ENHANCED SMALL-SCALE FARADAY ROTATION IN THE GALACTIC SPIRAL ARMS

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ABSTRACT

We present an analysis of the rotation measures (RMs) of polarized extragalactic point sources in the Southern Galactic Plane Survey. This work demonstrates that the statistics of fluctuations in RM differ for the spiral arms and the interarm regions. Structure functions of RM are flat in the spiral arms, while they increase in the interarms. This indicates that there are no correlated RM fluctuations in the magnetoionized interstellar medium in the spiral arms on scales larger than ~0'5, corresponding to ~17 pc in the nearest spiral arm probed. The nonzero slopes in interarm regions imply a much larger scale of RM fluctuations. We conclude that fluctuations in the magnetoionic medium in the Milky Way spiral arms are not dominated by the mainly supernova-driven turbulent cascade in the global ISM but are probably due to a different source, most likely H II regions.

Subject headings: H II regions — ISM: magnetic fields — ISM: structure — radio continuum: ISM — techniques: polarimetric — turbulence

1. INTRODUCTION

Structure in the neutral and ionized interstellar gas of the Milky Way is ubiquitous and present on many scales. There have been many observational, theoretical, and computational papers concerning turbulence in the neutral gas and molecular clouds, but relatively little is known about the structure of the warm ionized gas component (see Elmegreen & Scalo 2004; Scalo & Elmegreen 2004 for an overview). Turbulence in the ionized gas is suggested by observations of nonthermal line widths in Hα (Reynolds 1985; Tufte et al. 1999) and modeled in numerical simulations of the multiphase interstellar medium (ISM; see Vázquez-Semadeni et al. 2003 and references therein). Furthermore, observed power spectra or structure functions of electron density show power-law behavior indicative of incompressible hydrodynamic turbulence (Cordes et al. 1985; Armstrong et al. 1995). However, care should be taken in interpretation of these density spectra, as the connection between density and velocity structure is not unambiguous and fluctuations in electron density can be created by a number of different processes besides turbulence, such as small-amplitude plasma waves or differences in ionization fraction.

The observed density fluctuations in the ionized ISM in the Galactic plane differ from those in the halo. The plane shows enhanced scattering of extragalactic radio sources (Spangler & Reynolds 1990), higher rotation measures (RMs) from extragalactic sources (e.g., Clegg et al. 1992), and increased scintillation of pulsars and angular broadening of extragalactic sources (e.g., Cordes et al. 1985). Although fluctuations on scales of hundreds of parsecs have been observed out of the Galactic plane (e.g., Armstrong et al. 1995), the gas in the plane may be partly dominated by structures on much smaller scales (Haverkorn et al. 2004). Internal structure in individual H II regions in the Galactic plane may be responsible for these enhanced fluctuations in the ionized ISM (Spangler & Reynolds 1990; Haverkorn et al. 2004).

These previous studies have considered how the properties of fluctuations in the ISM vary with Galactic latitude. In this Letter, we examine structure in the thermal electron density and magnetic field in the warm ionized ISM as a function of longitude, to detect any change in characteristics between spiral arms and interarm regions.

2. THE SOUTHERN GALACTIC PLANE SURVEY

The SGPS is a radio survey in the H I line and in 1.4 GHz polarized continuum covering the ranges 253° < l < 358° and 5° < l < 20° and |b| < 1° at ~1° resolution, observed with the Australia Telescope Compact Array (ATCA) and the Parkes 64 m radio telescope (McClure-Griffiths et al. 2005; M. Haverkorn et al. 2006, in preparation). The polarized continuum has been observed only with the ATCA, in twelve 8 MHz wide frequency bands from 1336 to 1432 MHz (where the 1400 MHz band is omitted due to radio interference). This enables determination of RMs both from diffuse Galactic synchrotron emission (Gaensler et al. 2001) and from unresolved polarized extragalactic point sources, discussed here. RMs of polarized point sources in the range 253° < l < 358° have been determined using the technique explained in Brown et al. (2003); a full analysis of these sources will be given elsewhere. RMs were determined for 151 sources, the distribution of which can be approximated by a Gaussian centered on +60 rad m⁻² with a standard deviation of 233 rad m⁻².

3. STRUCTURE FUNCTIONS OF ROTATION MEASURE

The second-order structure function SF(r) of a function f as a function of scale r is defined as $SF(r) = \langle |f(x) - f(x + r)|^2 \rangle$, where $\langle \cdot \rangle$ denotes averaging over all positions x. We determined SFs of RM for five regions at different Galactic longitudes, selected so that the major part of the probed sight line traced either spiral arms or interarm regions. SFs were averaged azimuthally to obtain a one-dimensional SF as a function of
angular scale $\theta$. Because a large-scale gradient in the field will show up as a positive slope in the SF, care has to be taken to correct for any large-scale gradients. Visual inspection of the data did not show any clear gradients, and a first-order correction was made by subtracting a best-fit gradient from the RM data before evaluating the SF. The displayed errors are propagated errors in the RM values. These errors are derived from the linear fit of polarization angle with wavelength squared, and based on signal-to-noise ratios in Stokes $Q$ and $U$. Assuming that the distribution is homogeneous and isotropic, the effect of noise in the SF can be corrected for. If the observed RM is $RM_{\text{obs}} = RM(x) + \delta(x)$, where $\delta(x)$ is the noise contribution, the SF of RM corrected for noise is $SF_{RM} = SF_{RM_{\text{obs}}} - SF_{\delta}$ (Haverkorn et al. 2004).

Figure 1 shows the SF of RM as a function of angular scale $\theta$ for five regions in the SGPS. These were the regions with the least confusion between spiral arms and interarm regions along the line of sight. The top three plots, with Galactic longitude range as denoted in the figure, are at sight lines predominantly through interarm regions, while the bottom two plots show SFs of RMs mostly in spiral arms. The Galactic latitude range of all regions is the latitude range of the SGPS, i.e., $|b| < 1^\circ$. The behavior of the SF is different at the positions of the spiral arms, indicating that the structure in RM changes in the arms. In the interarm regions the SFs display a power law of RM fluctuations, whereas the SF slopes in the spiral arms are consistent with zero. The SFs in the interarm regions saturate at the maximum at which fluctuations exist, called the outer scale (or integral scale).

The SF slopes $\beta$ [$SF(r) \propto r^{-\beta}$] for the three interarm regions are $\beta = 0.42 \pm 0.04$, $0.47 \pm 0.04$, and $0.79 \pm 0.04$, with a weighted mean $\langle \beta \rangle = 0.55 \pm 0.05$. The probability that the spiral arm points are consistent with $\langle \beta \rangle$ is $< 10^{-10}$. The standard deviation of RM seems to be higher in the spiral arms as well: the standard deviation of RM in the selected spiral arm regions is $\sigma_{RM} = 263 \pm 32$ rad m$^{-2}$, and the probability that the standard deviations of RM in the selected spiral arm regions ($398 \pm 132$ and $415 \pm 125$ rad m$^{-2}$) are equal to $\sigma_{RM}$ is 0.07.

An independent determination of the fluctuations in thermal electron density $n_e$ can be attempted using H$\alpha$ observations to obtain emission measures $EM = \int n_e^2 \, ds$, where $ds$ is the path length through the ionized gas. However, H$\alpha$ data suffer from high and variable extinction in the Galactic plane, which introduces additional power in the SF. Instead, we try an alternative method using dispersion measures $DM = \int n \, ds$ of pulsars, which do not suffer from extinction. Since pulsars are located inside the Galaxy, the path length over which DM is calculated is smaller than the path length of the RM measurements toward extragalactic sources. However, since the approximate distances to the pulsars are known, we can select a sample of pulsars sufficiently far away that their path length is predominantly through spiral arms or through interarm regions. Furthermore, we consider pulsars at approximately the same distances, so that their spatial separation on the sky scales linearly with their angular separation.

Pulsars were selected from the ATNF Pulsar Catalogue (Manchester et al. 2005). We found 41 pulsars in the SGPS region with distances $D$ in the range $8 \, $kpc $< D < 10 \, $kpc using the DM values in the catalog combined with the NE2001 model (Cordes & Lazio 2003). Errors in NE2001 are assumed to be mainly on small scales, so that the uncertainty in the estimated pulsar distance is independent of spatial scale. As a result, the error in the distance will increase the amplitude of the SF but not influence its scale.

Unfortunately, the number of pulsars in each selected region was so low that the SF of DM could be calculated (asterisks). The top three plots show regions with sight lines predominantly through interarm regions, which show rising SFs. The bottom two plots sample mostly spiral arms and show flat SFs, indicating that there is no correlated structure in the spiral arms on the scales sampled. The lines represent linear fits through the rising part of the SFs.

**4. Discussion and Conclusions**

We have shown that in the Galactic spiral arms no correlated fluctuations exist in the magnetized interstellar plasma on scales larger than $\sim 0.5$, corresponding to $\sim 17$ pc in the nearest spiral arm probed, i.e., the Carina arm, which starts at $\sim 2$ kpc distance in this direction (Georgelin & Georgelin 1976; Russell 2003). In the interarm regions, however, correlated magnetionic fluctuations are present on large scales. Since the RM is a line-of-sight average through the entire Galaxy, it is not possible to associate a spatial scale to this angular scale. But assuming that the largest angular scales represent nearby structure at a fairly arbitrary distance of $\sim 1$ kpc away, an outer scale of 4$^\circ$–5$^\circ$ in the interarm regions would correspond to a spatial scale of about 100 pc.

The measured slopes of RM SFs in the interarm regions roughly agree with slopes of velocity SFs in simulations of incompressible (magneto-) hydrodynamic turbulence (Kolmogorov 1941; Maron & Goldreich 2001; Cho et al. 2002). This suggests that the density and velocity spectra may be coupled, which is only the case for subsonic or mildly supersonic turbulence (Kim & Ryu 2005; Beresnyak et al. 2005). Therefore, if the RM fluctuations are connected to velocity structure, the turbulence in the interarm ionized gas must be subsonic or only mildly supersonic, in agreement with observational results from H$\alpha$.

On the other hand, the RM structure observed in spiral arms is probably not a part of the turbulent cascade in the diffuse ionized medium. If the density spectrum traces the velocity spectrum, this would mean that the outer scale of turbulence
would be \(\approx 17\) pc. However, the dominant source of turbulent driving is believed to be supernova remnants and superbubbles, injecting energy on much larger scales (Mac Low 2004; de Avillez & Breitschwerdt 2005).

A shallow RM SF can also be caused by highly supersonic compressible turbulence, which will flatten the density SF (Kim & Ryu 2005; Beresnyak et al. 2005), or by MHD turbulence in the absence of a mean field (Schekochihin et al. 2004). However, as mentioned before, it is doubtful whether the ionized gas in the spiral arms is very supersonic.

Therefore, the fluctuations in RM in the spiral arms are probably not connected to the turbulent cascade in the diffuse ionized ISM at all. Instead, a probable source of these fluctuations is H\(\text{\textsc{ii}}\) regions, which are of the correct size, sufficiently abundant (Haverkorn et al. 2004), and concentrated in spiral arms. Widespread interstellar turbulence injected by H\(\text{\textsc{ii}}\) regions is not expected to be significant (Mac Low 2004), but the structure could be caused by the H\(\text{\textsc{ii}}\) regions themselves or by turbulence inside them.

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