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Enhanced magneto-ionic fluctuations in the Milky Way's spiral arms

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Abstract

The 1.4 GHz polarized continuum data of the Southern Galactic Plane Survey are ideally suited to study spatial variations in the turbulent properties of the magneto-ionic interstellar medium. Statistical analysis of rotation measures in the inner Galactic plane suggests an additional source of fluctuations in electron density and/or magnetic field in the Galaxy's spiral arms, with an outer scale of a few parsecs. A probable source for this additional component of structure is HII regions from relatively late-type stars, which are sufficiently abundant and of the appropriate size to account for the additional structure.

1 Introduction

Although turbulence in the Galactic interstellar medium (ISM) has been ubiquitously observed in both velocity and density, properties such as the spectral index, the outer scale of the fluctuations at which energy is injected into the medium, and the inner diffusion scale where the energy is dissipated are still not known. There are indications of the existence of a power law in electron density on scales from thousands of kilometers to hundreds of parsecs (Armstrong et al. 1995), although the largest few orders of magnitude of this power spectrum are very uncertain. The power spectral index of these data is consistent with the standard theory of incompressible hydrodynamic turbulence (Kolmogorov 1941).

However, fluctuations with properties not in agreement with Kolmogorov turbulence have been observed as well. From rotation measures (RMs) of polarized extragalactic sources in different regions of the sky, Simonetti & Cordes (1986) found variable spectral indices. Minter & Spangler (1996) used RMs and emission measures (EMs) in a region at medium Galactic latitudes to show that there is a change in turbulent behavior at a scale of about 4 parsec. Furthermore, very shallow spectral indices were found both from RMs from diffuse Galactic synchrotron emission (Haverkorn et al. 2003) and from RMs from polarized extragalactic sources (Sun & Han 2003). All these observations indicate that turbulent properties vary with position in the sky, observing technique and frequency.

To study this position variation, turbulent properties must be measured over a significant fraction of the sky using a consistent technique. This can ideally be done using the polarized continuum data in the Southern Galactic Plane Survey (SGPS), which is part of the International Galactic Plane Survey (IGPS, see Taylor et al. 2003 for Canadian part, and Taylor et al. 2002 for the VLA part of the IGPS).

2 The Southern Galactic Plane Survey

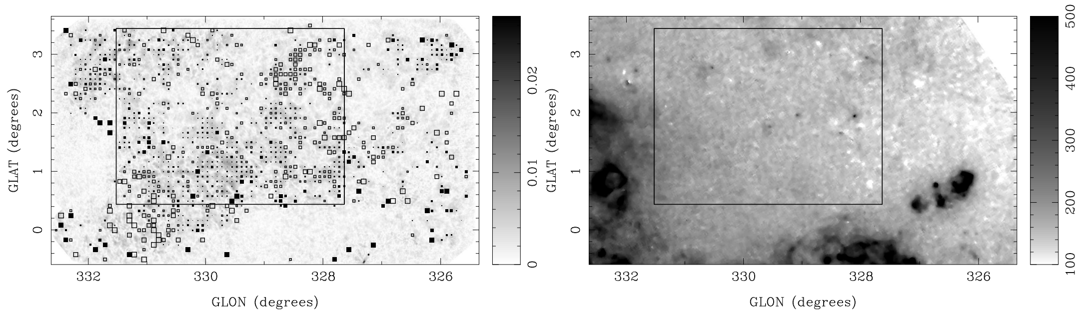

Figure 1: Left: Polarized intensity in the SGPS test region in Janskys. Overlaid are rotation measures (RM), where the sizes of the squares scale with the magnitude of RM for $|\mathrm{RM}| < 100$ rad m^{-2} and are constant for $|\mathrm{RM}| > 100$ rad m^{-2}. Filled (open) squares denote positive (negative) RMs. Right: emission measures (EM) in the same region, from the Southern H Alpha Sky Survey (SHASSA, Gaustad et al. 2001), in deciRayleighs (1 rayleigh $= 10^6/4\pi$ photons cm^{-2} s^{-1} sr^{-1}). The box in both maps denotes the region over which structure functions were computed.

The SGPS (McClure-Griffiths et al. 2001, Gaensler et al. 2001) covers most of the inner Galactic plane at $253^\circ < l < 20^\circ$ and $|b| < 1.5^\circ$, including a $10^\circ \times 10^\circ$ region around the Galactic center. It contains neutral hydrogen 21cm data at 1 km s^{-1} spectral resolution and 1.4 GHz full-polarization continuum data, both at a spatial resolution of 1 arcmin. The SGPS consists of data from the Australia Telescope Compact Array (ATCA) and the Parkes 64m single dish telescope, although the polarization observations presented here contain only interferometric data.

The continuum data consist of 12 frequency bands in the range 1336 MHz to 1432 MHz, each 8 MHz wide, which allow determination of the Faraday rotation[1] in the medium. About 15% of the data show a linear relation between ϕ and λ^2 with high enough signal-to-noise, so that rotation measures could be defined at these positions. Caution is needed as these interferometer-only data do not include large-scale structure. However, as missing large-scale structure in general destroys the linear $\phi(\lambda^2)$ relation, the quality of the linear fit over 12 data points at the positions where RMs could be determined suggests that large scale components are not important at those positions.

A test region was observed as a precursor to the SGPS (Gaensler et al. 2001), the polarization data of which are shown in the left hand map of Fig. 1. Here, we analyze the polarized continuum emission only in the test region, and study polarized extragalactic sources of SGPS data in the whole fourth quadrant. Analysis of the polarized continuum emission in the entire SGPS is the subject of a forthcoming paper.

We include analysis of Hα data from the Southern H Alpha Sky Survey (SHASSA, Gaustad et al. 2001), shown in the right hand panel in Fig. 1. Comparing the two maps in Fig. 1, it is clear that depolarization occurs at the positions where the electron density is highest.

[1]Faraday rotation of the polarization angle ϕ by a magneto-ionized medium is $\Delta\phi = \mathrm{RM}\lambda^2$, where the rotation measure $\mathrm{RM} = 0.81 \int n_e \vec{B} \cdot \vec{ds}$, with n_e the electron density in cm^{-3}, $\vec{B}$ the magnetic field strength in μG, and $\vec{ds}$ the path length in parsecs.

Here the electron density, and possibly magnetic field, varies on scales smaller than the beam size, so that the synchrotron emission is depolarized (Gaensler et al. 2001). Furthermore, a gradient in EM is visible toward the upper right corner of the EM map.

3 Structure function analysis

We analyzed the fluctuations in RM and EM in Fig. 1 using the second order structure function SF, where

$$\mathrm{SF}_f(r) = \langle (f(x) - f(x+r))^2 \rangle_x \tag{1}$$

is the structure function of a quantity f as a function of scale r, and $\langle\rangle_x$ denotes averaging over all positions x. The one-dimensional structure functions of RM and EM from the boxed region in Fig. 1 are shown in Fig. 2 as a function of angular scale θ, for various position angles on the sky α superimposed. Both structure functions show a shallow power law over the range $\sim 0.07°$ to $\sim 5°$, and variations in slope with position angle at large scales. Furthermore, the structure function of RM shows a break in the slope at a scale of $0.07°$, while the resolution of the EM data is too poor to determine if the break is present there as well.

The variation of the structure function slope on large scales is sinusoidal with position angle, and is most likely caused by a gradient in RM and EM across the field (Haverkorn et al. 2004). Indeed, the direction in which the structure functions show the steepest slope is the direction of the gradient in EM in Fig. 1. The shallow slope and break in the structure function can be explained if we assume that the rotation measure is caused by two spiral arms acting as Faraday screens. Gaensler et al. (2001) showed that most synchrotron radiation is emitted in the Crux spiral arm, which means that the emission crosses the Carina and Local arms before detection. If fluctuations in both arms show power law behavior on similar spatial scales, the outer scales of these fluctuations will occur on different *angular* scales. This causes a shallow slope of the structure function, and a break at the angular scale of the outer scale of structure in the farther Faraday screen, i.e. the Carina arm (Haverkorn et al. 2004). Fig. 2 therefore indicates an outer scale of structure in the Carina arm of approximately 2 pc, and a lower limit for the outer scale in the Local arm of about the same size.

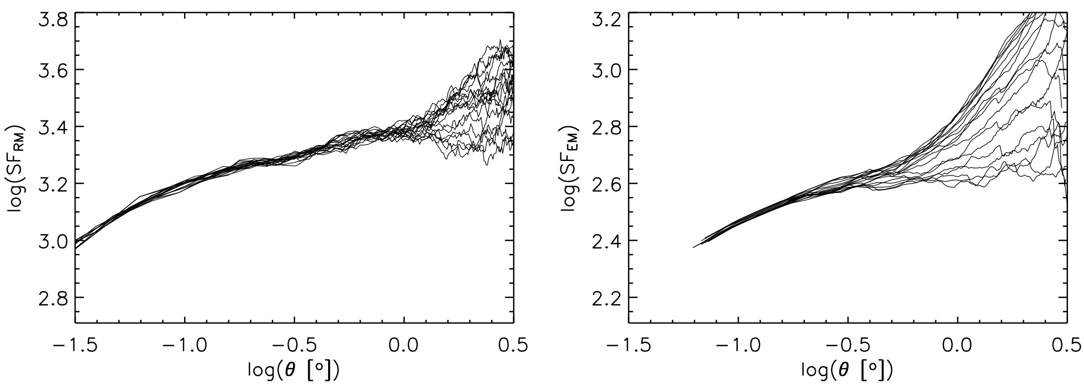

Figure 2: One-dimensional structure functions of rotation measure (left) and emission measure (right) in the SGPS test region, as a function of angular scale θ. Superimposed lines are structure functions for different position angles α.

This conclusion is supported by structure functions of RM from polarized extragalactic sources in the SGPS (Brown et al. in prep). About 150 extragalactic sources for which reliable RMs could be determined were found. Structure functions were calculated for various longitude ranges, separated into regions where the main part of the line of sight passes through spiral arms, and regions where the main line of sight is not associated with a spiral arm. The results are shown in Fig. 3, where the left hand plots show structure functions of RMs in interarm regions, whereas the right hand plots show the regions in spiral arms. To guide the eye, Kolmogorov-type structure functions of arbitrary amplitude are shown as dashed lines. The arm and interarm regions clearly display very different features: the interarm regions show a rising structure function up to scales of several degrees, the slopes of which are in agreement with Kolmogorov-like turbulence. On the other hand, the structure functions in directions through spiral arms are flat, indicating that the outer scale of structure in the arms is on scales smaller than the scales probed here. Because RMs probe the medium integrated over the line of sight, it is hard to ascribe a spatial scale to the angular scales presented in Fig. 3, but the Figure does make clear that the outer scale of structure in spiral arms must be several orders of magnitude smaller than that in interarm regions.

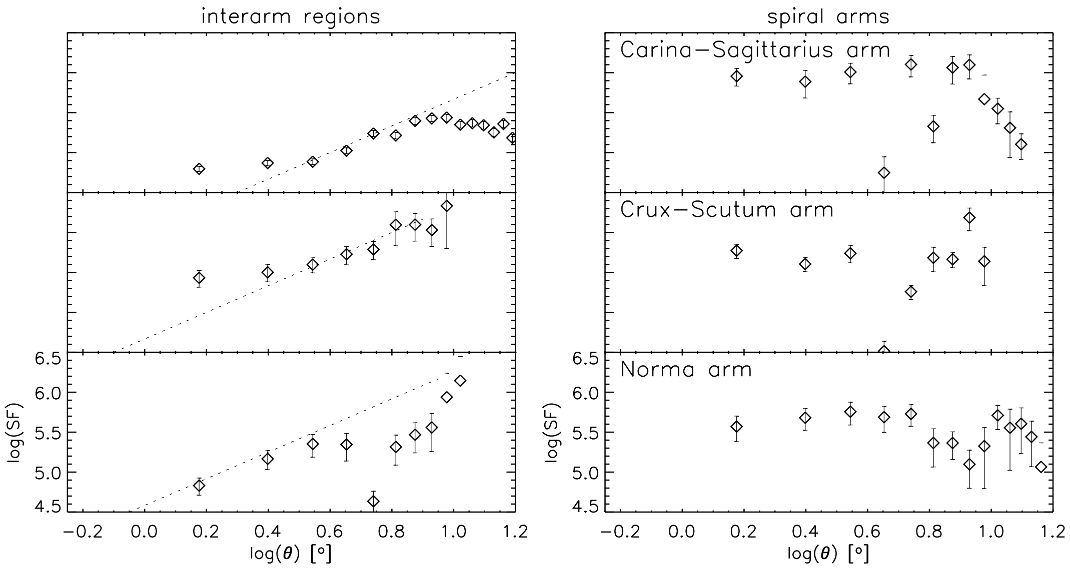

Figure 3: Structure functions of RM from polarized extragalactic sources. Directions where most of the line of sight passes through interarm regions are shown in the left panels, whereas directions through spiral arms are shown on the right hand side. The dashed lines in the left hand plots denote Kolmogorov turbulence of arbitrary amplitude.

4 Discussion

More evidence for the existence of an additional source of structure in thermal electron density in the Galactic plane comes from RMs of extragalactic sources (Clegg et al. 1992, Simonetti & Cordes 1986) and from scattering and angular broadening of extragalactic point sources and scintillation of pulsars (Spangler & Reynolds 1990, Rao & Ananthakrishnan 1984). Sources

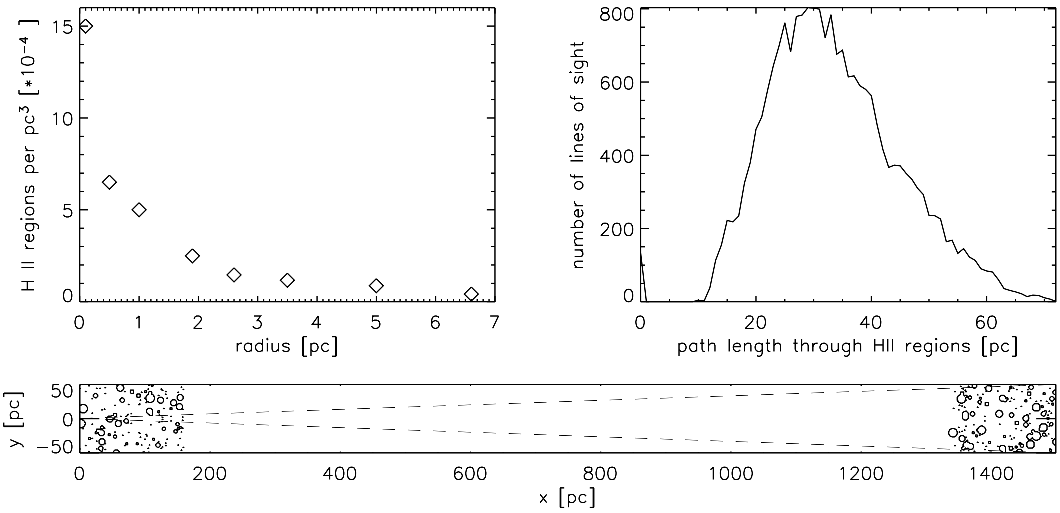

Figure 4: Top left: number of HII regions per cubic parsec as a function of their radii (Prentice & ter Haar 1969). Top right: histogram of the fraction of the total path length through HII regions in parsecs for each line of sight. Bottom: birds' eye view of a part of the Galaxy, where the observer is in $(x, y) = (0, 0)$ and the field of view, given by the dashed lines, goes through the local and Carina spiral arms. The circles are the HII regions denoted in the top left plot, randomly distributed over the two arms.

for this clumpy component of electron density have been suggested to be HII regions (Spangler & Reynolds 1990) or shocks associated with stellar winds and supernova shells (Cordes et al. 1985). Here we investigate the possibility that HII regions from relatively late-type stars, i.e. approximately B3 to A0 stars, are responsible for the additional structure. These stars are more ubiquitous than the O stars with giant HII regions, and produce HII regions of a few parsecs in size. We performed some simple modeling to test if these HII regions could be sufficiently abundant to be a dominating source of fluctuations in electron density and possibly magnetic field. The upper left panel in Fig. 4 shows the number of stars of all types per cubic parsec, and the radius of their HII regions (Prentice & ter Haar 1969). These HII regions we distributed randomly over the Local and Carina arms, as depicted in the lower panel in Fig. 4. For each line of sight, its fraction going through HII regions is computed. The upper right panel of Fig. 4 shows that a line of sight passes through on average ~ 35 pc of HII regions. Therefore, these HII regions are sufficiently abundant to be a significant source of structure in the spiral arms. Note that these fluctuations can be caused by turbulence in the ambient medium driven by the HII regions, turbulence inside the HII regions, the concrete shapes and sizes of the HII regions or their ionization fronts, or a combination of these. Therefore, the additional source of fluctuations is not necessarily turbulence.

5 Conclusions

We find evidence for an additional source of fluctuations in thermal electron density and/or magnetic field in the Galactic spiral arms, and derive an estimate of the outer scale of this structure. The outer scale is estimated to be a few parsecs from two independent datasets, viz. RMs from Galactic synchrotron emission and RMs from polarized extragalactic sources. A probable source for the additional fluctuations in electron density are HII regions from relatively late-type stars, which are much more abundant than the classical giant HII regions and have an average radius of a few parsecs. These HII regions are shown to be abundant enough to be able to dominate the electron density fluctuations in the spiral arms.

Acknowledgments

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