Polarization Shadows of Extragalactic Sources by the Local Magnetoionic Interstellar Medium

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ABSTRACT

We report depolarization of extragalactic sources in the NRAO VLA Sky Survey (NVSS) by local structures in the interstellar medium. The sky density of polarized sources drops by a factor of 2–4 in regions with angular scales \(\sim 10^6\) arcmin, implying up to 40% depolarization on average per source. Some of these polarization shadows are associated with \(\text{H} \alpha\) regions, but three are associated with regions of depolarized diffuse Galactic emission. The absence of a correlation between the depth of polarization shadows and \(\text{H} \alpha\) intensity suggests that some shadows are related to structure in the magnetic field. At least some polarization shadows are caused by partial bandwidth depolarization in the NVSS. Alternatively, some may be caused by regions with small-scale (\(\lesssim 1^\circ\)) variations in rotation measure.

Subject headings: ISM: magnetic fields — ISM: structure

1. INTRODUCTION

Observations of polarized radio emission provide a way to study magnetic fields in galaxies. The observed plane of polarization of optically thin, linearly polarized synchrotron emission is perpendicular to the direction of the magnetic field projected on the sky, unless Faraday rotation changes the plane of polarization as the radiation travels through a plasma with a magnetic field component along the line of sight. The plane of polarization of emission with wavelength \(\lambda\) (m) rotates by an angle \(\Delta \theta\) (rad), according to

\[
\Delta \theta = 0.81\lambda^2 \int_{\text{source}} n_e B_\parallel \, dl = \lambda^2 \text{RM},
\]

with electron density \(n_e\) (cm\(^{-3}\)), line-of-sight component of the magnetic field \(B_\parallel\) (\(\mu\)G), and line-of-sight distance element \(dl\) (pc). The rotation measure RM (rad m\(^{-2}\)) is a property of the medium along the line of sight from the source to the observer. Rotation measures can be derived from multifrequency observations of polarized emission, fitting \(\Delta \theta\) as a function of \(\lambda^2\). Rotation measures of compact polarized sources have been used to constrain models of the Galactic magnetic field (e.g., Han et al. 1999; Brown et al. 2003).

Observations of diffuse polarized Galactic emission have revealed structures in the magneto-ionic medium that remain undetected in total intensity, because an ionized region can have negligible emission measure yet still produce measurable Faraday rotation (Uyaniker et al. 2003). However, interpretation of structures in diffuse polarized emission is difficult, as both polarized emission and Faraday rotation may occur intermixed anywhere along the line of sight.

Gaensler et al. (2005) and Haverkorn (2006) reported depolarization of extragalactic sources by regions of high emission measure in the Large Magellanic Cloud (LMC) and the Southern Galactic Plane Survey (SGPS; Haverkorn et al. 2006a), respectively. In this Letter, we report detection of depolarization of extragalactic sources on much larger angular scales by the local magneto-ionic medium.

2. POLARIZATION SHADOWS

The main data set for our analysis is the NRAO VLA Sky Survey (NVSS; Condon et al. 1998), a single-frequency 1.4 GHz continuum survey of the sky north of declination \(-40^\circ\) with the VLA in D configuration (45° angular resolution). The NVSS bandwidth is the sum of two 42 MHz wide bands, but separated by 70 MHz in frequency. The principal data products are images in Stokes \(I\), \(Q\), and \(U\) and a source catalog of two-dimensional Gaussians fitted to compact structures in these images. The mean noise level of the NVSS in \(Q\) and \(U\) is 0.29 mJy beam\(^{-1}\).

Figure 1 shows images of the number density \(\Sigma_{\text{pol}}\) (sources per square degree) of NVSS sources with polarized intensity \(p > 1\) mJy beam\(^{-1}\), smoothed to a resolution of \(2^\circ\). \(\text{H} \alpha\) intensity composed by Finkbeiner (2003) from the VTSS (Dennison et al. 1998), SHASSA (Gaustad et al. 2001), and WHAM (Haffner et al. 2003) surveys, and diffuse polarized intensity at 1.4 GHz from the DRAO 26 m polarization survey (Wolleben et al. 2006). The number density of polarized sources shows distinct depressions (dark areas) on angular scales \(\sim 10^6\), some of which coincide with enhanced \(\text{H} \alpha\) emission. Most conspicuous is a ring centered on \((l, b) = (−106^\circ, +4^\circ)\) that coincides with an \(\text{H} \alpha\) shell associated with the Gum nebula. We refer to these structures as polarization shadows.

For the most significant features in Figure 1a, Table 1 lists Galactic coordinates, angular diameter, minimum source density \(\Sigma_{\text{pol, min}}\), \(\text{H} \alpha\) intensity averaged over a 2° box at the minimum of \(\Sigma_{\text{pol}}\), identification with known \(\text{H} \alpha\) regions, and distance. These features have values of \(\Sigma_{\text{pol}}\) a factor of 2–4 smaller than the mean background of 6.6 sources deg\(^{-2}\). The rms noise level \(\sigma\) in Figure 1a caused by statistical fluctuations in \(\Sigma_{\text{pol}}\) is 1.3 sources deg\(^{-2}\). The contour in Figure 1a at half the background source density is therefore 2.5 \(\sigma\) below the mean value of \(\Sigma_{\text{pol}}\). Table 1 is complete for features with \(\Sigma_{\text{pol, min}} < 2.7\) deg\(^{-2}\). A comprehensive analysis of smaller structures will be deferred to a later paper.

The association of several polarization shadows with nearby \(\text{H} \alpha\) regions is the strongest indication that these shadows are real. \(\text{H} \alpha\) regions are also known to depolarize diffuse emission (Gray et al. 1999; Gaensler et al. 2001). We inspected NVSS images and also verified that the structures were robust against variation of the threshold in \(p\). The polarization shadows have no counterpart in the all-sky images of total NVSS source...
density, or NVSS noise amplitude. The structures are also visible in an image of mean fractional polarization, demonstrating that the mean fractional polarization is lower in these regions. Some apparent excesses in $\Sigma_{\text{pol}}$ are seen near bright radio emission in the Galactic plane. These excesses, seen in white in Figure 1a, are the result of confusion from small-scale structure in Galactic emission, and residual sidelobes around bright emission. We exclude these regions from our analysis.

The NVSS contains small areas (typically <1° across) with missing polarization data. Most of these areas exist along lines of constant right ascension in the declination range $-10^\circ$ to $+25^\circ$, which intersects the Galactic equator at $l \approx +40^\circ$. We have verified that the features in Table 1 are not the result of holes in the sky coverage of the NVSS. We have identified these holes, and their effect on $\Sigma_{\text{pol}}$ is almost always lost in the noise.

Three extended polarization shadows listed in Table 1 are found in regions where $I_{\text{vis}} \approx 10 R$. Despite the low H{$\alpha$} intensity, these shadows are among the deepest in $\Sigma_{\text{pol},\text{min}}$. These shadows coincide with minima in diffuse polarized emission in the DRAO 26 m polarization survey (Wolleben et al. 2006) shown in Figure 1c. One of these is shown in Figure 2. The features seen in the DRAO survey also exist in the Effelsberg medium latitude survey by Uyaniker et al. (1999). This polarization shadow coincides with an edge in diffuse polarized emission. A diffuse polarized intensity filament coincides with a higher polarized source density between the two strongest shadows. Large changes in polarization angle are also seen associated with the depressions in $\Sigma_{\text{pol}}$.

The polarization shadow in Figure 2 overlaps in part with the Canadian Galactic Plane Survey (CPGS; Taylor et al. 2003). Uyaniker et al. (2003) note a diagonal band of low diffuse polarization intensity extending from $(l, b) = (87.6^\circ, +4.5^\circ)$ to $(l, b) = (94.0^\circ, -2.0^\circ)$, the approximate course of the polarization shadow. A triangular region of depolarization noted by these authors at $84.5^\circ < l < 89.5^\circ, b = -3^\circ$ coincides with the deeper part of this shadow. Rotation measures of polarized sources in this region are $\sim 350$ rad m$^{-2}$, with large variations.
on the scale of a few degrees (Brown et al. 2003). Unpublished rotation
measure data with more complete longitude coverage confirm a negative excess in rotation measure in the longitude range 84° < l < 90° (J.-A. Brown 2007, private communication) that appears to be associated with this polarization shadow.

3. DISCUSSION

Polarization shadows in Figure 1 indicate depolarization of the background sources, leaving fewer sources with polarized intensity above the threshold of 1 mJy. The mean amount of depolarization can be estimated using the fact that the differential polarized source counts for unresolved extragalactic sources vary approximately as $dN/dp \sim p^{-2.5}$ for 1 mJy beam$^{-1} < p < 10$ mJy beam$^{-1}$ (Tucci et al. 2004; Taylor et al. 2007). If $f_{pol}$ is a fraction of the background value, the polarized intensity per source must on average be decreased by a factor $f_{pol} = f_{0.4}^{0.7}$. The value $f_{pol} \sim 0.5$–0.25, typical for the shadows we detect, corresponds to $f_{pol} \sim 0.76$–0.57. The polarized intensity of extragalactic sources in these regions is therefore decreased by up to 40%.

The large angular size of the polarization shadows suggests that these structures are relatively nearby.

Extragalactic sources may be depolarized if $|RM|$ is high enough to produce differential Faraday rotation over the frequency band (bandwidth depolarization), or if significant RM fluctuations exist over the solid angle of the source (beam depolarization). Complete bandwidth depolarization for NVSS sources requires $|RM| \sim 340$ rad m$^{-2}$, but Figure 23 in Condon et al. (1998) shows that values of $f_{pol} \sim 0.76$–0.57 require $|RM| \sim 150$–200 rad m$^{-2}$. Most polarization shadows are poorly covered by published rotation measures, but shadows near $l = 90°$ that overlap with the CGPS, coincide with areas where RM $\sim -350$ rad m$^{-2}$, enough to cause bandwidth depolarization in the NVSS. The polarization shadow associated with the Gum nebula comes from a shell seen in H$\alpha$ emission. Vallée & Bignell (1983) detected this shell through individual rotation measures $\sim 200$ rad m$^{-2}$, consistent with partial bandwidth depolarization of NVSS sources by the shell.

If the depolarization in the NVSS is bandwidth depolarization, Figure 1 shows regions of high RM up to Galactic latitude $\pm 20°$, with the contour corresponding to $|RM| \approx 150$ rad m$^{-2}$. This RM amplitude map does not depend on sparsely sampled rotation measures to individual sources, but it provides complete sampling of the sky north of declination $-40°$, outside the Galactic plane. We found no evidence for large-scale structure in an image of $\Sigma_{pol}$ convolved to a resolution of 5°, providing an upper limit $f_{pol} > 0.94$, or $|RM| < 70$ rad m$^{-2}$ for an extended component outside the Galactic plane. This upper limit is in general agreement with all-sky RM images constructed by interpolation of rotation measures of extragalactic sources (Frick et al. 2001; Johnston-Hollitt et al. 2004; Dineen & Coles 2005), although these images do not show structure on angular scales $\approx 20°$ because of the limited sky density of published rotation measures.

Most polarization shadows appear around $l \approx 90°$ where the line of sight is approximately along the local Galactic magnetic field. Larger values of $|RM|$ are expected here, which can increase the amount of bandwidth depolarization, but other depolarization mechanisms may also be enhanced.

Beam depolarization of extragalactic sources implies RM fluctuations over the solid angle of the source. Gaensler et al. (2005) and Haverkorn (2006) report beam depolarization of extragalactic sources behind the LMC and in the SGPS. Beam depolarization is also a possible mechanism for at least some of the polarization shadows observed here. Polarized sources fainter than 100 mJy in total intensity provide most of the signal in Figure 1a. Beam depolarization of these sources would require RM fluctuations on angular scales less than their median angular size of 1° (Windhorst 2003). The present data do not allow us to identify shadows with low $|RM|$, where bandwidth depolarization can be excluded. More rotation measures of background sources in polarization shadows are needed to resolve this question. If beam depolarization is significant for compact sources, it must also be significant for diffuse emission. Polarization shadows caused by beam depolarization should therefore provide valuable information for the interpretation of diffuse polarized Galactic emission.

While some deep extended polarization shadows are located in regions with low H$\alpha$ intensity, Table 1 also lists shadows associated with H$\alpha$ regions where the H$\alpha$ emission is a factor of $\sim 10$ brighter. Inspection of Figure 1 shows that some bright H$\alpha$ emission does not give rise to a polarization shadow, for example, the H$\alpha$ region NGC 1499 at $(l, b) = (160°, -13°)$, and the Orion region at $(l, b) \approx (-150°, -15°)$. Some bright H$\alpha$ emission from the Gum nebula at negative latitudes also does not give rise to a polarization shadow.

In the absence of extinction, H$\alpha$ intensity in R is related to emission measure EM in cm$^{-6}$ pc following

$$I_{H\alpha} = 2.25 \int_{\text{observer}} n_e^2 \, dl = 2.25 EM$$

(Haffner et al. 2003) for gas at a temperature of 8000 K. Regardless of the depolarization mechanism, RM structure caused exclusively by variations in electron density would imply a correlation between emission measure and the depth of polarization shadows. The lack of correlation between $\Sigma_{pol}$ and $I_{H\alpha}$ in Table 1, and the observation that some high EM objects do not give rise to polarization shadows, suggests that structure in the magnetic field is important in the formation of some or all polarization shadows. If all polarization shadows were caused by bandwidth depolarization in the NVSS, the shadows may be regions in the interstellar medium where the magnetic field is more regular and aligned with the large-scale magnetic field than elsewhere. If all polarization shadows were caused by beam depolarization, they would represent a more random magnetic field than elsewhere. Both beam depolarization and bandwidth depolarization may occur, but in either case polarization shadows suggest a different magnetic structure from their surroundings.

The size and $|RM|$ of the polarization shadows are of the same order of magnitude as the outer scale (4°–5°) and standard deviation (263 ± 32 rad m$^{-2}$) of RM fluctuations in interarm regions in the SGPS reported by Haverkorn et al. (2006b). The polarization shadows may be nearby examples of structures corresponding to this outer scale of RM fluctuations.

4. CONCLUSIONS

We demonstrate that nearby structures in the magneto-ionic medium create polarization shadows observed as depressions in the sky density of polarized sources in the NVSS. Some polarization shadows are associated with H$\alpha$ regions, but other shadows are related to depolarized areas in diffuse Galactic radio emission. Partial bandwidth depolarization in the NVSS is responsible for at least some polarization shadows, suggesting that these shadows are local regions of high $|RM|$. 
Such regions may affect estimates of the scale height of the Galactic magnetic field from RM data. If beam depolarization dominates, polarization shadows constrain depolarization mechanisms for diffuse polarized emission.

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REFERENCES

Brandt, J. C., Stecher, T. P., Crawford, D. L., & Maran, S. P. 1971, ApJ, 163, L99
Brown, J. C., Taylor, A. R., Wielebinski, R., & Mueller, P. 2003, ApJ, 592, L29
Chanot, A., & Sivan, J. P. 1983, A&A, 121, 19
Condon, J. J., Cotton, W. D., Greisen, E. W., Yin, Q. F., Perley, R. A., Taylor, G. B., & Broderick, J. J. 1998, AJ, 115, 1693
Dennison, B., Simonetti, J. H., & Topasna, G. A. 1998, Publ. Astron. Soc. Australia, 15, 147
Dineen, B., & Coles, P. 2005, MNRAS, 362, 403
Finkbeiner, D. 2003, ApJS, 146, 407
Frick, P., Stepanov, R., Shukurov, A., & Sokoloff, D. 2001, MNRAS, 325, 649
Gaensler, B., Haverkorn, M., Staveley-Smith, L., Dickey, J. M., McClure-Griffiths, N. M., Dickel, J. R., & Wolfeben, M. 2005, Science, 307, 1610
Gaustad, J. E., McCullough, P. R., Rosing, W., & Van Buren, D. 2001, PASP, 113, 1326
Gaensler, B. M., Dickey, J. M., McClure-Griffiths, N. M., Green, A. J., Wieringa, M. H., & Haynes, R. F. 2001, ApJ, 549, 959
Gray, A. D., Landecker, T. L., Dewdney, P. E., Taylor, A. R., Willis, A. G., & Normandeau, M. 1999, ApJ, 514, 221
Haffner, L. M., Reynolds, R. J., Tuft, S. L., Madsen, G. J., Jaehrig, K. P., & Percival, J. W. 2003, ApJS, 149, 405
Han, J. L., Manchester, R. N., & Qiao, G. J. 1999, MNRAS, 306, 371
Haverkorn, M. 2006, preprint (astro-ph/0611090)

Haverkorn, M., Gaensler, B. M., Brown, J. C., Bizunok, N. S., McClure-Griffiths, N. M., Dickey, J. M., & Green, A. J. 2006a, ApJS, 167, 230
Haverkorn, M., Gaensler, B. M., McClure-Griffiths, N. M., Dickey, J. M., & Green, A. J. 2006b, ApJ, 637, L33
Johnston-Hollitt, M., Hollitt, C. P., & Ekers, R. D. 2004, in The Magnetized Interstellar Medium, ed. B. Uyaniker, W. Reich, & R. Wielebinski (Katlenburg-Lindau: Copernicus GmbH), 13
Madsen, G. J., & Reynolds, R. J. 2005, ApJ, 630, 925
Madsen, G. J., Reynolds, R. J., & Haffner, L. M. 2006, ApJ, 652, 401
Markova, N. 2002, A&A, 385, 479
Taylor, A. R., et al. 2003, AJ, 125, 3145
Uyaniker, B., Forst, E., Reich, W., Reich, P., & Wielebinski, R. 1999, A&AS, 138, 31
Uyaniker, B., Landecker, T. L., Gray, A. D., & Kothes, R. 2003, ApJ, 585, 785
Vallée, J. P., & Bignell, R. C. 1983, ApJ, 272, 131
Windhorst, R. A. 2003, NewA Rev., 47, 357
Wolleben, M., Landecker, T. L., Reich, W., & Wielebinski, R. 2006, A&A, 448, 411
Wood, K., Haffner, L. M., Reynolds, R. J., Mathis, J. S., & Madsen, G. 2005, ApJ, 633, 295