude.

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### NOTE ADDED IN PRESS

Since this paper was accepted it has become clear that the $\sigma_{\text{RM}}$ from Gaensler et al. and Johnston-Hollitt et al. can contain significant contributions from their errors in RM, which I should have taken into account. However, this does not affect the conclusions from this Letter.
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