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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 (‘$\sigma_{\rm RM}$’) in specific regions on the sky. I test 4 models of the free electron column density (which I will abbreviate to ‘$\rm DM_\infty$’) of the Milky Way, and the best model builds up $\rm DM_\infty$ on a characteristic scale of a few kpc from the Sun. $\sigma_{\rm RM}$ correlates well with $\rm DM_\infty$. The measured $\sigma_{\rm RM}$ can be modelled as a Galactic contribution, consisting of a term $\sigma_{\rm RM,MW}$ that is amplified at smaller Galactic latitudes as $1/\sin|b|$, in a similar way to $\rm DM_\infty$, and an extragalactic contribution, $\sigma_{\rm RM,EG}$, that is independent of latitude. This model is sensitive to the relative magnitudes of $\sigma_{\rm RM,MW}$ and $\sigma_{\rm RM,EG}$, and the best fit is produced by $\sigma_{\rm RM,MW} \approx 8$ rad/m^2 and $\sigma_{\rm RM,EG} \approx 6$ rad/m^2. The 4 published values for $\sigma_{\rm RM}$ as a function of latitude suggest an even larger $\sigma_{\rm RM,MW}$ contribution and a smaller $\sigma_{\rm RM,EG}$. This result from the NVSS RMs and published $\sigma_{\rm RM}$ shows that the Galactic contribution dominates structure in RM on scales between about $1^\circ - 10^\circ$ on the sky. I work out which factors contribute to the variation of $\sigma_{\rm RM}$ with Galactic latitude, and show that the $\sigma_{\rm RM,EG}$ I derived is an upper limit. Furthermore, to explain the modelled $\sigma_{\rm RM,MW}$ requires that structure in $\langle B_\parallel \rangle$ has a 1-σ 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, Jansson 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, $n_{\rm e}$, and the magnetic field component along the line of sight, $B_\parallel$, that the emission encounters along its path:

$$\mathrm{RM\ [rad/m^2]} = 0.81 \int_{\rm source}^{\rm observer} n_{\rm e}\ [\mathrm{cm^{-3}}]\ B_\parallel\ [\mu\mathrm{G}]\ \mathrm{d}l\ [\mathrm{pc}]$$

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 ($\sigma_{\rm RM}$) 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. 3 I describe the analysis that led to the observation that $\sigma_{\rm RM}$ 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 $\sigma_{\rm RM}$, 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°. 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 nπ 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 |RM| < 300 rad/m^2 and Galactic latitudes $|b| \geqslant 20°$ 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$_\infty$. Fig. 5 from Taylor, Stil and Sunstrum (2009) also shows this increase in $\sigma_{\rm RM}$. 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 $\sigma_{\rm RM}$ when left uncorrected. I divided each strip along Galactic latitude into bins, and determined the average RM for each bin. For latitudes within 77° of the plane bins are 5°/cos(b) × 4° in size ($\Delta l \times \Delta b$). The 1/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 Δl does not significantly influence the results from Sect. 5. I divided the cap regions above $|b|$ = 77° into intervals with Δl = 20° that converge at b=± 90°. 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°). 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 $\langle$RM$\rangle$ that would increase $\sigma_{\rm RM}$ are strongly reduced.

Second, the $\sigma_{\rm RM}$ 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 $\sigma_{\rm RM}$ 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[1] to find a distribution of RM based on these 1000 errRM. I then calculate the $\sigma_{\rm RM}$ 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°. An analysis of the $\sigma_{\rm RM}$ found after each run shows that the spread due to the errors in NVSS RMs gives a $\sigma_{\rm errRM}$ = 10.4 ± 0.4 rad/m^2.

For 2 Gaussians, the widths (σ) add quadratically, and

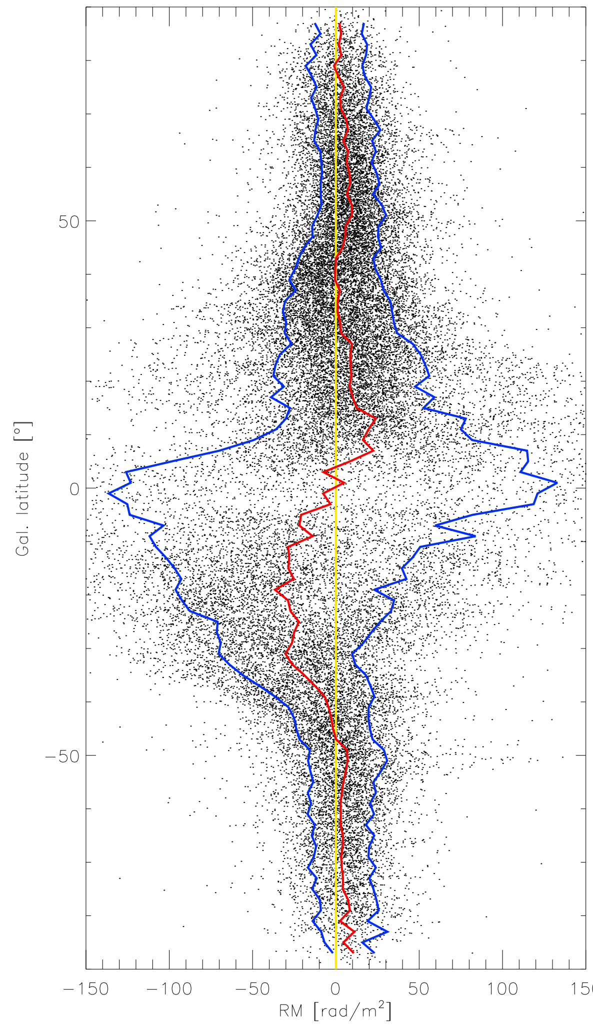

Figure 1. Distribution of NVSS RMs as a function of Galactic latitude, which clearly shows the broadening of the RM distribution closer to the Galactic plane. The average RM and 1-σ spread around the average RM are calculated for 2° bins in Galactic latitude, and are shown as the red line and the blue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

[1] The `randomn` generator in IDL, which is similar to the `ran1` generator from Sect. 7.1 in Press et al. (1992)

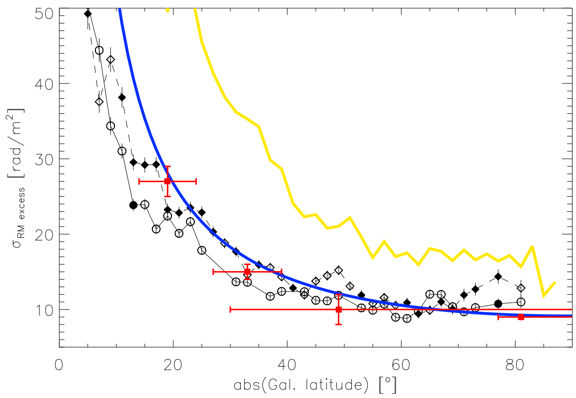

Figure 2. Distribution of the excess $\sigma_{\rm RM}$ as a function of Galactic latitude; circles (connected by a solid line) and squares (connected by a dashed line) indicate positive and negative Galactic latitudes respectively. The data points at Galactic latitudes of ±1° and ± 3° are missing, their $\sigma_{\rm RM}$ values are 117 rad/m^2 and 85 rad/m^2 resp. The plotted data points contain at least 15 RMs, and their RM distribution can be fitted by a Gaussian with a reduced $\chi^2 < 2$ (filled symbols) or between $2 < \chi^2_{\rm red} < 4$ (open symbols). The error bars (which are often smaller than the plot symbols) are calculated as the error in the mean RM of each latitude bin. Also shown are the uncorrected $\sigma_{\rm RM}$ calculated from Fig. 1 (yellow line; sampled in 2° bins, and averaged over positive and negative latitudes) and the $\sigma_{\rm RM}$ (not the excess $\sigma_{\rm RM}$!) from Table 1 (red symbols). The red horizontal error bars indicate the range in Galactic latitude that is covered by these data sets. To illustrate how well the DM$_\infty$ distribution traces the excess $\sigma_{\rm RM}$ at $|b| > 20°$, I plot this distribution after scaling it by a factor of 0.37 (blue line; see Sect. 4).

$\sigma^2_{\rm errRM\,+\,nature} = \sigma^2_{\rm errRM} + \sigma^2_{\rm nature}$. The 'excess $\sigma_{\rm RM}$', $\sigma_{\rm nature}$, can then be recovered from the $\sigma_{\rm errRM\,+\,nature}$ measured with NVSS, and the $\sigma_{\rm errRM}$ 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 $\sigma_{\rm RM}$ excess and the measured $\sigma_{\rm RM}$ excess, if the latter is 10 rad/m^2 (this difference decreases with increasing $\sigma_{\rm RM}$ excess). I corrected the $\sigma_{\rm RM}$ excess for this effect, and I will use these corrected $\sigma_{\rm RM}$ in the remainder of the Letter.

In Fig. 2 I plot the distribution of the excess $\sigma_{\rm RM}$ as a function of Galactic latitude for both positive (solid line) and negative (dashed line) latitudes; in Fig. 3 I will distinguish between positive and negative latitudes in the same way. I also show the $\sigma_{\rm RM}$ distribution of the uncorrected NVSS RM data (yellow line). It is striking that there is a gap in $\sigma_{\rm RM}$ between positive and negative latitudes of about 2 rad/m^2, but its origin is unknown to me. Taylor, Stil and Sunstrum (2009) and Mao et al. (2010) noticed a similar RM difference between the north and south Galactic caps.

I compiled a list of published values of $\sigma_{\rm RM}$ in different regions on the sky, which I show in Table 1, and which I also include in Figs. 2 – 3. These data sets are not limited by having only 2 frequency bands like the NVSS RMs. Feain et al. (2009) removed a large-scale RM gradient from their data before calculating $\sigma_{\rm RM}$, and Mao et al. (2010) found an (almost) flat power spectrum for their Galactic cap regions, so their $\sigma_{\rm RM}$ is not appreciably increased by a variation in RM. Johnston-Hollitt et al. (2004) argue that Galactic RM contributions are unimportant at latitudes

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

Table 1. Values of $\sigma_{\rm RM}$ compiled from the literature.

[a] : calculated as the standard error in the mean, using the number of sources that the authors listed to lie outside the target object.

[b] : and Ann Mao, private communication

[c] : $\langle b \rangle$ calculated as the surface-area-weighted average Galactic latitude of that data set

[d] : and Melanie Johnston-Hollitt, private communication

$|b| > 30°$, and they would therefore not increase $\sigma_{\rm RM}$. It turns out that there is some variation in Galactic RM even at these latitudes, which means that their $\sigma_{\rm RM}$ is an upper limit to the excess $\sigma_{\rm RM}$. Gaensler et al. (2005) did not correct for a smooth variation in RM, and also their $\sigma_{\rm RM}$ is therefore an upper limit. A variation in RM only increases $\sigma_{\rm RM}$, but since the $\sigma_{\rm RM}$ that Johnston-Hollitt et al. (2004) and Gaensler et al. (2005) calculate are very similar to the excess $\sigma_{\rm RM}$ that I calculate from the NVSS RMs at these latitudes, their $\sigma_{\rm RM}$ can be considered as tight upper limits. Since the data sets from Table 1 have (very) small measurement errors in RM, I will use the $\sigma_{\rm RM}$, not the excess $\sigma_{\rm RM}$, of these data sets. Since the data from Johnston-Hollitt et al. (2004) and the polar cap regions from Mao et al. (2010) span a wide range in Galactic latitudes, I plotted these symbols at their surface-area-weighted average Galactic latitudes[2], which are $\langle b \rangle = 49°$ and $\langle b \rangle = 81°$ respectively. A uniform source density will result in more sources at smaller Galactic latitudes, so using the surface area to weigh the Galactic latitudes reflects a weighting with the number of sources in each annulus.

The correction for the variation in $\langle {\rm RM} \rangle$ 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 χ^2 ($\chi^2_{\rm red}$) of the Gaussian fits. However, Figs. 2 and 3 show that there is a reasonable agreement between the $\sigma_{\rm RM}$ from Table 1, and the excess $\sigma_{\rm RM}$ that I calculated, an indication that the corrections that I applied to the $\sigma_{\rm RM}$ of the NVSS sources work well. Furthermore, latitude bins with $\chi^2_{\rm red}$ between 2 – 4 show the same global behaviour with latitude as the bins with $\chi^2_{\rm red} < 2$. For my analysis in the remainder of this Letter I will therefore use the excess $\sigma_{\rm RM}$ of the NVSS sources with $\chi^2_{\rm red} < 4$, and the $\sigma_{\rm RM}$ from the literature. I will distinguish excess $\sigma_{\rm RM}$ from NVSS with $\chi^2_{\rm red} < 2$ from those with $2 < \chi^2_{\rm red} < 4$ by using filled symbols for the former, and open symbols for the latter.

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 accu-

[2] I define the surface-area averaged Galactic latitude as

$$\langle b \rangle = \frac{\int_{b > b_{\rm min}}^{90°} \text{area in annulus} \times b \, {\rm d}b}{\int_{b > b_{\rm min}}^{90°} \text{area in annulus} \, {\rm d}b} \quad \text{for data with } b > b_{\rm min}.$$

racy of the NE2001 model by Cordes & Lazio (2002)[3], 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 $n_{e,0} = 0.02 \pm 0.0001$ cm^{-3} and scale height $h = 1.225 \pm 0.007$ 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 $\sqrt{65} \approx 8$), 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: $\mathrm{DM}_\infty = 24.4/\sin|b|$. $\mathrm{DM}(b{=}\pm90°) = 24.4$ 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 $\mathrm{DM}_\infty(b{=}\pm90°) = 21.7$cm^{-3}pc, and Gaensler et al. 2008 find $\mathrm{DM}_\infty(b{=}\pm90°) = 25.6$ cm^{-3}pc) In Fig. 2 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 $\sigma_{\mathrm{RM}} \times \sin|b|/24.4$ for NVSS RMs at $|b| \geqslant 20°$. The resulting match in Fig. 2 is not perfect, since the values of $\sigma_{\mathrm{RM}} \times \sin|b|$ from Fig. 3 depend on latitude. In Sect. 5 I will show that the match can be improved by taking the b-independent contribution from $\sigma_{\mathrm{RM,EG}}$ 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, $\langle \mathrm{dist} \rangle_{n_e}$[5] $= h/\sin|b|$. Note that $\langle \mathrm{dist} \rangle_{n_e}$ is somewhat larger than the distance over which half the DM_∞ is built up, $\mathrm{DM}_{1/2} = \ln(2) \times h/\sin|b| \approx 0.7\ \langle \mathrm{dist} \rangle_{n_e}$. When going from $|b|=90°$ to $|b|=20°$, $\langle \mathrm{dist} \rangle_{n_e}$ increases from 1 to $2h$, 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, $\langle \mathrm{dist} \rangle_{n_e}$ 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 $\langle \mathrm{dist} \rangle_{n_e}$ is already $4h$ (5 kpc), and at 5°, $\langle \mathrm{dist} \rangle_{n_e} = 8h$ (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 $\sigma_{\mathrm{RM}} \times \sin|b|$ as a function of Galactic latitude. The data points from Table 1 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, $\langle B_\parallel \rangle$, is defined as

$$\langle B_\parallel \rangle \equiv \frac{\int_{\mathrm{source}}^{\mathrm{observer}} n_e\, B_\parallel\, \mathrm{d}l}{\int_{\mathrm{source}}^{\mathrm{observer}} n_e\, \mathrm{d}l} = \frac{\mathrm{RM}}{0.81\ \mathrm{DM}_\infty}$$

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

$$\mathrm{RM} = \mathrm{RM}_{\mathrm{MW}} + \mathrm{RM}_{\mathrm{EG}} = 0.81 \langle B_\parallel \rangle\, \mathrm{DM}_\infty + \mathrm{RM}_{\mathrm{EG}} \quad (1)$$

with variance

$$\sigma^2_{\mathrm{RM}} = 0.81^2 \mathrm{DM}^2_\infty \sigma^2_{\langle B_\parallel \rangle} + 0.81^2 \langle B_\parallel \rangle^2 \sigma^2_{\mathrm{DM}_\infty} + \sigma^2_{\mathrm{RM,EG}} \quad (2)$$

(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 $\langle \mathrm{RM} \rangle$ from the NVSS data (Sect. 3) or within the area covered by the data sets from Table 1.

A priori only $\sigma_{\mathrm{RM,EG}}$ 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 $\sigma_{\mathrm{RM}}(b) = \sqrt{\left(\frac{\bar{\sigma}_{\mathrm{RM,MW}}}{\sin|b|}\right)^2 + \bar{\sigma}^2_{\mathrm{RM,EG}}}$. (I will use '$\bar{\sigma}$' to distinguish the parameters from this model from the standard deviations in Eqn. 2) The model amplifies $\bar{\sigma}_{\mathrm{RM,MW}}$, 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 $\bar{\sigma}_{\mathrm{RM,EG}}$ 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 $|b| \geqslant 20°$). The parameters that produce these fits at positive (/negative) latitudes are $\bar{\sigma}_{\mathrm{RM,MW}} = 6.8 \pm 0.1$ (8.4 ± 0.1) rad/m^2 and $\bar{\sigma}_{\mathrm{RM,EG}} = 6.5 \pm 0.1$ (5.9 ± 0.2) rad/m^2; the values for the reduced χ^2 of these fits

[3] and their website, http://rsd-www.nrl.navy.mil/7213/lazio/ne_model/

[4] http://www.atnf.csiro.au/research/pulsar/psrcat/

[5] I define the electron-density weighted average distance, $\langle \mathrm{dist} \rangle_{n_e}$, as $\langle \mathrm{dist} \rangle_{n_e} = \frac{\int_0^\infty l n_e\, \mathrm{d}l}{\int_0^\infty n_e\, \mathrm{d}l}$, where both integrals are along the line of sight. For a free electron density that decreases exponentially away from the Galactic plane, $\langle \mathrm{dist} \rangle_{n_e} = h/\sin|b|$

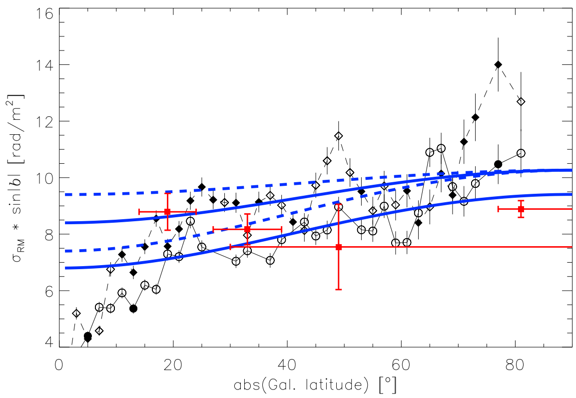

Figure 3. Distribution of $\sigma_{RM} \times \sin|b|$ as a function of Galactic latitude, for the data points shown in Fig. 2. The data points at ± 1° and ± 3° are not shown; their $\sigma_{RM} \times \sin|b|$ are 2.0 and 4.5 resp. I fitted the model described in Sect. 5 to the data points at $|b| > 20°$ for positive and negative latitudes separately, and show the best fits (solid blue lines). To illustrate the sensitivity of the modelled σ_{RM} to $\sigma_{RM,MW}$, I also draw 2 curves on either side of the best-fitting curve to the data at negative latitudes, that only differ in $\sigma_{RM,MW}$ by 1 rad/m^2 from the best-fitting value. (dashed blue lines)

are 4.4 and 3.9. I fitted the σ_{RM} at positive and negative latitudes separately because they are off-set in Fig. 2. To illustrate how sensitive the modelled σ_{RM} are to different $\bar{\sigma}_{RM,MW}$, I show for negative latitudes also the best-fitting σ_{RM} models for $\bar{\sigma}_{RM,MW}$=9.4 rad/m^2 (top dashed curve) and $\bar{\sigma}_{RM,MW}$=7.4 rad/m^2 (bottom dashed curve). Since the values of $\sigma_{RM} \times \sin|b|$ depend much less on Galactic latitude for the data from table 1 than for the NVSS RMs, their σ_{RM} can be modelled with a much smaller $\bar{\sigma}_{RM,EG}$ contribution.

Now the $\bar{\sigma}_{RM,MW}$ and $\bar{\sigma}_{RM,EG}$ parameters from the model can be identified with the terms in Eqn. 2. The $DM_\infty \sigma_{\langle B_\parallel \rangle}$ and $\langle B_\parallel \rangle \sigma_{DM_\infty}$ terms can both have b-independent parts, but since these terms add quadratically to $\sigma_{RM,EG}$, $\sigma_{RM,EG} \leqslant \bar{\sigma}_{RM,EG}$. The b-dependent part of Eqn. 2 is modelled as $\bar{\sigma}_{RM,MW}/\sin|b|$. When all the structure of the latitude-dependent part would be produced only by $\sigma_{\langle B_\parallel \rangle}$, which is equivalent to setting σ_{DM_∞}=0, then $\sigma_{\langle B_\parallel \rangle}$ = $\bar{\sigma}_{RM,MW}/(0.81 \times DM_\infty(b=90°))$. σ_{DM_∞} will however not be zero, since it contains a contribution from the variation in modelled DM_∞ over the region of interest, and from local structure in the free electron density that is not included in the smooth DM_∞ model from Sect. 4. This structure in DM_∞ can explain part of the observed structure in σ_{RM}, and the calculated $\sigma_{\langle B_\parallel \rangle}$ is therefore an upper limit. (again since the σ terms add quadratically) Using $DM_\infty(b=90°)$=24.4 cm^{-3}pc, and an average value of $\bar{\sigma}_{RM,MW}$ = 7.6 rad/m^2, then gives $\sigma_{\langle B_\parallel \rangle} \leqslant 0.4\ \mu$G. The σ_{RM} from Table 1 give the same value when calculating $\sigma_{RM} \times \sin|b|/(0.81 \times 24.4)$. (I ignored the $\sigma_{RM,EG}$ term in this case – please see the end of the previous paragraph)

The magnitude of the $\sigma_{RM,MW}$ term compared to the $\sigma_{RM,EG}$ term implies that the Milky Way dominates structure in RM on scales between about 1 – 10 degrees, which can affect studies of the RMs of extragalactic sources. (the lower limit is set by the size scale probed by the NVSS RMs, and the upper limit is set by the size of the bins used to subtract the variation in ⟨RM⟩)

6 CONCLUSIONS

In this Letter I show that the σ_{RM} of NVSS sources can be modelled as a dominant Galactic contribution ($\sigma_{RM,MW} \approx 8$ rad/m^2) that is amplified at smaller Galactic latitudes as $1/\sin|b|$, similar to the increase in the Galactic free electron column density, DM_∞, and an extragalactic contribution that is independent of Galactic latitude ($\sigma_{RM,EG} \approx 6$ rad/m^2). I corrected the σ_{RM} of NVSS sources for the variation in ⟨RM⟩ along Galactic longitude, and for the broadening of the RM distribution that is produced purely by the uncertainties in the NVSS RMs. The 'excess' σ_{RM} correlates well with DM_∞. To calculate DM_∞, I compared 4 models of the free electron density, and I decided which one is the best based on how well it predicts the DM of pulsars at known distances. This model builds up DM_∞ on a characteristic scale of a few kpc for latitudes $|b| > 20°$. I model the behaviour of σ_{RM} with Galactic latitude as an extragalactic RM distribution, which does not depend on Galactic latitude, and the Galactic RM contribution, which is amplified at small Galactic latitudes to simulate the increase in DM_∞. The model follows the observed global behaviour in σ_{RM} well, although there are significant localized deviations between the model and the observations. The best fitting values for the Galactic and extragalactic contributions to RM for positive (/negative) Galactic latitudes $\sigma_{RM,MW}$ = 6.8 ± 0.1 (8.4 ± 0.1) rad/m^2 and $\sigma_{RM,EG}$ = 6.5 ± 0.1 (5.9 ± 0.2) rad/m^2. By deriving which factors contribute to σ_{RM} I show that this $\sigma_{RM,EG}$ is an upper limit. The spread in $\langle B_\parallel \rangle$ that is required to produce a $\sigma_{RM,MW}$ = 7.6 rad/m^2 is 0.4 μG. However, fluctuations in the free electron density will also contribute to $\sigma_{RM,MW}$, which means that this $\sigma_{\langle B_\parallel \rangle}$ is an upper limit. I also compiled σ_{RM} values from the literature, that have more accurate RM determinations. These sources suggest that the $\sigma_{RM,MW}$ contribution is even larger, and that $\sigma_{RM,EG}$ is very small by comparison.

This result implies that structure in RM on angular 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 σ_{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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