Electron distribution in the Galactic disc: results from a non-equilibrium ionization model of the interstellar medium

Miguel A. de Avillez,1,2,E Ashish Asgekar,3 Dieter Breitschwerdt2 and Emanuele Spitoni1

1Department of Mathematics, University of Évora, R. Romão Ramalho 59, 7000 Évora, Portugal
2Zentrum für Astronomie und Astrophysik, Technische Universität Berlin, Hardenbergstrasse 36, D-10623 Berlin, Germany
3ASTRON, the Netherlands Institute for Radio Astronomy, PO Box 2, 7990 AA Dwingeloo, the Netherlands

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ABSTRACT
Using 3D non-equilibrium ionization hydrodynamical simulation of the interstellar medium, we study the electron density, \( n_e \), in the Galactic disc and compare it with the values derived from dispersion measures (DMs) towards pulsars with known distances located up to 200 pc on either side of the Galactic mid-plane.

The simulation results, consistent with observations, can be summarized as follows: (i) the DMs in the simulated disc lie between the maximum and minimum observed values; (ii) the log \( \langle n_e \rangle \) derived from lines of sight crossing the simulated disc follows a Gaussian distribution centred at \( \langle n_e \rangle = 0.04 \pm 0.01 \text{ cm}^{-3} \); (iii) the highest electron concentration by mass (up to 80 per cent) is in the thermally unstable regime \( (200 < T < 10^3.9 \text{ K}) \); (iv) the volume occupation fraction of the warm ionized medium is 4.9–6 per cent and (v) the electrons have a clumpy distribution along the lines of sight.

Key words: atomic processes – hydrodynamics – ISM: general – Galaxy: disc.

1 INTRODUCTION
Dispersion measures (DMs) towards pulsars with known distance \( d \) can be used to derive the mean electron density in the Galaxy through the relation \( \langle n_e \rangle = \text{DM} / d \). For pulsars located at \( |b| < 5^\circ \), the derived mean electron density in the Galactic plane is \( \langle n_e \rangle \sim 0.02–0.1 \text{ cm}^{-3} \) and \( 0.01–0.017 \text{ cm}^{-3} \) in the spiral arms and interarm regions, respectively (Ferriere 2001; Gaensler et al. 2008). Berkhuizen & Fletcher (2008), using the DMs towards 34 pulsars, mostly outside the galactic plane, showed that the log \( \langle n_e \rangle \) follows a Gaussian distribution, relating it to the nature of the interstellar turbulence (see e.g. reviews by Elmegreen & Scalo 2004). So far, numerical (magnetized and unmagnetized) 3D simulations have assumed collisional ionization equilibrium (CIE) conditions for the interstellar medium (ISM). In fact, the thermal evolution of the ISM is determined by heating and cooling processes, which in general are not synchronized with ionization and recombination processes, respectively (e.g. Kafatos 1973; Shapiro & Moore 1976). Hence, below \( 10^6 \text{ K} \), deviations from CIE conditions occur, thereby affecting the ionization structure of the interstellar gas and thus the local electron density. In particular, if delayed recombination plays a role, the number of free electrons may be severely underestimated (Breitschwerdt & Schmutzler 1994).

Here we study the electron density, \( n_e \), and its mean, \( \langle n_e \rangle \), in the Galactic disc (up to 200 pc on either side of the mid-plane) using the first to date global hydrodynamical simulation of the interstellar gas, evolving under non-equilibrium ionization (NEI) conditions. Furthermore, we compare simulation results with estimates of \( \langle n_e \rangle \) obtained from available pulsar DMs. In forthcoming papers, we explore the \( n_e \) distribution and its topology in the thick disc and halo of the Milky Way and other galaxies.

This Letter is organized as follows. Section 2 deals with the model set-up; Sections 3 and 4 present the observational data and simulation results, respectively. A discussion and final remarks in Section 5 close the Letter.

2 MODEL AND NUMERICAL SET-UP
We simulate hydrodynamically the supernova (SN) driven ISM in a patch of the Galaxy centred at the solar circle with an area of \( 1 \text{ kpc}^2 \) and extending to \( 15 \text{ kpc} \) on either side of the Galactic mid-plane following de Avillez & Breitschwerdt (2005, 2007, hereafter AB05 and AB07, respectively). The simulations are carried out with the EAF-parallel adaptive mesh refinement code coupled to the newly developed e(A+S)+PEC code1 (de Avillez & Breitschwerdt

1 For a description of the code, ionization fractions, cooling and emission spectra, see www.lca.uevora.pt/research.html.
2012) featuring the time-dependent calculation on the spot (at each grid cell) of the ionization structure of H, He, C, N, O, Ne, Mg, Si, S and Fe and emissivities.

The physical model includes Types Ia, Ib+c and II SNe, a gravitational field provided by the stars in the disc, local self-gravity (excluding the contribution from the newly formed stars), heat conduction (Dalton & Balbus 1993), uniform heating due to a UV radiation field normalized to the Galactic value and varying with $z$, and photoelectric heating of grains and polycyclic aromatic hydrocarbons.

$\xi(A+M)_{PEC}$ uses the recommended abundances of Asplund et al. (2009), and calculates electron impact ionization, inner-shell excitation autoionization, radiative and dielectronic recombination, charge-exchange reactions (recombination with H\textsc{i} and He\textsc{i}, and ionization with H\textsc{ii} and He\textsc{ii})), continuum (bremsstrahlung, free-bound, two-photon) and line (permitted, semiforbidden and forbidden) emission in the range 1Å–610$\mu$m. The code also includes ionization of H\textsc{i} by Lyman continuum photons emitted during the recombination of helium. The internal energy of the plasma includes the contributions due to the thermal translational energy plus the energy stored in (or delivered) from high-ionization stages. Electron impact ionization rates are taken from Dere (2007), while radiative and dielectronic recombination rates are based on AUTOSTRUCTURE calculations (Badnell et al. 2003; Badnell 2006a), including the latest corrections to Fe ions by Badnell (2006b), Nikolić et al. (2010) and Schmidt et al. (2008). Radiative and dielectronic recombination rates for S\textsc{ii} and Fe\textsc{vii} are from Mazzotta et al. (1998). For the remaining ions, we adopt the total recombination rates derived with the unified electron–ion recombination method (Nahar & Pradhan 1994) and available at NORAD-Atomic-Data.\footnote{www.astro.cornell.edu/~shami/psrvlb/parallax.html}

A coarse grid resolution of 8 pc is used, while the finest AMR resolution is 0.5 pc (four levels of refinement) for $|z| \leq 2$ kpc, 4 pc for $|z| > 4$ kpc, and 1 pc elsewhere. Periodic and outflow boundary conditions are set along the vertical faces and top/bottom ($z = \pm 15$ kpc) of the grid, respectively.

\section*{3 THE ELECTRON DENSITY IN THE DISC}

To make a detailed comparison between simulation results (discussed below) and the electron density distribution derived from DMs towards pulsars, we reassessed the existing data to select pulsars with best possible distance estimates. Density PDFs were created using pulsars located up to 8 kpc away from the Sun and with $|z| < 200$ pc from the Galaxy’s mid-plane.

For our analysis, we chose pulsars from the ATNF catalogue (Manchester et al. 2005) with independent distance estimates, i.e. estimates without using NE2001 model (Cordes & Lazio 2003, hereafter CL03). These estimates resulted from parallax measurements, absorption-line (H\textsc{i} 21-cm or OH line) studies, physical associations or timing towards pulsars in the galactic disc ($|z| < 200$ pc).

Most parallax estimates were obtained from Verbist, Lorimer & McLaughlin (2010), which are updated by Chatterjee S.\footnote{www.astronomy.ohio-state.edu/~nahar and references therein.}

For our study, we augmented the ATNF catalogue by including distance estimates from absorption studies wherever available from the literature, including two measurements from associations (Frail et al. 1996; Saravanam et al. 1996; Johnston et al. 2003; Minter et al. 2008; Weisberg et al. 2008, see references therein). To quantify errors in distance estimates, we compute the fractional error involved in parallax and absorption studies from the difference between the upper and lower estimates. Firm error estimates are not available for several pulsars in the ATNF catalogue, whereas the fractional error was computed from the difference between the distance estimate and the best estimate available from NE2001 model (parameter DIST1 in ATNF catalogue). Errors in distance estimates using parallax measurements range between 2 and 35 per cent. The median error in distance estimate in our overall sample is 18 per cent, a significant improvement over estimates using NE2001 model (CL03).

A total of 122 pulsars with reliable distance estimates were thus selected, 33 of which have $|z| < 200$ pc. Nine pulsars were removed from this sample as they are located within the vicinity of the Sun, and measurements of electron density towards those sightlines are significantly affected by local structures, such as the Local Bubble, Gum Nebula and Loop I (e.g. CL03). The histogram of the computed $\log(n_e)$ derived from the sample DMs and the best-fitting Gaussian curve are shown in Fig. 1 (black lines). The fit is centred at $\log(n_e) = -1.47 \pm 0.02$ and has a dispersion of $\sigma = 0.17 \pm 0.02$, with a $\chi^2$/d.o.f. = 1.62. These values compare well with those derived directly from our pulsar sample data: $\log(n_e) \sim 1.42$ and $\sigma \sim 0.23$.

\section*{4 SIMULATION RESULTS}

The simulated SN-driven ISM is characterized by several evolutionary phases that have already been described in previous works: (i) domination of initial conditions being only wiped out after some 80 Myr of evolution; (ii) the full establishment of the continuous disc–halo–disc circulation (also known as the Galactic fountain) and (iii) the dynamical equilibrium (occurring at 200–220 Myr of evolution) in a statistical sense that determines the dynamics of the ISM in the Galactic disc and its interaction with the halo. As a result of this evolutionary path driven mainly by SNe, the ISM becomes frothy and turbulent with a mean Mach number of 3 (AB05; AB07). Low-temperature gas (high density) is concentrated into filamentary structures and molecular clouds (black regions in the left-hand panel of Fig. 2, showing the Galactic mid-plane density at 400 Myr of evolution), while hot gas (low-density regions in the same panel)
Electron distribution in the Galactic disc

Figure 2. Total (left) and electron (right) density distributions (in log scale) in the Galactic mid-plane at 400 Myr of evolution. Red regions in the left-hand panel represent high-density material, with molecular clouds being represented by black. Electron densities smaller than log $n_e = -4$ (white regions; right-hand panel) are located in both high (atomic and molecular clouds) and lower (bubbles) density regions.

is concentrated into bubbles and superbubbles that dominate the landscape.

The turbulent nature of the simulated ISM, the ongoing physical processes and driving mechanisms (e.g. SNe and stellar winds) affect the electron distribution, which follows the topology of the medium. Most of the electrons are distributed into the thermally unstable regime ($200 < T < 10^{4.9}$ K) with a volume ($f_v$) and mass ($f_M$) filling fractions of 56–60 and 77–80 per cent, respectively (Fig. 3, top panel); 32–40 per cent of the electron mass is locked in filamentary structures and shells, having $f_v = 6$–7 per cent. The electron distribution in warm ionized medium (WIM) has $f_v \simeq 4.9$–6 per cent and $f_M = 7$–10 per cent. These are time-dependent variations whose time average (over a period of 100 Myr using 1001 disc snapshots taken at every 0.1 Myr) histogram of log $n_e$ (Fig. 3, bottom panel) is fitted with a composition of two Gaussians centred at log $n_e = -1.437$ (for $T < 10^{4.2}$ K gas) and log $n_e = -2.64$ (for $T > 10^{4.2}$ K gas), respectively, with the latter representing mostly photoionized regions.

Further insight into the simulated electron distribution can be obtained directly from DMs along lines of sight (LOS), with length $d$, crossing the simulated ISM, allowing the determination of the mean electron density. The LOS have increasing lengths (with a step length of 10 pc) up to 1 kpc from a vantage point located at $(x, y, z) = (0, 0, 0)$ (left bottom corner of the electron density maps in Fig. 2) for $|z| \leq 200$ pc and spanning $90^\circ$ (with a $1^\circ$ separation) when projected on to the Galactic mid-plane.

Fig. 4 shows the DM along the LOS with lengths varying between 100 and 1000 pc, with a step length of 100 pc at 350 and 400 Myr (top two panels) and its time average (bottom panel) over 501 disc snapshots taken every 0.1 Myr for 350–400 Myr of evolution. Due to the ongoing turbulent processes in the Galactic disc, the DM has variability along and between the LOS (Fig. 4, top two panels). The longitudinal variation is due to the inhomogeneity of the ISM (e.g. bubbles and superbubbles) as well as due to the turbulent nature of the regions crossed by the LOS. These variations with distance and among LOS are still present in the time-averaged DM, although

Figure 3. Top panel: time evolution between 300 and 400 Myr of the electrons volume (solid lines) and mass (dashed lines) occupation fractions in the simulated disc for thermally unstable regime (orange), gas in shells and filamentary structures (red), and WIM (cyan). Bottom panel: time-averaged histogram of the total (black), and the two Gaussian fits (dashed black lines) of the electron density in the simulated disc over the evolution time 300–400 Myr. The electron densities in different temperature regimes are displayed.

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the longitudinal variations are smoothed in the averaging process. However, a record of any event that prevailed over a large period of time (e.g. a superbubble whose contribution to the DM is small as in the case of the observed hump in the DM between 48° and 65°) is kept.

We further compare the DMs and \langle n_e \rangle derived from pulsars observations (Section 3), with those resulting from averaging over all the LOS crossing the simulated disc (|z| < 200 pc) and up to 4 kpc from the Sun at specific times (e.g. 310 and 360 Myr) and over the period 350–400 Myr. Top panel of Fig. 5 displays the observationally derived DMs and the averaged DMs at 310 Myr (\langle DM \rangle_{310 \text{ Myr}}; red lines), 360 Myr (\langle DM \rangle_{360 \text{ Myr}}; green lines) and over the period 350–400 Myr (\langle DM \rangle_{350–400 \text{ Myr}}; black lines). The blue circles represent the DMs (top) and \langle n_e \rangle (bottom) derived from pulsars observations.

Though inevitable here, may introduce artefacts in the simulation results, but we do not expect that our results are strongly affected though, because the simulation shows a certain pattern repetition in the ISM density and temperature distributions on scales of the order of a few correlation lengths (i.e. a few times 75 pc, according to AB05 and AB07). The averaged \langle DM \rangle_{350–400 \text{ Myr}}, after a steep growth in the first 100 pc, reaches a smooth increase for \(d > 500 \text{ pc}\), with the deviations of the minimum and maximum regarding the mean becoming constant over distance – consistent with the DMs variations in \(d\) observed in Fig. 4. The averaged DMs at 310 and 360 Myr vary widely, but with values within the pulsar-derived DMs. Therefore, the terms minimum and maximum of the \langle DM \rangle_{350–400 \text{ Myr}} should not be taken as strict upper and lower values for all times, as they only represent an average over a specific time window of the simulation.

After the large variation in the first few hundred parsecs, the mean of the simulated \langle n_e \rangle, for the cases shown in the bottom panel of Fig. 5, reaches a constant value (0.04 ± 0.002 cm\(^{-3}\)) and dispersion over large distances. This reflects the clumpy nature of the electrons in the turbulent ISM as would be expected if they are predominantly found in filaments and shells (Berkhuijsen & Fletcher 2008). The histogram of the log \langle n_e \rangle_{350–400 \text{ Myr}} and its best Gaussian fit are displayed in Fig. 1 by solid and dashed red lines, respectively. The fit is centred at log \langle n_e \rangle = -1.4 ± 0.1 with \(\sigma = 0.21 ± 0.01\). In the simulated disc, the clumpy material dominates the LOS and volume-averaged PDFs which explains the similar means between the electron density of the \(T < 10^4 \text{ K}\) regime (Fig. 3) and the time-averaged \langle n_e \rangle (Fig. 1, red lines). These fit parameters are similar to those displayed in Fig. 1 (black lines) for observationally derived \langle n_e \rangle. This similarity is indicative of the smoothing out of low- and
5 DISCUSSION AND FINAL REMARKS

In this Letter, we discuss the electron density distribution in the Galactic disc using the first to date 3D high-resolution NEI simulations of the ISM. The simulations trace the dynamical and thermal evolution of the interstellar gas, calculating on the spot the ionization structure, electron distribution and cooling function of the gas at each cell of the grid into which the computational domain is discretized. We did not take into account stellar ionizing photons and their transport, but an averaged diffuse photon field, which should be a reasonable approximation, when describing the mesoscale ISM. The NEI structure modifies the cooling function, which in turn enhances the number of free electrons.

Both the simulated DMs and electron density are consistent with the observations: (i) most DMs lie within the maximum and minimum observed values; (ii) log(n_e) is consistent with a Gaussian distribution; (iii) the mean electron density is 0.04 ± 0.01 cm^{-3} and (iv) the volume filling fraction of the WIM is bracketed between 4.9 and 6 per cent. These results lie in between the estimates by Gaensler et al. (2008) and Berkhuijsen, Mitra & Müller (2006) and Berkhuijsen & Müller (2008) for the electron density in the disc and WIM. Furthermore, the observed Gaussian distribution is present, irrespective of whether the ISM is isothermal (see discussion in Berkhuijsen & Fletcher 2008, and references therein) or not. This can be explained in two complementary ways. A fully developed turbulent system can be considered as a large number of independent random variables, with the logarithm of each having a certain distribution approaching a Gaussian as the number of variables goes to infinity (central limit theorem), being the case of SN-driven ISM simulations reaching a statistical equilibrium (see e.g. Vásquez-Semadeni & García 2001). Or, alternatively, we can use the principle of maximum entropy. The information entropy of a continuous random variable X with probability density function p(x) is defined as \( H(X) = \int_{-\infty}^{\infty} p(x) \log p(x) dx \). The lognormal distribution of X maximizes H(X), implying the least prior knowledge of the system (Sveshnikov 1976). This is exactly what is expected in homogeneous and isotropic turbulence with a large number of independent random variables. We study deviations from lognormal distributions in a forthcoming paper.

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REFERENCES

Breitschwerdt D., Schnurzter T., 1994, Nat, 371, 774
Ferrière K., 2001, Rev. Modern Phys., 73, 1031

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