First Year Project Report — Part 1. Where are the Clumps?

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ABSTRACT

The NE2001 model for the free electron distribution of the Milky Way includes ad hoc electron “clumps” to reconcile line of sight observables with basic model predictions (Cordes et al. 2002). While MAGPIS (Multi-Array Galactic Plane Imaging Survey) is insensitive to emission from individual diffuse HII regions \( n_e \sim 10 \text{ cm}^{-3} \), by investigating the 20 cm maps we are able to verify their assumption that compact HII regions are not responsible for the anomalous radio observables.

1. Introduction

Refining the model of free electron distribution in the Milky Way serves three purposes. First, it allows radio observers to better interpret images distorted by interactions between electromagnetic waves and the interstellar medium. Second, it offers improved distance estimates to pulsars for which only the dispersion measure is known. Third, it offers direct insight into the structure of the warm ionized component of our galaxy.

To date, J. M. Cordes and T. J. W. Lazio have created the most comprehensive model of the free electron distribution, titled “NE2001” (Cordes et al. 2002). This model succeeds the one published by J. H. Taylor and J. M. Cordes in 1993 (Taylor & Cordes 1993). Cordes et al. created NE2001 using the same methodology as in the 1993 model, but with a significant increase in the amount of data used to derive the distribution. The aim at the start of this project was to use MAGPIS radio continuum maps to further constrain some of the model parameters.
2. NE2001

The fundamental inputs to the model are radio pulsar observables in conjunction with some form of distance measurement to the same pulsars. The employed radio pulsar observables include dispersion measure, pulse broadening, scintillation bandwidth, and angular broadening. Angular broadening measurements of extragalactic sources are also used in the model. Independent distance estimates of pulsars are made through either parallax observations, HI absorption observations, or by association with globular clusters or supernova remnants.

Dispersion measure is defined as follows:

\[ DM \equiv \int_0^D n_e ds \]  

(Rybicki & Lightman 2004) where \( n_e \) is the electron density and the integral is evaluated along the line of sight between the observer and the source. DM is determined by measuring the change in arrival time of pulses over a certain bandwidth. The travel time of a pulse is proportional to \( \lambda^2 \).

The quantity scattering measure may be derived from either pulse broadening, scintillation bandwidth, or angular broadening. Scattering measure is related to the properties of the plasma along the line of sight through the following expression:

\[ SM \equiv \int_0^D C_{SM} F \pi_e^2 ds \equiv \int_0^D C n_e^2 ds. \]  

(Cordes et al. 2002) where \( C_{SM} \) is a constant, \( F \) is the fluctuation parameter, and \( \pi_e \) is the local mean electron density. Note that unlike in the case of dispersion measure, we need to distinguish the mean density \( \pi_e \) from one which includes small scale variations \( \delta n_e \) that dispersion measure is insensitive to. In the literature, \( C n_e^2 \) is referred to as the spectral coefficient of the electron density irregularity spectrum. The fluctuation parameter, one of the factors in the spectral coefficient, is important because it encapsulates several properties of the intervening medium:

\[ F = \zeta \epsilon^2 \eta^{-1} l_0^{-2/3}. \]  

(3)

\( \zeta \) takes density variations between clouds of free electrons along the line of sight into account, expressed as \( \langle \pi_e^2 \rangle / \langle \pi_e \rangle^2 \). \( \epsilon^2 \) captures the variance of electron density inside individual clouds, such that \( \epsilon^2 = \langle (\delta n_e)^2 \rangle / \langle n_e \rangle^2 \). \( \eta \) is the local volume filling factor, and \( l_0 \) is the outer scale of density fluctuations. For details of how SM is ascertained from radio observables, see Cordes et al. (2002).
NE2001 assumes several smoothly-varying, large scale components to describe the electron density distribution. These include the center of the galaxy, a thick disk, a thin disk, and the spiral arms. In addition, there are components to represent specific well-sampled regions of the galaxy, like the solar neighborhood. Cordes & Lazio employ an iterative likelihood algorithm to select the parameters that control the shape of these components (i.e. their scale height, their radial falloff exponents, etc.), such that the closest overall agreement is made between observables and independent distance measures.

3. Clumps

Some lines of sight have anomalously high scattering measures for either pulsars or extragalactic sources that cannot be accounted for by the large scale components. Cordes & Lazio assume that these are caused by intervening HII regions that behave in the model as “clumps” of locally high $n_e$ or $F$ or both. By inspecting Equations 1 and 2, it is apparent that over a path of uniform properties, $SM$ is proportional to $n_e^2$ whereas $DM$ is proportional to $n_e$. Therefore, only a relatively small perturbation in the predicted $DM$ is needed to explain the high scattering. In addition to clumps added due to scattering measures, a smaller amount of clumps are added for pulsars with anomalously high dispersion measures.

In some cases, there is a known source of strong scattering in between the observer and the pulsar. For example, the pulsar B1758-23 is seen just on the edge of supernova remnant W28 which is likely to be associated with the pulsar (Frail et al. 1993). The pulsar shows a relatively large scattering measure, log($SM$) = 0.71. Cordes & Lazio note the coincidence with W28 in their summary of special lines of sight (Cordes et al. 2003). A MAGPIS 20 cm map of the field centered on B1758-23 is shown in Figure 1.

Not even the most basic parameters describing a cloud which reconciles anomalous observables with NE2001 can be determined uniquely. Therefore, Cordes & Lazio can only assume reasonable parameters for each clump. Clump parameters are more constrained for lines of sight corresponding to pulsars than to extragalactic sources due to the measurability of $DM$ in addition to $SM$. The changes in these radio observables produced by any clump are

$$DM_c = n_e \Delta s$$
$$SM_c = C_{SM} F_c n_e^2 \Delta s$$

(4)

Each clump is specified in the model as a sphere of Gaussian density distribution. The
parameters free to be chosen for each clump are $F_c$, $n_{ec}$, and $\Delta s$. Using Equation set 4, one can choose a combination of size, density, and fluctuation that produces the observed scattering without conflicting with the dispersion measure (within expected errors). Distance along the line of sight is necessarily ambiguous in most cases, and the values specified are plausible at best. When the object likely to be associated with the anomalous observable has a distance estimate, such as a molecular maser in an HII complex, the clump is placed there.

4. MAGPIS Pulsar Fields

The Multi-Array Galactic Plane Survey is an in-progress project that is producing synthesized images of the plane of the Milky Way. It does so by combining interferometric data taken with the Very Large Array in multiple array configurations. Combining data from different interferometer configurations improves the dynamic range and allows features on a wider range of angular scales to be discerned. To date, the 20 cm wavelength component of MAGPIS has imaged the plane over the range $5^\circ < l < 32^\circ$ and $|b| < 0.8^\circ$ in B, C, and D configurations. The sensitivity, resolution, and dynamic range surpass those of previous surveys of the region by over an order of magnitude (Helfand et al. 2005).

The longitude range of MAGPIS covers a section of the plane of the Milky Way adjacent to the galactic center. Naturally, this part of the sky contains a high surface density of pulsars (90 in total over the 50 square degrees). This fact, in concert with the survey’s high sensitivity to continuum emission (root-mean-square level $\sim 0.25$ mJy/beam for a $6''$-wide beam) made the MAGPIS 20 cm maps an attractive arena for checking the consistency of the mesoscale features of NE2001. The online MAGPIS database ([http://third.ucllnl.org/gps/index.html](http://third.ucllnl.org/gps/index.html)) facilitated the automated retrieval of 20 cm maps centered around the ATNF Pulsar Catalog positions, along with 90 cm archival VLA maps, 20 $\mu$m images taken by the Midcourse Space Experiment (MSX), and multiband infrared images from the Galactic Legacy Infrared Mid-Plane Survey Extraordinaire (GLIMPSE). Thus we formed the Galactic Plane Pulsar Atlas, accessible at [http://www.astro.columbia.edu/~neil/magpis/psratlas.html](http://www.astro.columbia.edu/~neil/magpis/psratlas.html). In addition to the images, the basic information and properties of each pulsar are tabulated using data from the ATNF Pulsar Catalog.

Before inclusion in the Galactic Plane Pulsar Atlas, we wrote a script to process the 20 cm and 90 cm maps in the NRAO Astronomical Image Processing System (AIPS) so that the error boxes of the pulsar positions along with their names would be overlaid on
the pulsar fields. The Galactic Plane Pulsar Atlas reveals that out of the 84 radio pulsars in the survey bounds, 35 (∼40%) are detected as point sources in the 20 cm MAGPIS maps. Of those 35, 12 are also detected in the 90 cm maps.

Pulsar fields in the atlas are inspected and separated into overlapping subsets based on their features. The following subsets are employed: fields centered on MAGPIS-detected pulsars, fields containing diffuse MAGPIS sources, fields containing supernova remnants, and fields containing “curiosities”. As for the diffuse emission fields, by comparing images taken at wavelengths from 90 cm to infrared, one can qualitatively discern thermal from nonthermal sources based on the expected disparity in spectral index (Rybicki & Lightman 2004). For example, synchrotron radiation detected in a 90 cm map will rarely have a visible component in the corresponding GLIMPSE image. Conversely, close correlation between diffuse structure seen in MAGPIS and in GLIMPSE is strong evidence for thermal emission.

5. Detectability of Clumps

Of the 142 clumps that were added to NE2001 for pulsar lines of sight, six fall within the MAGPIS survey bounds. Their positions and properties as postulated by Cordes & Lazio are listed in Table 1. In this table, $d_\text{c}$ is the plausible distance assigned to the clump, and $r_\text{c}$ is the scale radius of the clump. Two of the six have no scattering measure listed. This is presumably because Cordes & Lazio added those clumps based on anomalous dispersion measure alone, rather than scattering measure.

<table>
<thead>
<tr>
<th>LOS</th>
<th>$l$ (deg)</th>
<th>$b$ (deg)</th>
<th>$d_\text{c}$ (kpc)</th>
<th>$DM_\text{c}$ (pc cm$^{-3}$)</th>
<th>log $SM_\text{c}$</th>
<th>$r_\text{c}$ (pc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1758-23</td>
<td>6.81</td>
<td>-0.08</td>
<td>6.63</td>
<td>17.9</td>
<td>0.71</td>
<td>10</td>
</tr>
<tr>
<td>B1815-14</td>
<td>16.41</td>
<td>0.61</td>
<td>4.83</td>
<td>11.7</td>
<td>0.34</td>
<td>10</td>
</tr>
<tr>
<td>B1820-14</td>
<td>17.25</td>
<td>-0.18</td>
<td>3.50</td>
<td>301.3</td>
<td>...</td>
<td>10</td>
</tr>
<tr>
<td>B1830-08</td>
<td>23.39</td>
<td>0.06</td>
<td>4.40</td>
<td>141.8</td>
<td>...</td>
<td>10</td>
</tr>
<tr>
<td>B1832-06</td>
<td>25.09</td>
<td>0.55</td>
<td>2.06</td>
<td>36.5</td>
<td>1.32</td>
<td>10</td>
</tr>
<tr>
<td>B1839-04</td>
<td>28.35</td>
<td>0.17</td>
<td>2.23</td>
<td>15.8</td>
<td>0.60</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 1: Clumps in MAGPIS survey bounds; all data from Cordes et al. (2003).

There is sufficient information here to predict the brightness of the individual clumps if we assume they are fully ionized HII regions in thermal equilibrium at a temperature of $10^4$ K. The large uncertainty in distance is not an issue because of the conservation of
intensity with distance. We start by deriving a convenient form for the optical depth of the clumps:

$$d\tau = \frac{0.08235n_e^2}{\nu^{2.1}T_e^{1.35}}ds$$

(5)

where $n_e$ is in cm$^{-3}$, $T_e$ is in K, $\nu$ is in GHz, and $s$ is in pc (Vershuur & Kellerman 1988). The product $n_e^2ds$ is a differential increment in the quantity known as emission measure (EM) (Cordes et al. 2002). Setting $T_e = 10^4$ K and $\nu = 1.4$ GHz, we have

$$d\tau = 1.62 \times 10^{-7}n_e^2ds.$$  

(6)

Following the form of the clumps used in NE2001, they each have an electron density distribution given by

$$n_e(s) = Ae^{-s^2/r_c^2}$$

(7)

where $A$ is a constant. The free electron density and the dispersion measure contribution of the clump can be related since

$$DM_c = \int_{-\infty}^{\infty} n_e(s)ds = A\int_{-\infty}^{\infty} e^{-s^2/r_c^2} ds = Ar_c\sqrt{\pi}.$$  

(8)

We can also evaluate emission measure:

$$EM = \int_{-\infty}^{\infty} n_e^2(s)ds = A^2\int_{-\infty}^{\infty} e^{-2s^2/r_c^2} ds = A^2r_c\sqrt{\pi/2} = \frac{DM_c^2}{r_c\sqrt{2\pi}}.$$  

(9)

Now we can relate the optical depth expressed in Equation 5 to the dispersion measure contribution and scale size:

$$\tau_c = 1.62 \times 10^{-7} \int_{-\infty}^{\infty} n_e^2(s)ds = 1.62 \times 10^{-7} \frac{DM_c^2}{r_c\sqrt{2\pi}} = 6.45 \times 10^{-8}\frac{DM_c^2}{r_c}$$  

(10)
where $DM_c$ is in the standard units pc cm$^{-3}$ and $r_c$ is measured in pc. The standard radiative transfer equation in the Rayleigh-Jeans regime is used to predict the brightness:

$$I = \frac{2k_BT_e}{\lambda^2}(1 - e^{-\tau_c})$$

$$\approx \frac{2k_BT_e}{\lambda^2}\tau_c$$

(11)

since $\tau_c \ll 1$ (Vershuur & Kellerman 1988). Plugging in the physical constants gives a brightness of

$$I \approx 6.03 \times 10^{-15}\tau_c \text{ erg} \frac{\text{erg}}{\text{s} \cdot \text{cm}^2 \cdot \text{Hz} \cdot \text{ster}}.$$  

(12)

In order to convert these units into those that are convenient for comparison with the MAGPIS 20 cm maps, we must determine the effective beam area. The beam is an ellipse with a major axis of 3.1” and a minor axis of 2.7”. The resulting solid angle projected onto the celestial sphere is $6.2 \times 10^{-10}$ ster. From this we can assert that 1 mJy/beam in a MAGPIS 20 cm image corresponds to $1.6 \times 10^{-17}$ erg/(s · cm$^2$ · Hz · ster). Combining this fact with Equations 10 and 11 gives

$$I = 2.4 \times 10^{-5}\frac{DM_c^2}{r_c} \text{ mJy/beam.}$$

(13)

From Table 1 it is clear that the brightest clump would be the one corresponding to B1820-14, with a $DM_c$ of 300. The brightness predicted by Equation 13 is 0.22 mJy/beam, a factor of ten below the root-mean-square level of the MAGPIS 20 cm images.

If all of these clumps, presumed to be HII regions, are far below the detection limit of MAGPIS, then why are we able to see so many other HII regions in the 20 cm maps, and furthermore in far less sensitive surveys? The reason is that a 20 cm survey such as MAGPIS will only be sensitive to thermal emission from compact HII regions, which have higher electron densities ($> 10^4$ cm$^{-3}$ (Vershuur & Kellerman 1988)), and correspondingly higher optical depths, because of the $n_e^2$ dependence of $\tau$. Compact HII regions represent an earlier stage in the evolution of the Stromgren sphere, lasting on the order of $10^4$ yr before growing into diffuse HII regions. Compact HII regions can also have diffuse components that extend to large scales (Megeath et al. 1990); therefore it is worth noting their position even if the observable emission does not directly coincide with the line of sight.

We can demonstrate that the proposed clump parameters are consistent with diffuse HII regions, and not compact HII regions. We know Cordes & Lazio set their scale sizes, 10 pc, so as to match the typical value. But, we also need to derive the associated electron densities. First of all, it can be shown that our optical depth estimates increase by a
factor of only $\sim 5/4$ if we change the Gaussian density distribution to one of a uniform sphere. Therefore, making the simplifying assumption of uniform density will not affect our analysis. The average densities within the clumps are implicitly set by $D M_c$ and $r_c$, and we now show that they are in accordance with established Stromgren sphere densities. The B1820-14 clump must have the largest density of the six listed. Assuming a uniform density distribution, this electron density is $\sim 15 \, \text{cm}^{-3}$, a typical value for an evolved Stromgren sphere (Osterbrock & Ferland 2006), but orders of magnitude below the range of compact HII region densities. As an additional check, we can examine the properties of a typical, well studied HII region. The Rosette Nebula (NGC 2237-2239) has been approximated as a 37-pc-diameter sphere with an electron density of $\sim 9 \, \text{cm}^{-3}$ (Kraus 1986). These properties are within a factor of two of the ones describing the B1820-14 clump. It can be easily shown that such an object would also have too low of an optical depth to be detected in MAGPIS.

6. Clump Fields

Plots of the 20 cm MAGPIS fields containing the clumps are appended on the following pages. Contours are overlaid on the grayscale plots. We examined each of the six fields for evidence of free electron structures that could be responsible for the measured scattering and dispersion. In all cases, we only detect peripheral objects that could have undetected, low density components that extend into the lines of sight.

1) B1758-23 — Figure 1. The pulsar line of sight intersects the edge of supernova remnant W28; due to the likely association, it is fair to attribute the strong scattering to the shell (Cordes et al. 2003).

2) B1815-14 — Figure 2. There is no detected emission coinciding with B1815-14. The GLIMPSE image of the same field also reveals no sources.

3) B1820-14 — Figure 3. There is faintly detected, amorphous emission throughout this field. Nearby the pulsar position are two compact sources—one 1.5' away, and one 3' away. Their appearance in the corresponding GLIMPSE image suggests they are thermal, but neither extend into the line of sight.

4) B1830-08 — Figure 4. There is a bright, thermal source 10' away from the field center.

5) B1832-06 — Figure 5. Amorphous, faintly detected emission throughout field.

6) B1839-04 — Figure 6. Line of sight is 2' away from a nonthermal shell.
There is a reason Cordes & Lazio set the parameters of their clumps to resemble diffuse as opposed to compact HII regions. Their sizes (0.1 – 1 pc by definition) are such that the probability of one eclipsing a pulsar is very low. MAGPIS provides a unique opportunity to check this assumption, as it provides a definitive atlas of the hundreds of compact HII emission regions in its survey area. Therefore, we examined all pulsar fields to check for coincidence between pulsars and compact HII thermal emission. No pulsars directly coincide with unambiguously detected thermal structure. However, six are within 2’ of detected compact HII regions. If the radius is extended to 10’, ~25 more fields are included, some with multiple instances. Our analysis of these fields is incomplete.

7. Conclusions

We showed that despite its high sensitivity to continuum emission, MAGPIS 20 cm maps cannot detect individual diffuse HII regions ($n_e \sim 10\text{cm}^{-3}$). Therefore, we can neither prove nor disprove the existence of the clumps as postulated by Cordes & Lazio. We did, however, confirm the validity of their assumption that the objects responsible for the anomalous scattering and dispersion are not compact HII regions.
Fig. 1.— MAGPIS 20 cm image of 20 arcminute field centered around B1758-23.

Fig. 2.— MAGPIS 20 cm image of 20 arcminute field centered around B1815-14.
Fig. 3.— MAGPIS 20 cm image of 20 arcminute field centered around B1820-14.

Fig. 4.— MAGPIS 20 cm image of 20 arcminute field centered around B1830-08.
Fig. 5.— MAGPIS 20 cm image of 20 arcminute field centered around B1832-06

Fig. 6.— MAGPIS 20 cm image of 20 arcminute field centered around B1839-04
REFERENCES


Verschuur, G.L., Kellermann, K.I. 1988, Galactic and Extragalactic Radio Astronomy, (Berlin: Springer-Verlag)

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