A RELATION BETWEEN THE WARM NEUTRAL AND IONIZED MEDIA OBSERVED IN THE CANADIAN GALACTIC PLANE SURVEY

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ABSTRACT

We report on a comparison between 21 cm rotation measure (RM) and the optically thin atomic hydrogen column density (\(N_H\)) measured toward unresolved extragalactic sources in the Galactic plane of the northern sky. H\textsc{i} column densities integrated to the Galactic edge are measured immediately surrounding each of nearly 2000 sources in 1 arcmin 21 cm line data, and are compared to RMs observed from polarized emission of each source. RM data are binned in column density bins \(4 \times 10^{20} \text{ cm}^{-2}\) wide, and one observes a strong relationship between the number of hydrogen atoms in a 1 cm\(^2\) column through the plane and the mean RM along the same line of sight and path length. The relationship is linear over one order of magnitude (from 0.8 to 14 \(\mu\)G) of column densities, with a constant RM of \(45.0 \pm 13.8 \text{ rad m}^{-2}\) in the presence of no atomic hydrogen. This slope is used to calculate a mean volume-averaged magnetic field in the second quadrant of \(\langle B \rangle \sim 1.0 \pm 0.1 \mu\text{G}\) directed away from the Sun, assuming an ionization fraction of 8% (consistent with the warm-neutral medium; WNM). The remarkable consistency between this field and \(\langle B \rangle = 1.2 \mu\text{G}\) found with the same RM sources and a Galactic model of dispersion measures (DMs) suggests that electrons in the partially ionized WNM are mainly responsible for pulsar DMs, and thus the partially ionized WNM is the dominant form of the magneto-ionic interstellar medium.

Key words: ISM: atoms – ISM: magnetic fields – techniques: polarimetric

Online-only material: color figures

1. INTRODUCTION

The Milky Way interstellar medium (ISM) harbors gas in a variety of temperature and density regimes, all coexisting in an uneasy equilibrium readily disrupted by large-scale forces (e.g., gravitational) or smaller scale ones (e.g., stellar winds, shocks). Two of these regimes are the warm-neutral (WNM) and warm-ionized medium (WIM). The Galactic magnetic field (GMF) couples to the ionized component of the ISM creating the so-called magneto-ionic medium (MIM), and plays an essential but not well understood role in the mixing of the neutral and ionic ISM phases. Because of the partial ionization by cosmic rays and X-rays, the fractional ionization of the WNM, \(x_e\), the fractional ionization of the WNM, \(x_e\), is non-zero. However, it remains very much an unreliably measured parameter, and is key to ISM studies (see the review by Kulkarni & Heiles 1988). Nonetheless, this partial ionization blurs the boundary between the WNM and the WIM/MIM somewhat, and hence the field may be expected to couple with the WNM as well. To what degree is a matter of debate.

The MIM and WNM can be linked by two observables: rotation measure (RM) and atomic hydrogen column density (\(N_H\)). Each can be, respectively, written as path integrals of spatial densities of electrons (\(n_e\)) and of atoms (\(n_H\)):

\[
\frac{\text{RM}}{\text{rad m}^{-2}} = 0.81 \langle B \rangle \times \text{DM} = 0.81 \frac{\langle B \rangle}{(\mu\text{G})} \int n_e \text{d}r \quad \text{(cm}^{-3}\text{pc})
\]

\[
N_H = 1.82 \times 10^{18} \sum \frac{T_B(v_i)}{(\text{K})} \frac{\Delta v}{(\text{km s}^{-1})} = \int n_H \text{d}r \quad \text{(cm}^{-2}\text{)}
\]

where the path integrals are taken over the entire observable path through the Galactic disk, and the magnetic field \(B\) is the line-of-sight (LOS) average value (indicated by brackets \(\langle \rangle\) and is assumed uncorrelated with the electron density \(n_e\). The ratio between RM and \(N_H\) is then related to the ionization fraction

\[
x_e = \frac{n_e}{n_H + n_{H_1}} \simeq 1/(1 + n_{H_1}/n_e)
\]

by

\[
\frac{\text{RM}}{N_H} \left( \frac{\text{rad m}^{-2}}{10^2 \text{ cm}^{-2}} \right) \simeq 2.632 \times 10^2 \langle B \rangle \left( \frac{1}{\langle x_e \rangle} \right)^{-1},
\]

where \(\langle x_e \rangle\) is the path-averaged ionization fraction, related by Equation (3) to the ratio of path-averaged atomic and electron densities, i.e., \(n_H/\langle x_e \rangle = \langle n_{H_1} \rangle \int \text{d}r/(\langle n_e \rangle \int \text{d}r) = \int n_{H_1} \text{d}r/\int n_e \text{d}r\). As long as both are observed through the same length column, RM/\(N_H\) is independent of path length, and Equation (4) is true for any column length. Equation (4) links the WNM and MIM through the ionization fraction, and is an alternative expression to the usual ratio of rotation-to-dispersion measure (RM/DM) for estimating \(\langle B \rangle\) (see Section 5).

An order of magnitude estimate of the ratio RM/\(N_H\) can be made with currently accepted estimates for the LOS magnetic field strength in the ISM. \(\langle B \rangle \approx -1 \text{ to } -2 \mu\text{G}\) is found by various authors for the uniform field (e.g., Sun et al. 2008; Van Eck et al. 2011) near the Sun (where the negative sign indicates that the field is directed away from the receiver), thus the LOS component \(\langle B \rangle\) is at most these values or smaller. For the ionization fraction in the WNM, Jenkins (2013) find 8% at a canonical WNM density of \(n_{H_1} = 0.5 \text{ cm}^{-3}\) within a few hundred parsecs of the Sun, whereas Wolffe et al. (1995)
obtain 2% for the WNM from a two-phase model calculation. We use a mean of $\chi_e = 5\%$ here for illustration; from Equation (4) then one might expect to find ratios in the range of $-15$ to $-30$ rad m$^{-2}$/10$^{21}$ atoms cm$^{-2}$.

2. OBSERVATIONS AND METHOD

To measure the ratio $RM/N_{H_\text{II}}$ in Equation (4) we use RMs of 1970 extragalactic sources, calculated from CGPS (Taylor et al. 2003) Stokes $Q$ and $U$ data in four 7.5 MHz-wide sub-bands observed around the 1420 MHz line. The CGPS is an interferometric survey that extends from the first to the third quadrants of the Galactic plane, covering $52^\circ \leq \ell \leq 193^\circ$, and $-3.5^\circ \leq b \leq +5.5^\circ$ in latitude, with a small extension up to $b = +18^\circ$ in the range $99^\circ \leq \ell \leq 118^\circ$.4 The method used to extract the RMs is described in Brown et al. (2003a). We assume that there is little Faraday rotation from both the intergalactic medium and from within the source itself, relative to the path-integrated Galactic disk. Typical uncertainties in RM are in the range of 5%–20%. The catalog of CGPS RMs, uncertainties and statistics is presented in J. C. Brown et al. (2013, in preparation).

The high density of RMs in this catalog provides an unmatched ability to trace large-scale Galactic magnetism. For example, Brown et al. (2003a) demonstrate that while some CGPS RMs suffer from random rotation due to H$\text{II}$ regions along the LOS, removing RMs most correlated with emission measure (EM $\propto n_e^2$, traced by H$\alpha$ emission toward them) does not change the distribution of the sample nor the mean RM in any significant way. The catalog we use here includes the sources in Brown et al. (2003a) but is more extended; nonetheless, while some RMs in our sample are undoubtedly affected by H$\text{II}$ regions, the option to average RMs within a narrow range of longitudes provides the ability to extract the large-scale structure of the field, and to trace the MIM on the large scale (also demonstrated by Brown et al. 2007 for southern-sky RMs).

Integrated atomic hydrogen column densities toward each background source are measured from CGPS 21 cm H$\text{I}$ line data, which has essentially the same elliptical synthesized beam as the 21 cm continuum (FWHM $\sim 1 \times 1$ cosec$\delta$), and a spectral resolution of 1.3 km s$^{-1}$. Each velocity channel is $\Delta v = 0.824$ km s$^{-1}$ wide. The mean H$\text{I}$ brightness temperature $T_B$ (Kelvin) in the $i$th channel is measured in an annulus around each source with an inner radius of 1 FWHM in each of the major and minor axes of the elliptical beam, and oriented in the same direction as the beam. The annulus has a width of $36^\circ$ in both dimensions. The observed column density is accumulated as in Equation (2) over 256 velocity channels. The sum through all velocity channels records the column density through the entire Galactic disk, which is the same path length over which RMs are accumulated. Equation (2) is appropriate for warm ($T_e \gtrsim 200$ K) and hence optically thin ($\tau \rightarrow 0$) atomic H, which is the main constituent of the WNM and the phase which would most likely couple with the WIM/MIM. The additional advantage of integrating the H$\text{I}$ emission is that our column densities emphasize the smooth large-scale Galactic H$\text{I}$ distribution of the WNM, as opposed to H$\text{I}$ absorption which shows very local, dense (and optically thick) neutral hydrogen clouds that mainly are found associated with discrete features like young H$\text{II}$ regions (e.g., stellar wind bubbles and expanding shocked shells; Foster et al. 2004; Kothes & Kerton 2002, respectively) and spiral arm shock fronts (Gibson et al. 2005). These denser discrete clouds are not included in the column density integrated from H$\text{II}$ emission only.

The uncertainty in each value of $N_{H_\text{II}}$ is estimated from the standard deviation of brightness temperatures within the annulus in each H$\text{I}$ channel. This value is typically $\pm 2$–3 K per channel, and these are summed in quadrature to obtain an estimate for our error in $N_{H_\text{II}}$.

3. RESULTS

Figure 1 shows a plot of H$\text{I}$ column density, $N_{H_\text{II}}(\tau \rightarrow 0)$ (units of $10^{21}$ atoms cm$^{-2}$) versus RM (rad m$^{-2}$). An underlying trend of increasing magnitude of RM (negative values) with increasing column densities is readily seen, and the scatter about a mean RM for a given column $N_{H_\text{II}}$ does not overwhelm this trend. We see RMs on either side of zero, suggesting that a random component to the field plays a significant role in the scatter. The mean RM through the CGPS is negative, reflecting the LOS projection of the GMF in this area of the Milky Way which points away from the Sun. The scatter in RM for a given column can come from three broad sources: (1) scatter caused by a small-scale “random” component related to the large-scale GMF, (2) scatter from large-scale magnetic field reversals along the LOS, and (3) scatter from smaller scale “anomalous” regions with a magnetic field independent of the GMF and/or electron densities different from the bulk MIM (such as H$\text{II}$ regions).

The distribution and sign (+, −) of the RMs across the CGPS is shown in Figure 2, with longitude and latitude zones colored to roughly match the color bar in Figure 1. Generally in the plane ($|b| < 5^\circ$), lower $N_{H_\text{II}}$ are observed toward higher longitudes. We can divide Figure 1 into four column density zones shown in Figure 2, from lowest to highest: (1) high-latitude sources with $+5^\circ < b < +18^\circ$ which all have measured column densities lower than $3 \times 10^{21}$ cm$^{-2}$ (blue violet points between $100^\circ < \ell < 120^\circ$); (2) Galactic anticenter sources (orange points with $150^\circ < \ell < 190^\circ$) generally between 3 to $6 \times 10^{21}$ cm$^{-2}$; (3) intermediate-$\ell$ sources through the outer Galaxy ($90^\circ < \ell < 150^\circ$, blue–violet–red) with $N_{H_\text{II}} = 6$ to $9 \times 10^{21}$ cm$^{-2}$; and (4) low-longitude sources with $\ell < 90^\circ$ that pass through the inner and outer Galaxy and that generally have the highest columns in the sample ($N_{H_\text{II}} \gtrsim 9 \times 10^{21}$ cm$^{-2}$), though many have smaller columns where we look down the lower-density interarm region between the Sagittarius and Local arms.

A general analysis of the RM scatter in each column density zone is telling. In 21 cm CGPS continuum maps no H$\text{II}$ regions are observed in zone 1, and given that sources in this region have RM near zero, the strength of the GMF here and the $n_e$, relative to the plane regions, are small. Hence the scatter in zone 1 RMs is dominated by the small-scale random component of the field. Zone 2 is also a region of low RM (since the LOS projection of the large-scale GMF is diminished toward the anticenter), but these sources are in the Galactic plane and are seen toward many bright cataloged H$\text{II}$ regions; scatter in this region would thus be due to both the effects of small-scale variations in the GMF and of random fields and high $n_e$ in H$\text{II}$ regions. However, the scatter in zone 2 is barely higher than in zone 1, thus the scatter in RM, and the mean RM itself in these directions is not dominated by the H$\text{II}$ regions seen along these paths. Zone 3 shows moderately increased scatter with more true “outliers” on either side of the mean, likely reflecting the longer integrated path length which would intercept more H$\text{II}$ regions. However, the majority of zone 3 sources are tightly clustered

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4 The complete CGPS 21 cm line, continuum and polarization data are available at the CADC; http://cadc.hia.nrc.ca
The strong linear correlation between the mean RM and $N_{\text{H}1}$ could arise because each depends on something else in common. For example, lower RMs and column densities are both found in directions where the integrated path length is smaller through the disk; i.e., high longitudes (near the anticenter) or high latitudes. Directions near $\ell = 180^\circ$ are also where there would be no LOS component of a purely azimuthal field, since geometrically $B_\ell = |B| R_0 / \sin \ell$, and for a circularly oriented field of uniform strength $B_\ell \propto \sin \ell$ along a circle of radius $R$. Along the LOS through the outer Galaxy, the uniform field’s strength and the electron density fall with $R^{-1}$ (see Brown et al. 2003b), whereas the density of H I stays nearly constant to at least $R = 13$ kpc (see Figure 7.15; Burton 1988), falling thereafter with an exponential decay (e.g., Foster & MacWilliams 2006). In high-latitude directions the atomic and electron densities and the field strength also diminish, each with different characteristic heights (e.g., Dickey & Lockman 1990; Gaensler et al. 2008; Kronberg & Newton-McGee 2011), but the amount of disk matter sampled along each direction changes in a more complicated way than it would across longitude-varying directions at constant latitude due to the warping of the midplane and the flaring of its thickness (Foster & MacWilliams 2006).

To test this possibility, we isolate two regions of the CGPS. In region 1 we restrict the dependence to longitude only by looking at sources across a wide longitude strip $90^\circ \leq \ell \leq 180^\circ$ in a narrow latitude range centered on the plane ($-3.5^\circ \leq b \leq +5^\circ$; 1110 sources). For region 2, we take sources in a vertical strip across a wide latitude ($-3.5^\circ \leq b \leq +18^\circ$) centered within a narrow longitude range ($95^\circ \leq \ell \leq 125^\circ$; 692 sources). The dependence of integrated path length on direction across each strip should be markedly different, since it is expected that $n_e, n_{\text{H}1}$, and $B_\|$ are changing in very different ways and for different reasons across each region. If there is an underlying dependence on direction the observed relationship between RM and $N_{\text{H}1}$ in each should also be different. Remarkably, however, the fitted lines in region 1 (slope $-23.2 \pm 2.3$, intercept $45.0 \pm 13.8$, $r = 0.87$) and region 2 ($-26.9 \pm 2.5$ rad m$^{-2}$/10$^{21}$ atoms cm$^{-2}$, $44.0 \pm 10.9$ rad m$^{-2}$, $r = 0.79$) are essentially identical (Figure 4), evidence that the ratio of RM/$N_{\text{H}1}$ is independent of direction $\ell$ and of direction $b$.

A linear relationship observed between these variables would still exist whether or not we correct each for the same direction/path, with only the slope potentially changed. The remarkable constancy of the slope in different regions of the survey is

### 4. DISCUSSION OF RESULTS

The coefficient of the points after binning is

$$r = 0.78.$$
thus indicating that something other than mutual directional dependence is being observed.

5. MAGNETIC FIELD AND IONIZATION FRACTION ESTIMATES

We can use Equation (4) to estimate the bulk mean GMF strength in the CGPS region for a given mean ionization fraction, and vice versa. For this we must be mindful that if there are reversals along the LOS, the value of the ratio $\text{RM}/N_{\text{H}1}$ will be closer to zero and calculated values for $\langle B_i \rangle$ or $x_e$ will be lower limits to the actual values. For our estimate, we avoid RMs in the inner Galaxy quadrant I (to avoid the field reversal), and restrict our estimate to QII ($90^\circ \leq \ell \leq 180^\circ$) where the uniform component will be pointed away from the observer and RMs tracing the field will be negative. Other smaller-scale contributors to RM (H ii regions, for example) are expected to have an unsubstantial impact on the mean since the large number of LOSs we use ensures that localized regions do not dominate the large-scale trends in each bin (again, see Brown et al. 2003a). A ratio $\text{RM}/N_{\text{H}1} = -21.8 \pm 1.5 \text{ rad m}^{-2}/10^{21} \text{ atoms cm}^{-2}$ is found, with $r = 0.94$.

Within a few hundred parsecs of the Sun, Jenkins (2013) find $x_e \sim 0.08$ (for a mean total H density of $n_{\text{H}} = 0.5 \text{ cm}^{-3}$). If we take this as representative of the bulk volume-averaged value, then the LOS component of the outer Galaxy GMF is $\langle B_i \rangle \sim -0.95 \pm 0.06 \mu G$. A slightly higher mean field of $-1.0 \pm 0.1 \mu G$ is found if we also restrict sources to the immediate Galactic plane; $|b| \leq 5^\circ$ (region 1 in Section 4; see Figure 4; $\text{RM}/N_{\text{H}1} = -23.2 \pm 2.3 \text{ rad m}^{-2}/10^{21} \text{ atoms cm}^{-2}$, intercept $45.0 \pm 13.8 \text{ rad m}^{-2}$). Both are very consistent with $\langle B \rangle = -1.2 \pm 0.48 \mu G$, the value near the Sun from Van Eck et al. (2011) and an upper-limit for the mean LOS-projection component (Van Eck et al. use the same RMs as we do but rely on the $n_e$ model of Cordes & Lazio 2002).

Alternatively, we can use Equation (4) to crudely estimate a lower limit to the ionization fraction in the Galactic plane, QII, given a mean field strength estimate for the ISM $\langle B \rangle = -1.2 \pm 0.48 \mu G$ in Van Eck et al. 2011, again as an upper-limit to $\langle B_i \rangle$. With this, $x_e \gtrsim 6.8\%$, which is above the WNM phase calculation of $\lesssim 2\%$ by Wolfire et al. (1995; for $n_{\text{H}} = 0.4 \text{ cm}^{-3}$) and more consistent with the Jenkins result for the local ISM of $8\%$. If we use the local regular magnetic field strength estimate $\langle B \rangle = -2 \mu G$ of Sun et al. (2008), then $x_e \gtrsim 4.2\%$, intermediate between the two previously published results. In any case, using our measured slope $\text{RM}/N_{\text{H}1}$ in Equation (4) with widely accepted values for the uniform field strength results in low (<10%) ionization fractions that are consistent with the range accepted for the WNM.

6. DISCUSSION AND SUMMARY

The consistency of the field estimated from Equation (4) (using WNM values for $x_e$) with the field estimated by Van Eck et al. (2011; using DMs from the $n_e$ model of Cordes & Lazio 2002) suggests that most of the electrons in the large-scale MIM responsible for pulsar DM are related to the atoms in the

![Figure 3](image1.png)

Figure 3. Sources in Figure 1 binned in column density bins $4 \times 10^{20}$ atoms cm$^{-2}$ wide. The robust mean and error in RM for each bin is plotted. (A color version of this figure is available in the online journal.)

![Figure 4](image2.png)

Figure 4. Left: region 1 described in Section 4. Right: region 2. The dashed line plotted in each is the one fitted to the entire set of RMs, shown in Figure 3. (A color version of this figure is available in the online journal.)
WNM. Our observed ratio \( \text{RM}/N_{\text{H}_1} \) seems to be sufficient to predict the magnitude of the magnetic field in the general MIM, suggesting that electrons from fully ionized regions of the WIM account for very little RM and that a very large fraction of the electrons seen in the Galactic plane arise from the partially ionized WNM, compared to the fully ionized, low density WIM. However, as the field and ionization fractions of the WNM are not known with terrific accuracy, we cannot provide a viable quantitative estimate of this fraction. Nonetheless, qualitatively it appears that the boundary between the WNM and MIM is very much indistinct and that the GMF itself may be supported by the partially ionized WNM.

Using observations from the CGPS, we have found a linear correlation between RM and H\( ^1 \) column density (for the optically thin WNM gas). The slope \( \text{RM}/N_{\text{H}_1} \) observed is of the same order expected from a simple theoretical calculation (Equation (4)) with current estimates of the ionization fraction in the WNM and the bulk LOS magnetic field in the outer Galaxy. Since the ratio \( \text{RM}/N_{\text{H}_1} \) ultimately has units of radians of rotation per \( 10^{21} \) H atoms, it is independent of path length and its observed value can be used to estimate mean magnetic fields and/or ionization fractions in any region of interest, regardless of its dimension. Therefore, measurement of this ratio and Equation (4) may offer a way of studying either the (unknown) magnetic field or ionization fraction in smaller discrete regions of the ISM where the other (known) parameter can be more safely assumed constant throughout. This may offer some advantage over the current approach of estimating field strengths with the (path-integrated) DM.

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