ANTISYMMETRY IN THE FARADAY ROTATION SKY CAUSED BY A NEARBY MAGNETIZED BUBBLE

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ABSTRACT

Rotation measures (RM)s of pulsars and extragalactic point sources have been known to reveal large-scale antisymmetries in the Faraday rotation sky with respect to the Galactic plane and halo that have been interpreted as signatures of the mean magnetic field in the Galactic halo. We describe Faraday rotation measurements of the diffuse Galactic polarized radio emission over a large region in the northern Galactic hemisphere. Through application of RM synthesis we achieve sensitive Faraday rotation maps with high angular resolution, capable of revealing fine-scale structures of ~1° in the Faraday rotation sky. Our analysis suggests that the observed antisymmetry in the Faraday rotation sky at b > 0° is dominated by the magnetic field around a local H1 bubble at a distance of 100 pc, and not by the magnetic field of the Galactic halo. We derive physical properties of the magnetic field of this shell, which we find to be 20–34 µG strong. It is clear that the diffuse polarized radio emission contains important information about the local magneto-ionic medium, which cannot yet be derived from Faraday RM of extragalactic sources or pulsars alone.

Key words: Galaxy: halo – ISM: bubbles – ISM: magnetic fields – magnetic fields – polarization

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1. INTRODUCTION

Linearly polarized radio emission is Faraday rotated as it passes through the interstellar medium (ISM) by an angle

$$\Delta \theta = \frac{\phi \lambda^2}{0.81 \int_{\text{nearside}} n_e(l) B_1(l) dl \lambda^2},$$

where \(\phi\), called the Faraday depth, is the integral along the line of sight (l.o.s.) \(l/(\text{pc})\) of the product of the free electron density \(n_e/(\text{cm}^{-3})\) and the component of the magnetic field along the l.o.s. \(B_1/(\mu\text{G})\). For wavelengths \((\lambda/\text{(m)})\) greater than a few centimeters, \(\Delta \theta\) is a few degrees or more for typical interstellar values of \(n_e \approx 0.1 \text{ cm}^{-3}\) and \(B_1 \approx 1 \mu\text{G}\) along kpc path lengths. Thus, in principle, the Faraday rotation of polarized emission can be used to identify the structure of the magnetic field of the Milky Way.

The Faraday rotation of (mainly unresolved) polarized extragalactic sources (EGS) and pulsars can be readily measured but provides an irregularly sampled, sparse grid of \(\phi\) which may include contributions from Faraday rotation within the sources. In the case of EGS, the Faraday rotation arising in the Galactic magneto-ionic medium is integrated along the entire l.o.s. through the Milky Way, while using pulsars one can try to compare the Faraday rotation from pulsars that are nearby on the sky but lie at different distances to sample the magnetic field in localized regions. In either case, the existence of small-scale, high rotation measure (RM) structures in the Galactic neighborhood makes it difficult to distinguish the contributions of large

local features, such as the North-Polar Spur (NPS), from the global Milky Way magnetic field structure. The interpretation of the data requires careful statistical analysis and modeling to try to tease apart these effects.

In the case of polarized synchrotron emission originating from the diffuse ISM, the Faraday rotation is uniformly sampled at the scale of the telescope beam but a major problem is that Faraday rotation can depolarize the emission, with a nonlinear dependence on frequency, so \(\phi\) cannot always be reliably identified with the rotation measure

$$\text{RM} = \Delta \theta / \lambda \lambda^2,$$

obtained from observations at different wavelengths (see Burn 1966; Sokoloff et al. 1998). This can be partly overcome using RM synthesis (Brentjens & de Bruyn 2005) with observations that contain many frequency channels across a wide band. Choosing a value for \(\phi\), the observed polarization vector in each frequency channel is derotated by \(\phi \lambda^2\) and the rotated vectors are coherently added to obtain an image of polarized intensity (PI) at that value of Faraday depth. The final product of RM synthesis is a three-dimensional data cube (of polarized emission) with the first and second dimensions being the coordinates on the sky, and the third dimension being Faraday depth, \(\phi\) \((\text{rad m}^{-2})\). Faraday depth is usually not related to physical distance.

We have produced an RM-synthesis cube of a large field toward the Galactic center, using new wide-band data obtained with the 26 m Telescope of the Dominion Radio Astrophysical Observatory (DRAO). In this paper, we present evidence that a nearby H1 bubble produces a large-scale RM pattern on the sky that mimics the effect that an overall antisymmetry in the
Milky Way’s regular magnetic field would have on EGS and pulsar Faraday rotation, both in magnitude and sign. Our results demonstrate the power of RM synthesis and high-resolution polarization surveys in separating global from local magnetic field structures in the Milky Way.

2. OBSERVATIONS

The polarization data presented in this paper are the first results from the Global Magneto-Ionic Medium Survey (GMIMS\textsuperscript{11}). The frequency coverage is 1277–1740 MHz with the band split into 2048 frequency channels. The angular resolution at the present sky coverage is $\sim 1^\circ$. The rms noise at this stage of the survey is 25 mK in a single channel and is 1 mK in an RM-synthesis frame. The reader is referred to Wolleben et al. (2009, 2010) for more information on observing and calibration.

RM synthesis was performed on data cubes of Stokes $U$ and $Q$. Incomplete frequency coverage causes sidelobes in the rotation measure spread function (RMSF, the response function with which the RM-synthesis spectra are convolved) which were partially removed by applying a CLEAN algorithm to the data cube. The expected width of the RMSF is 132 rad m\(^{-2}\) (note that structures at different Faraday depths can be distinguished with higher accuracy). By using a narrower RMSF for the cleaning process a final resolution of 60 rad m\(^{-2}\) was achieved.\textsuperscript{12}

Intrinsic polarization angles cannot be recovered accurately from our RM-synthesis data due to the low signal-to-noise ratio of the emission associated with the bubble. For a detailed discussion see Brentjens & de Bruyn (2005).

2.1. Errors and Uncertainties

Systematic errors in the data are caused by two uncertainties in the calibration. First, the aperture efficiency of the DRAO 26 m Telescope, which is used to calculate main beam brightness temperatures in $U$ and $Q$, is known only at 1.4 GHz. For the data calibration, we assumed this value to be constant over the band, neglecting possible variation of up to a few percent. The effect of a 20% gradient of aperture efficiency over the band on the final RM-synthesis frames was tested and, while the systematic error in the polarized intensities was found to be $\lesssim 10\%$, the shape and position of polarized structures were not affected on a level relevant for this analysis. The second uncertainty is the absolute calibration (zero levels) of $U$ and $Q$, which was derived by subtracting ground emission profiles obtained by averaging over a region of the sky relatively free of Galactic emission—a method shown to work reasonably well for long scans, if confusion with Galactic emission can be avoided.

In order to estimate the reliability of the calibrated data we compared PI with an older, precisely calibrated survey at 1.4 GHz (Wolleben et al. 2006). We find a good correlation down to PI $\approx 100$ mK. Since the correlation can be expected to suffer from bandwidth depolarization in the wide-band data, we use this value as a conservative estimate of the reliability threshold in our RM-synthesis data. In the present analysis, we consider only polarized structures above that threshold.

2.2. Filaments of Strong Polarized Emission Associated with H\textsc{i} Shells

Figure 1 shows a Faraday rotation map obtained from the RM-synthesis cube. Shown in this map is $\phi$ of the dominant emission in each pixel (i.e., the Faraday depth of the strongest polarized emission, which is not necessarily the highest or lowest $\phi$ along that l.o.s.). The global properties of the Faraday rotation shown in this map resemble the large-scale pattern of pulsar and EGS RMs seen in the same field (e.g., Han et al. 1997; Taylor et al. 2009) in both sign and magnitude of the Faraday rotation. The high sensitivity to local polarized emission as well as the unprecedented angular resolution of our data, however, allow us to also clearly identify small-scale structures.

We see filamentary structures of high positive $\phi$ in the region $10^\circ < l < 60^\circ$ and $0^\circ < b < +50^\circ$, embedded in a large region of positive RMs.

Figure 2 shows three RM-synthesis maps at $\phi = +60$ rad m\(^{-2}\), 0 rad m\(^{-2}\), and $-50$ rad m\(^{-2}\). The emission in these maps was Faraday rotated by the corresponding $\phi$ somewhere along the l.o.s. Note that these are not the only RM-synthesis frames that contain polarized emission from this region: the frames shown in Figure 2 have been selected in order to highlight filamentary structures at different Faraday depths. However, there is polarized emission with Faraday depths up to $\pm 100$ rad m\(^{-2}\). The filaments seen in Figure 1 appear again in the $+60$ rad m\(^{-2}\) map as emission structures but also in the 0 rad m\(^{-2}\) map as depressions: the $\phi = 0$ rad m\(^{-2}\) frame shows a “negative imprint” of the filaments and the amplitudes of the polarized emission in the two frames in this region are similar. The missing emission in the 0 rad m\(^{-2}\) frame has simply been shifted into the $+60$ rad m\(^{-2}\) frame by the action of a Faraday screen.

More polarized emission filaments are identified at $\phi = 0$ rad m\(^{-2}\) and $-50$ rad m\(^{-2}\). The three filaments in the $-50$ rad m\(^{-2}\) map (red lines in Figure 2(c)) are strongest in PI at $\sim -20$ rad m\(^{-2}\) but are most easily distinguished from the background in the map shown here.

Figure 3 shows H\textsc{i} at a velocity of $15$ km s\(^{-1}\), obtained from the LAB-H\textsc{i} survey (Kalberla et al. 2005) at a resolution of $\sim 0\text{.}\!06$ for the same field as Figures 1 and 2. At this velocity, shells of H\textsc{i} emission forming a bubble (or bubbles) are clearly visible. Projected onto the sky the bubble is elongated in Galactic longitude with a major axis of about 70°, a minor axis of about

\textsuperscript{11} https://www.astrosci.ca/users/drao/gmims
\textsuperscript{12} We carefully checked that all conclusions derived from the super-resolved RM cube also apply to the un-CLEANED RM cube.
40°, and centered at $l = 10°$ and $b = +25°$. The filaments of polarized emission (Figures 1 and 2) closely follow the shape of the H$\text{I}$ shells, with the connection becoming even clearer when scrolling through the H$\text{I}$ emission in neighboring velocity channels.

In the following sections, we discuss the physical properties of this 2200 deg$^2$ H$\text{I}$ bubble and deduce its magnetic field structure from our RM-synthesis cube. Note that the region we are discussing covers $1/20$ of the sky.

3. DISTANCE TO AND ORIGIN OF THE FILAMENTS

Large, extra-planar, expanding H$\text{I}$ shells in the direction of the Galactic center are associated with stellar winds and supernova remnants (SNRs) originating in the stars of the Scorpius-Centaurus OB association (de Geus 1992). Of the three identified subgroups in Sco-Cen, two have been identified with the origin of the Local Bubble and the Loop 1 superbubble (Maíz-Apellániz 2001). The third subgroup, Upper Scorpius (also known as Sco OB2_2), is the furthest away at a distance of 145 pc (de Zeeuw et al. 1999) and its position of $l = −8°$, $b = +21°$ places it in the center of the western side of the H$\text{I}$ shells shown in Figure 3. Five megayears ago, when this subgroup formed, it was located at $l = 15°$, $b = +21°$ (Maíz-Apellániz 2001): the first OB stellar winds and SNRs in the Upper Sco subgroup, expected to occur when it was 3–5 Myr old, will have occurred as it traveled along the major axis of the system of H$\text{I}$ shells. Furthermore, 5 Myr ago the 14–15 Myr old subgroup Upper Centaurus Lupus (UCL) was located at $l = 4°$, $b = +9°$ about 100 pc away (Maíz-Apellániz 2001). The H$\text{I}$ filaments in the northeast of Figure 3 could plausibly have been swept up by SNRs and winds from the UCL subgroup.

If the center of the H$\text{I}$ bubble is at a distance of 145 pc then its linear size is about 200 pc $\times$ 100 pc. If the cross section along the l.o.s. is circular then the nearside of the bubble is 95 pc away and the far side 195 pc distant. These dimensions are compatible with other, independent, information that constrains the bubble size: since it shows no sign of breaking out of the disk its height above the mid-plane must be less than the warm H$\text{I}$ scale height of about 300 pc; the depolarizing effect of the 170 pc distant H$\text{II}$ region Sh2-27 (center at $l = 6°:1$, $b = +23°:6$, diameter of 11°) can be seen in Figure 2(b) so most of the polarized emission in this region must originate beyond 170 pc; the wall of the local cavity is about 80 pc distant in this direction so the H$\text{I}$ shells of this bubble should be no nearer than this.

Mixed emitting and Faraday-rotating regions produce polarized emission from a continuous range of Faraday depths because emission from the near edge undergoes little Faraday
rotation whereas emission from the far side is rotated by the whole layer. The observed RM spectra for l.o.s. in this region generally have a strong peak (with polarized intensities >100 mK), which we interpret as the Faraday rotation of the background polarized emission, but many l.o.s. show weak emission from a range of Faraday depth, indicating that low level (<50 mK) emission might also be coming from the shell. The shell acts as a Faraday screen to the strong background polarized emission (thin in $\phi$) and also as a much weaker mixed emitting and rotating slab. No radio continuum emission from this bubble is seen in total intensity at 408 MHz (Haslam et al. 1982) and 1.4 GHz (Reich 1982; Reich & Reich 1986), but ~50 mK emission is too low to stand out from the synchrotron background in these maps.

The Faraday depths of the emission rotated by the bubble allow us to determine its magnetic field configuration. Note that with 1° resolution all structures within the bubble that are bigger than about 3 pc are resolved. The positive $\phi$ in the east (Figure 2(a)) changes to negative $\phi$ in the west (Figure 2(c)), suggesting that the magnetic field is wrapped around the bubble, pointing toward us in the east and away from us in the west. The polarized emission at $\phi = 0$ along the center of the bubble links these two regions: $\phi = 0$ means that either $B_0 = 0$ or $n_e = 0$. In this central region, the magnetic field pattern indicated by optical polarization measurements of local stars (Heiles 2000), as well as radio polarization data at 1.4 GHz (Wolfeben et al. 2006), shows that $B_\perp$ closely follows the shape of the H$_1$ bubble. This suggests that, in this part of the shell, $B_0$ must be small with a $B_\parallel$ component of unknown strength. The bottom of the bubble lies near the Galactic plane and is not clearly visible in any $\phi$ frame.

Theoretical models of magnetic fields in interstellar bubbles symmetrically inflated by stellar winds and SNRs (e.g., Ferriere et al. 1991; Tomisaka 1992) predict that the ambient B-field is compressed in a shell by the expanding shock wave. The shape and implied magnetic field configuration of this H$_1$ bubble suggest that it has expanded asymmetrically. In particular, for $B_0$ to have constant magnitude but opposite signs at the two ends of the bubble indicates that its expansion is constrained to only one direction along the l.o.s. The dense wall of the Local Bubble lies in the right direction and at the right distance to constrain the expansion of shells powered by the Upper Scorpius subgroup (5–6 Myr old) toward us. It seems likely that magnetic pressure in the wall of the Local Bubble has caused an asymmetric expansion. Figure 4 shows a sketch of the deduced bubble and magnetic field configuration.

4. DISCUSSION

We have searched the combined VTSS/SHASSA/WHAM survey (Finkbeiner 2003) for signs of the H$_1$ shells and bubble in H$_\alpha$ emission but could not find any. Assuming no optical extinction, this suggests that the high Faraday rotation from the shells is caused by a local enhancement of magnetic field and not electron density. The emission measure toward the shells is around 2.4 cm$^{-6}$ pc. Assuming a scale height for the warm ionized medium of 0.9 kpc (Savage & Wakker 2000) to 1.8 kpc (Gaensler et al. 2008), we have an average electron density along $b = 20^\circ$ of 0.03–0.02 cm$^{-3}$. The shells have an approximate thickness of 5° or $\delta r \approx 13$ pc, giving a maximum path length through a shell of $L \approx 2\sqrt{2}\delta r \approx 100$ pc. At the ends of the major axis of the bubble, where we expect the magnetic field to be mainly directed along the l.o.s., the observed Faraday depth of $|\phi| \approx 50–60$ rad m$^{-2}$ corresponds to a magnetic field strength of $B_1 \approx 20–34$ $\mu$G. It is noteworthy that the Faraday rotation pattern has been fractured into confined filaments; naively one would expect a Faraday rotation distribution which changes smoothly from positive on one side to negative on the other.

Such strong magnetic fields are difficult to reconcile with a simple sweeping up of a typical ambient 2–3 $\mu$G field by a strong advective shock, such as an SNR in the Sedov–Taylor phase, which has a compression ratio of only 4. Two possibilities to explain the strong magnetic fields are (1) the SNR and/or stellar winds that inflated the bubble have entered the radiative stage of their evolution (plausible given the 5–6 Myr age of the subgroup), allowing stronger compression to occur; (2) the Upper Sco subgroup OB stars had already entered the dense wall of the local bubble, with its already compressed magnetic field of about 8–9 $\mu$G (Andersson & Potter 2006; Mao et al. 2010), when the new bubble expanded. The latter possibility is compatible with the elongated shape (Section 3).

The main astrophysical consequence of this nearby bubble and its associated Faraday rotation is its effect on the interpretation of EGS and pulsar Faraday rotation in terms of the global magnetic field structure of the Milky Way.

Maps of pulsar RMs (e.g., Han et al. 1997) show a clear antisymmetry in the sign of RM in the northern Galactic hemisphere looking toward the Galactic center, with positive RMs dominating in the region 60° $> l > 0^\circ$, $b > 0^\circ$ and negative RMs at 0° $> l > -60^\circ$, $b > 0$. The recent Faraday rotation map of NRAO VLA Sky Survey sources by Taylor et al. (2009), which provides the most densely sampled grid of RMs to date, shows a similar antisymmetric pattern of RMs. The RMs of pulsars and EGS in this region have magnitudes up to 100 rad m$^{-2}$, similar to the maximum Faraday depths found in our RM-synthesis cube.

It is tempting to interpret such large-scale antisymmetries in Faraday rotation as a signature of the regular magnetic field of the Milky Way (Andreasyan & Makarov 1988; Han et al. 1997; Sun et al. 2008), especially as galactic dynamo theory makes predictions about the expected mean field symmetries in the disk and halo (e.g., Beck et al. 1996). But several authors have pointed out that the antisymmetry may be due to radio Loop I and its bright, polarized segment, the NPS. Simard-Normandin & Kronberg (1980) find that the effect of the NPS on the RMs...
in the northern Galactic hemisphere is clearly visible and Inoue & Tabara (1981) point out the importance of avoiding the effect of irregularities in RMs due to local objects. In this paper, we have identified a nearby bubble and set of shells that covers a large area of the sky with the same Faraday rotation asymmetry as seen in the EGS and pulsar RMs. The discovery of small-scale structures in the Faraday rotation sky which are associated with nearby H\textsubscript{i} have the same sign, similar magnitude, and are embedded in the large-scale antisymmetry at $b > 0^\circ$ leads us to conclude that the observed antisymmetry has largely a local origin. Note that the structures discussed here are not associated with the NPS as they do not resemble the shape of the spur: thus the NPS can only add to the region of the northern sky where local structures dominate the Faraday rotation pattern. To minimize the effect of local RM structures on the picture of the mean Galactic magnetic field we suggest that point source RMs toward regions that show diffuse polarized emission at high Faraday depth should not be used.

Clearly the diffuse polarized radio emission contains important information about the local magneto-ionic medium, with better angular resolution than currently available from EGS source measurements. This must be taken into account when building a complete picture of the Galactic magnetic field. At present RM-synthesis data exist only for the northern sky. Observations for a southern sister-survey (STAPS, PI: M. Haverkorn) were just completed and RM synthesis should soon become available too. de Geus (1992) (in their Figure 1(b)) shows more H\textsubscript{i} filaments associated with Sco OB2\_2 in the southern sky. Our prediction is that there will be Faraday rotation structures also associated with these filaments.

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