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Pulsars and the interstellar medium

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Galactic structure and turbulence, pulsar distances, and the intergalactic medium

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Abstract. This paper summarizes how multi-wavelength measurements will be aggregated to determine Galactic structure in the interstellar medium (ISM) and produce the next-generation electron density model. Fluctuations in density and magnetic field from parsec scales down to about 1000 km cause a number of propagation effects in both radio waves and cosmic rays. Density microstructure appears to include Kolmogorov-like turbulence. The next generation electron-density model, NE2012, will include about double the number of lines of sight with dispersion and scattering measurements and it will be anchored with a much larger number of pulsar parallax distances. The foreground Galactic model is crucial for inferring similar ionized structures in the intergalactic medium (IGM) from scattering measurements on high-z objects. Intergalactic scattering is discussed with reference to distant sources of radio bursts. In particular, the cosmological radio scattering horizon is defined along with its analog for the ISM.

Keywords. plasmas, turbulence, stars: neutron, pulsars: general, ISM: magnetic fields, Galaxy: structure

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1. Introduction

A detailed model for the electron density (n_e) of the Milky Way is needed for several fundamental reasons.

A distance scale for Galactic radio pulsars is needed for establishing the space density, velocity distribution, and luminosities of neutron stars. The birth and death rates of radio pulsars and the association of pulsars with supernova remnants also rely on an accurate distance scale. Survey designs for pulsars and fast radio transients must take into account dispersion and scattering that smear pulses and reduce sensitivity. Establishing whether a fast radio transient is Galactic or extragalactic is straightforward if the range of dispersion measures (DM) from the Milky Way is known. The most extreme case is for pulsars close to Sgr A*, the black hole in the center of the Galaxy. There is strong interest in the Galactic magnetic field's structure and how it influences cosmic-ray propagation. The best constraints on the large-scale structure of the magnetic field as well as its variations come from Faraday rotation measurements. Inverting the rotation measure (RM, the integral of electron density and parallel magnetic field) into constraints on the field requires a Galactic model for n_e.

A Galactic model for n_e and its fluctuations δn_e allows intensity scintillations of cosmological sources (active galactic nuclei and gamma-ray burst afterglows) from the foreground interstellar medium (ISM) to be used to place constraints on source sizes. Finally, a Galactic model serves as a baseline for assessing the level of dispersion and scattering from the ionized intergalactic medium (IGM).

The NE2001 (Cordes & Lazio 2002) model has served the purposes described above since 2002. In this paper I summarize the development of a new model, NE2012, so-named because it will make use of input data that mostly obtained through the end of 2012.

2. Quantifying the ionized ISM

A number of line-of-sight (LoS) integrated measures are used to characterize the electron density and magnetic field. DM is the integral of n_e and includes variations δn_e on any and all length scales. The scattering measure (SM) is the LoS integral of the spectral coefficient C_n^2 of the electron density wavenumber spectrum. Scattering measurements (including angular broadening, pulse broadening, diffractive and refractive intensity scintillations [DISS, RISS]) are interpreted, often successfully, in terms of a power-law wavenumber spectrum

$$\delta n_e^2(q) = C_n^2 q^{-\beta}, \qquad \frac{2\pi}{\ell_0} \leqslant q \leqslant \frac{2\pi}{\ell_1}, \tag{2.1}$$

where the outer scale $\ell_0 \sim$ pc and the inner scale $\ell_1 \sim$ 100s of km. The spectral index is found to be $\beta \sim 4$ with consistency in many cases with the Kolmogorov value $\beta = 11/3$ but with other cases indicating a shallower spectrum. There is also strong evidence that fluctuations are highly anisotropic for some lines of sight, requiring a different form than in the equation, which applies to the isotropic case. Summing along an LoS will lessen the influence of anisotropies, which are likely caused by local magnetic fields that have a variety of orientations. As in NE2001 we use a cloudlet model to describe the ionized gas where microstructure in δn_e contained inside the cloudlets is described by Kolmogorov ($\beta = 11/3$) fluctuations. These yield the relations (where ds is the infinitesimal along the LoS),

$$\begin{aligned} C_n^2 &\propto F n_e^2 \\ d\mathrm{DM} &= n_e ds \\ d\mathrm{SM} &= C_n^2 ds \propto F n_e dDM \\ d\mathrm{EM} &= \frac{\zeta(1+\epsilon^2)}{\eta} n_e d\mathrm{DM} \propto \frac{\ell_0^{2/3}(1+\epsilon^2)}{\epsilon^2} \mathrm{dSM}. \\ d\mathrm{RM} &= B_{\|} d\mathrm{DM}, \end{aligned} \tag{2.2}$$

where $\epsilon = \delta n_e / n_e$ is the fractional variation *inside* ionized clouds; ζ = intercloud fractional variance; η = volume filling factor; $B_{\|}$ is the magnetic field component parallel to the LoS; and $F = \zeta\epsilon^2/\eta\ell_0^{2/3}$ is the "fluctuation" parameter that relates the square of the local mean electron density (n_e) to the spectral coefficient C_n^2.

3. Quick summary of electron density models

There is a long heritage of electron density models presented since the discovery of pulsars in 1967. For the most part these were simple, axisymmetric models and they did not include electron-density variations. The first model to allow predictions of scattering from δn_e was in Cordes *et al.* (1991) and the first to include spiral arms and scattering was the TC93 model (Taylor & Cordes 1993), with spiral arms defined by Georgelin & Georgelin from HII regions. Another axisymmetric model without any treatment of density variations by Gómez *et al.* (2001; hereafter GBC01) fitted a two-disk model to only those lines of sight where an independent distance was available along with values of DM. The NE2001 model made use of a larger database of dispersion and scattering measurements than was available at the time of the TC93 model and it used a significant number (54) of parallaxes (timing and interferometric) to constrain the local ISM (LISM). The spiral arms in NE2001 had predefined central axes but their scale heights, widths, and

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Table 1. Galactic electron density model components

Component	TC93	GBC01	NE2001	Comment
Thick Disk	✓	✓	✓	DM_∞ constrained
Thin Disk	✓	✓	✓	DM vs. latitude
Spiral Arms	✓		✓	Required by asymmetry in DM vs longitude
Local ISM	Gum Nebula		✓	Several components in NE2001
Galactic Center			✓	Scattering of Sgr A*, OH/IR masers; HII tracers
Clumps/Regions			✓	Identified from distance constraints or excess scattering
Voids			✓	Phase structure of ISM, chimneys; identified as with clumps/voids
Galactic Bar			(✓)	Stellar dynamics; no signal in DM or SM

central densities were individually fitted for. Table 1 compares the components included (as check marks) in the TC93, GBC01, and NE2001 models.

One of the simplest tests of any electron density model is to check whether the DM of a known pulsar can be accounted for. Figure 1 shows Aitoff projections in Galactic coordinates of deficits in DM for the three models. Deficits were calculated as the difference of each pulsar's DM and the integral of the model to a distance of 100 kpc. Out of 1943 pulsars with DM values, about 15% have deficits using the GBC01 model, compared to 13% for the TC93 model and less than 2% for NE2001. In all three cases, 19 pulsars in the Magellanic clouds contribute to the number of deficits; since none of the models include LMC and SMC components, the number of deficits should be reduced by this number. For NE2001 this implies that less than 1% of the catalogued pulsars show deficits. The most prominent deficits in the GBC01 and TC93 models are in the Galactic plane and correspond to directions where spiral arms contribute to the electron density. The large number of deficits for the symmetric GBC01 model is not surprising. The spiral arms of the TC93 model clearly cannot provide enough electrons and, in fact, the NE2001 model explicitly addressed this problem using the data available in 2001 (e.g. 1143 DM values). Clearly, NE2001 stands up well against the 800 additional pulsars now available.

4. How does NE2001 measure up?

The DM-deficit test shows only necessity and not sufficiency for any model. For example, a model could provide *too many* electrons and pass the DM-deficit test while providing highly biased distance estimates. It appears that in some directions, NE2001 does mis-estimate distances, although as both under-and-over predictions (e.g. Chatterjee *et al.* 2009). Figure 1 also shows a comparison of parallax and NE2001/DM distances for 54 pulsars. 70% of the objects have consistent parallax and DM distances to within 20%, while 17% have more than a factor of two discrepancy (7 objects nearer and 2 objects further than the DM distance) and 13% are discrepant by a factor of 0.2 to 2; for these 13%, the true distance is larger than the DM distance. These results indicate, unsurprisingly, that there is unmodeled Galactic structure in the form of both voids and enhancements in electron density. A simple change in scale height of the thick disk is not sufficient to rectify these differences.

Other diagnostics of the electron density model include a comparison of the implied emission measure (EM) in the direction of high-latitude pulsars and the scale height of pulsars for in different directions. Emission measures from the WHAM Hα survey compared with EM calculated from NE2001 using the cloudlet formalism suggest that the overall filling factor for electron density *increases* with distance $|z|$ from the Galactic plane and that there may be a larger scale height and lower mid-plane density for the thick disk (Berkhuijsen *et al.* 2006, Gaensler *et al.* 2008). Comparisons of SM and EM

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are challenging because the corresponding integrals are over different distances. That particular issue is alleviated for globular cluster pulsars at high latitudes that are well above the electron-density scale height. However, calculations of EM from SM must use an appropriate value of the outer scale (cf. Eq. 2.2), introducing another variable into the problem. Also, previous analyses have not included the extra variance in electron density due to the Kolmogorov turbulence internal to clouds (as quantified by the parameter ϵ above). The pulsar scale height deduced from pulsar surveys after correction for selection effects suggests that distances are underestimated by NE2001 because distant pulsars in the inner Galaxy have a smaller nominal height than do those near the Sun (Kramer *et al.* 2003; Lorimer *et al.* 2006). However the scale height should be somewhat smaller toward the inner Galaxy in accordance with the larger gravitational potential.

5. Development of NE2012

NE2012 is the next generation electron-density model. It will include all of the same components as NE2001 but all assumptions and methodologies are being revisited. The new model will make use of the much larger database of DM and SM values that have emerged over the last 10+ years from pulsar surveys along with scattering measurements of extragalactic sources. In addition, the number of pulsar parallaxes will have increased by a factor > 5, allowing major components of the new model to be nailed down. A new element of the model construction will involve usage of Faraday rotation measures of pul-

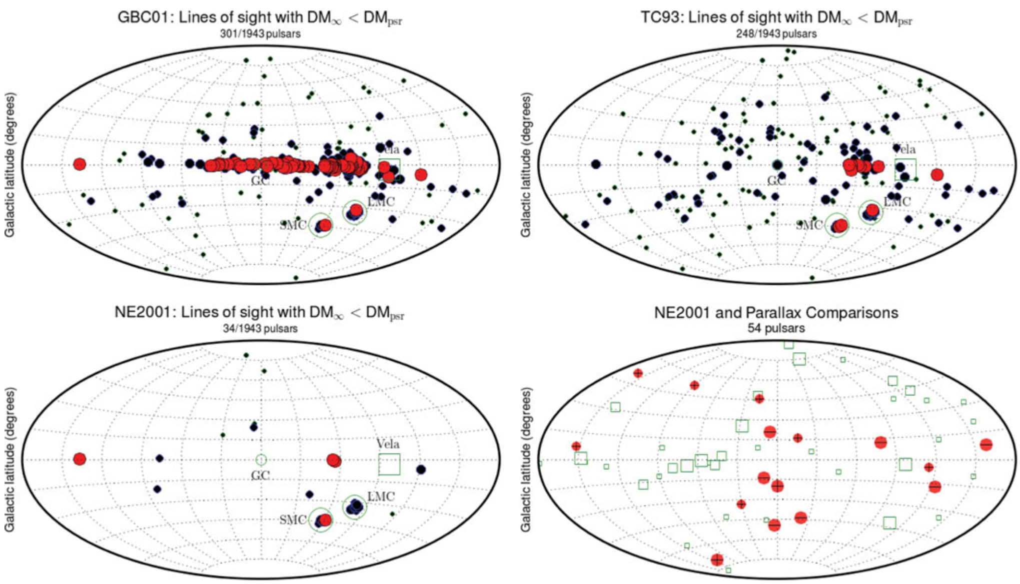

Figure 1. Plots of DM deficits for three electron density models. Models were tested with 1943 pulsars that have values of DM in the ATNF pulsar catalog (Manchester *et al.* 2005; http://www.atnf.csiro.au/research/pulsar/psrcat). Plotted circles show pulsars whose DMs are larger than can be accounted for by the model. In order of circle size, the model deficits are $\Delta\text{DM} < 10$ pc cm^{-3}, 10 to 50 pc cm^{-3}, 50 to 100 pc cm^{-3}, and > 50 pc cm^{-3}. Top left panel: deficits for the GBC01 model (301 pulsars); Top right panel: deficits for TC93 (248 pulsars); Bottom left panel : deficits for NE2001 (34 pulsars); Bottom right panel: Comparison of parallax distances and DM distances from the NE2001 model for 54 pulsars. Squares show DM and parallax distances that are consistent to within 20%. Circles indicate pulsars with differences of 20-50% (small circles) and > 50% (large circles). A plus (minus) sign implies that the parallax distance is larger (smaller) than the DM distance.

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sars and extragalactic sources, which also introduces additional model parameters, but allows both the electron density and the Galactic magnetic field to be better modeled. Hα measurements (EM) and and Galactic synchrotron radiation define spiral arms and the large scale magnetic field. Additional new input will include constraints on Galactic structure from the Spitzer/GLIMPSE survey (Churchwell *et al.* 2009), from the kinematics of methanol masers (Sanna *et al.* 2009), and from distance constraints on discrete ionized regions using the scintillation arc phenomenon (Stinebring *et al.* 2001). Also, the distance to the Galactic center is now being tightened up at a value not dissimilar to the official IAU distance of 8.5 kpc.

A major uncertainty that remains is the spiral-arm structure of the Galaxy. While the GLIMPSE survey categorically states that the Milky Way is a grand-design, two-armed spiral galaxy (Churchwell *et al.* 2009), studies of methanol masers favor a four-armed spiral as does a study of Faraday rotation measures and HII regions (Hou *et al.* 2009). The approach that will be taken in developing NE2012 is to consider several alternative structures as guided by these ancillary studies. Segments of some spiral arms may also be definable using DM and SM data combined with parallax measurements alone.

Development of the next generation model will proceed in stages. The first will not include Faraday rotation data and the complexities of the Galactic magnetic field. Succeeding stages will include the magnetic field and new pulsar parallaxes that will emerge over the next year. Accordingly, NE2012 will be rolled out in a series of versions.

6. Scattering of extragalactic sources

Two areas are of particular interest: (1) Using scattering measurements to probe the properties of the IGM; and (2) Assessing the reality and distances of fast transient sources that appear to be extragalactic.

Relevant sources include AGNs for which angular broadening has been measured or, in the case of intra-day variable (IDV) sources, that show RISS from foreground Galactic gas (e.g. Bignall *et al.* 2009). The measured angular broadening of some of these sources (i.e. after untangling scattering broadening from the intrinsic source size) potentially includes scattering in the IGM that adds to scattering from turbulence in the host galaxy of the source, in intervening galaxies, and in the Milky Way. While a complete analysis is not yet done, it is clear that scattering in the IGM is smaller than the angular broadening caused by the Milky Way. There are hints, however, that IGM scattering can be discerned as a slight excess over the Galactic contribution. To establish IGM scattering, Galactic scattering needs to be assessed carefully using a large number of measurements of AGNs to calibrate the Galactic electron density model. IDV sources indicate that apparent source sizes are as small as ~ 10 μarc sec as seen by an observer just outside the Milky Way (in order that RISS on intra-day time scales can occur), suggesting that at least for some lines of sight, IGM scattering is no larger than these angular sizes.

Fast transients — those short enough that dispersion and scattering are important — are of great interest and a few candidate events have been seen with large-enough DM to conclude that they may be extragalactic in origin.

Pulse broadening causes the detectability of fast transients to degrade over and above the effects of the inverse square law. Pulses will be selected against if scattering broadening is larger than the intrinsic pulse width W. We define the *Galactic horizon* in terms of DM by requiring that $\tau_d \lesssim W$. Figure 2 shows the expected distribution of τ_d for Galactic sources along with the IGM contribution to DM vs redshift. For 1 ms pulses, the horizon is about 5 kpc at 1 GHz while 1 μs pulses can be seen to only 2.4 kpc at 1 GHz. These values apply only to sources within the Galactic disk. Looking perpendicular to the disk,

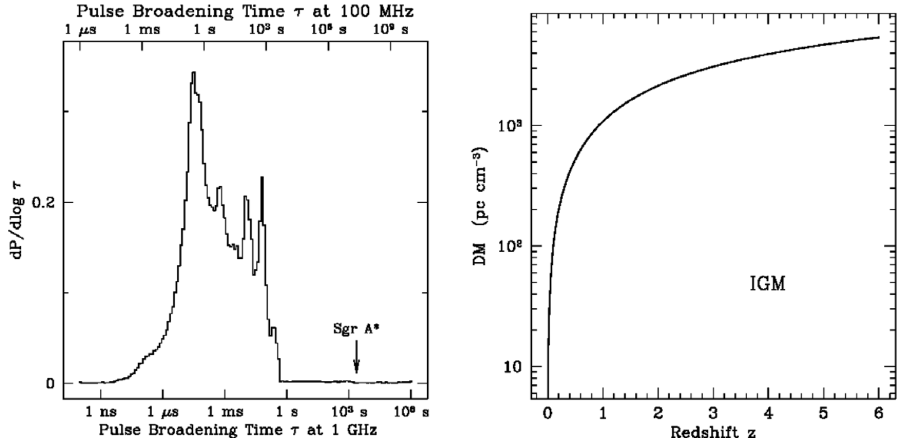

Figure 2. Left: Histogram of the pulse broadening time expected from sources distributed throughout the disk of the Milky Way, defined as a disk of radius 10 kpc and thickness 1 kpc. The scattering measure and pulse broadening were calculated using the NE2001 model (Cordes & Lazio 2002). The bottom horizontal scale gives values for a radio frequency of 1 GHz and the top axis for 100 MHz. Right: Dispersion measure from the intergalactic medium for a ΛCDM cosmology with $\Omega_{M\,0} = -0.27$, $\Omega_{b\,0} = 0.046$, and $H_0 = 70.4$ km s^{-1} Mpc^{-1}.

the seeing distance "breaks out" if it is more than about 1 kpc. At low frequencies, e.g. 100 MHz, a 1 μs pulse can be seen only to about 100 pc.

The *cosmological horizon* can be calculated form the variation of DM with redshift z assuming that the IGM is completely ionized and that the relationship of pulse broadening time to DM is the same as for Galactic sources; this is at best a very crude approach. We find that a 1 ms pulse can be detected to $z \approx 0.2$ and the broadening is $\tau_d \sim 100$ ms for transients originating at $z = 1$.

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