Turbulence measurements from H\textsc{i} absorption spectra

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ABSTRACT

We use the millennium Arecibo 21-cm absorption-line survey measurements to examine the issue of the non-thermal contribution to the observed Galactic H\textsc{i} linewidths. If we assume a simple, constant pressure model for the H\textsc{i} in the Galaxy, we find that the non-thermal contribution to the linewidth, $v_{\text{nth}}$, scales as $v_{\text{nth}}^2 \propto P$, for $v_{\text{nth}}$ larger than $\sim 0.7$ km s$^{-1}$. Here, $\ell$ is a derived length-scale and $\alpha \sim 0.7 \pm 0.1$. This is consistent with what one would expect from a turbulent medium with a Kolmogorov scaling. Such a scaling is also predicted by theoretical models and numerical simulations of turbulence in a magnetized medium. For non-thermal linewidths narrower than $\sim 0.7$ km s$^{-1}$, this scaling breaks down, and we find that the likely reason is ambiguities arising from Gaussian decomposition of intrinsically narrow, blended lines. We use the above estimate of the non-thermal contribution to the linewidth to determine corrected H\textsc{i} kinetic temperature. The new limits that we obtain imply that a significantly smaller ($\sim 40$ per cent as opposed to 60 per cent) fraction of the atomic interstellar medium in our Galaxy is in the warm neutral medium phase.

Key words: turbulence – ISM: atoms – ISM: general – ISM: kinematics and dynamics – ISM: structure – radio lines: ISM.

1 INTRODUCTION

The classical description of the Galactic atomic interstellar medium (ISM) is that it consists of the cold neutral medium (CNM) and the warm neutral medium (WNM), in rough pressure balance with each other (e.g. Field 1965; Field, Goldsmith & Habing 1969; Wolfire et al. 2003). Detailed modelling of the energy balance in a multiphase medium (e.g. Wolfire et al. 1995) shows that the pressure equilibrium can be maintained for H\textsc{i} in one of two stable ranges of kinetic temperature ($T_k$), viz. $40$–200 K for the CNM and $5000$–$8000$ K for the WNM. H\textsc{i} at intermediate temperatures is unstable and expected to quickly migrate into one of the stable phases, unless energy is intermittently being injected into the medium. Recent observations and simulations indicate that in our Galaxy a significant fraction of the atomic ISM is in the thermally unstable region (e.g. Vázquez-Semadeni, Gazol & Scalo 2000; Heiles 2001; Hennebelle & Audit 2007; Hennebelle, Audit & Miville-Deschênes 2007).

The classical method of determining the temperature of the atomic ISM is to compare the H\textsc{i} 21-cm line in absorption towards a bright continuum source with the emission spectrum along a nearby line of sight. Assuming that the physical conditions are the same along both lines of sight, one can measure the spin temperature ($T_S$) (or excitation temperature) of the H\textsc{i} (see e.g. Kulkarni & Heiles 1988, for details). While the H\textsc{i} spin temperature, strictly speaking, characterizes the population distribution between the two hyperfine levels of the hydrogen atom, it is often used as a proxy for the kinetic temperature of the gas. This is because, in high-density regions, $T_S$ is expected to be tightly coupled to the kinetic temperature via collisions, while in low-density regions, resonant scattering of Lyman $\alpha$ photons is generally expected to couple the spin temperature to the kinetic temperature (Field 1958).

The 21-cm optical depth of the WNM is extremely low (typically $< 10^{-3}$) which makes it very difficult to measure the H\textsc{i} absorption from gas in the WNM phase. Consequently, emission-absorption studies usually provide only a lower limit to $T_S$. If the particle and Lyman $\alpha$ number densities are low, $T_S$ could, in turn, be significantly lower than $T_K$. On the other hand, one could use the 21-cm emission linewidth to determine an upper limit to the kinetic temperature. The linewidth is an upper limit to the temperature because in addition to thermal motions of the atoms, both bulk motion of the gas (e.g. differential rotation) as well as turbulence contribute to the observed linewidth.

The presence of turbulence in the atomic ISM of our own Galaxy can be detected through, for example, the scale free nature of the power spectrum of the intensity fluctuations in H\textsc{i} 21-cm emission (Crovisier & Dickey 1983; Green 1993). In a turbulent medium, one would also expect the velocity dispersion to increase as a power of the length-scale. Such a power-law velocity width length-scale scaling has been observed in the atomic ISM of the Large Magellanic...
Cloud (LMC) (Kim et al. 2007). To the best of our knowledge, it has not been observed in the atomic ISM of our own Galaxy. In this Letter, we show that, assuming that the atomic ISM is in rough pressure equilibrium, the data from the millennium Arecibo 21-cm absorption-line survey (Heiles & Troland 2003a,b) is consistent with a velocity–length-scale relation of the form \( \sigma^2 \propto l^\gamma \). We also show that this scaling is, to zeroth order, consistent with that expected from turbulence in an medium with magnetic field of approximately few \( \mu \)G.

Once one has an estimate of the turbulent velocity contribution to the observed velocity width, one can correct for it, to derive a tighter limit to the kinetic temperature. We show that this correction leads to a substantially smaller fraction of the gas being in the WNM phase than if one does not take turbulence into account.

2 DATA, ANALYSIS AND RESULTS

The data we use are taken from the millennium Arecibo 21-cm absorption-line survey and consist of emission and absorption spectra with a velocity resolution of \( \sim 0.4 \) km s\(^{-1}\) towards a total of 79 background radio sources. The observational and analysis techniques are discussed in detail by Heiles & Troland (2003a), and the astrophysical implications are discussed in Heiles & Troland (2003b). A brief summary is that the absorption spectra were corrected for emission from gas in the telescope beam by interpolating multiple off-source spectra, after which both the emission and absorption spectra were modelled as a collection of multiple Gaussian components. For each component, the spin temperature, upper limits on kinetic temperature, column densities and velocities were derived using these fits. There are several systematic uncertainties in such an analysis, discussed for example in Heiles & Troland (2003a), in particular those associated with estimating and subtracting the emission, and the assumption that each Gaussian component is a physically distinct entity. While a more robust measurement of the absorption spectra can be done using interferometric observations (e.g. Kanekar, Subrahmanyan & Chengalur 2003), here we work with the fit parameters provided as part of the survey. All the systematic uncertainties relevant to the Arecibo millennium absorption survey hence also apply to our results.

The survey lists a total of 374 Gaussian components in the emission spectra towards the 79 continuum sources. Out of these, 205 components are also detected in H\(_I\) absorption and have \( T_S \) measurements. For 21 of these components either the spin temperature had to be set to zero (by hand) in order to attain convergence of the fit (Heiles & Troland 2003a) or the upper limit of the kinetic temperature computed from the linewidth is less than the spin temperature (or the lower limit of the spin temperature). The derived parameters for these components are clearly unphysical, and we do not use them in our analysis. We are hence left with a total of 353 Gaussian components consisting of 188 components detected both in emission and absorption and 165 components detected only in emission.

\[ n = N_{\text{HI}} / l \]

where \( N_{\text{HI}} \) is the column density and \( l \) is the length of the cloud. Putting these together, we have \( l = N_{\text{HI}} kT / P \). For the CNM clouds detected in absorption, it is quite reasonable to assume that the kinetic temperature is the same as the spin temperature \( T_S \). If we further assume that the pressure is roughly constant across clouds, then we have \( l \propto N_{\text{HI}} T_S \). Though the density and temperature of neutral ISM vary over a few orders of magnitude, this assumption is justified because the pressure changes, in most of the cases, only by a factor of a few since the turbulence in the gas is at most transonic. Further, for these components, the non-thermal component of the linewidth is given by \( v_{\text{obs}}^2 \propto (T_{\text{Kmax}} - T_S) \), where \( T_{\text{Kmax}} \) is the measured linewidth of this component. In Fig. 2, we show a scatter plot of \( (T_{\text{Kmax}} - T_S) \) against \( N_{\text{HI}} \), as discussed above, to zeroth order this can be regarded as a plot of non-thermal velocity against length-scale. The solid line in the figure is a dual power-law fit; at large length-scales \[ \log(N_{\text{HI}} T_S) \geq 21.4 \pm 0.2 \], the power-law index is 0.7 \pm 0.1, while at small length-scales, the power-law index is consistent with zero. The dotted line shows a fit which assumes that the measured \( T_{\text{Kmax}} \) is larger than the true \( T_{\text{Kmax}} \) by 60 K; it provides a reasonable fit to the data over five orders of magnitude in \( N_{\text{HI}} T_S \). The length-scale corresponding to a pressure
The ISM is known to have clumpy density and velocity structures, and is believed to be turbulent at scales ranging from au to kpc (Dieter, Welch & Romney 1976; Larson 1981; Deshpande, Dwarakanath & Goss 2000). Incompressible hydrodynamic turbulence leads to the famous Kolmogorov scaling \( \sigma^2 \propto L^{1/3} \) (Kolmogorov 1941), similar to what we see at large scales. However, the Galactic ISM cannot be modelled simply as an incompressible fluid. Recent theoretical studies and numerical simulations have investigated in details the turbulence of multiphase medium (Koyama & Inutsuka 2002; Audit & Hennebelle 2005; Gazol, Vázquez-Semadeni & Kim 2005; Vázquez-Semadeni et al. 2006; Hennebelle et al. 2007). In some of these cases (Vázquez-Semadeni et al. 2006; Hennebelle et al. 2007), synthetic HI spectra are computed to study the effect of turbulence. In general, these analytical and numerical works predict a Kolmogorov-like turbulence in two-phase neutral ISM. Hennebelle et al. (2007) also report, based on simulation results, a power-law scaling \( \sigma^2 \propto L^{p_{B}} \) consistent with our observation.

Now, since fractional ionization couples the HI to the magnetic field, the turbulence is expected to be magnetohydrodynamic (MHD) in nature. Though simple and ingenious models (e.g. Goldreich & Sridhar 1995) of incompressible MHD turbulence have been proposed, most of the insights into incompressible and compressible MHD turbulence again come from numerical simulations (Cho, Lazarian & Yan 2002, and references therein). Models (like Goldreich & Sridhar 1995) predict a Kolmogorov-like energy spectrum, \( E(k) \propto k^{-5/3} \), for incompressible MHD turbulence and this is supported by both numerical simulations and observations (see Cho et al. 2002, for details). In case of compressible MHD turbulence, Alfvén modes are least susceptible to damping mechanisms (Minter & Spangler 1997), and hence the energy transfer in Alfvén waves is of major interest. Again, numerical simulations show that the energy spectra of Alfvén modes follow a Kolmogorov-like spectrum.

In a situation where the bulk of the energy transfer is via Alfvén waves, the non-thermal velocity dispersion \( \delta v \) is related to the magnetic perturbation amplitude \( \delta B \) and HI number density \( n_{\text{HI}} \) as \( \delta v = \delta B / \sqrt{4\pi G n_{\text{HI}}} \) (Arons & Max 1975; Roshi 2007) where \( \mu = 1.4 \) is the effective mass of an H + He gas with cosmic abundance, \( n_{\text{HI}} \) is the mass of the hydrogen atom and it is usually assumed that \( \delta B \approx B \). Using this relation, the magnetic field is found to be of the order of few \( \mu \)G (column density-weighted mean and median values are 11.7 and 10.2 \( \mu \)G, respectively) with no significant trend related to ‘cloud’ size. We note that there are various uncertainties to the derived equipartition magnetic field. But our estimate is broadly consistent with the observed magnetic field in the diffuse neutral ISM and matches, within a factor of 2, with the median magnetic field estimated for a subsample of these components using Zeeman splitting measurements (Heiles & Troland 2005).

The break that is clearly seen in Fig. 2 requires some attention. This change in the power-law index cannot be explained just in terms of lower signal-to-noise ratio on the physical quantities at low \( N_{\text{HI}} \), \( T_{S} \) end. However, as shown in the figure, the data are well fit by a model in which the linewidth is overestimated by about \( \sim 60 \) K. There are three systematic effects that may contribute to the overestimation of the linewidth without much affecting \( N_{\text{HI}} \) and \( T_{S} \): (i) the finite spectral resolution, (ii) blending of two or more narrow components and (iii) velocity (but not \( T_{S} \)) fluctuations in the gas within the Arcario beam. The contribution from the first effect is quantified by estimating the width of a Gaussian signal after smoothing it to a spectral resolution of 0.4 km s\(^{-1}\) and adding noise similar to that in the actual spectra. The effect is found to be almost negligible because of the high spectral resolution. A similar numerical exercise with two Gaussian components was done to check the effect of blending of narrow components and ambiguities in Gaussian fitting. In this case, the effect is most significant when the blended lines are of comparable amplitudes and have separations comparable to their widths. For example, blending of components with \( T_{\text{Kmax}} = 60 \) K (width of the Gaussian \( \sim 0.7 \) km s\(^{-1}\)), with a separation of \( \sim 1.2 \) km s\(^{-1}\), results in typically 20–30 K overestimation of \( T_{\text{Kmax}} \). When the amplitudes of two Gaussian profiles are comparable, the linewidth is overestimated by up to \( \sim 60 \) K. The third possibility, that is, a fine-scale structure in the velocity (but not in the temperature) has been proposed earlier (e.g. Brogan et al. 2005; Roy, Chengalur & Srianand 2006) to explain the observed fine-scale HI opacity fluctuations (Dieter et al. 1976; Crovisier, Dickey & Kazés 1985). Such velocity fluctuations within the Arcario beam will also cause an overestimation of \( T_{\text{Kmax}} \). We, however, note that the scalelength (inferred from \( N_{\text{HI}} \) and \( T_{S} \)) of the components below the break is very small. Although the existence of tiny ‘clouds’ is supported by observations and numerical simulations (e.g. Braun & Kanekar 2005; Stanimirović & Heiles 2005; Nagashima, Inutsuka & Koyama 2006; Vázquez-Semadeni et al. 2006; Hennebelle & Audit 2007), their origin and physical properties are still unknown. The evaporation time-scale for these clouds is \( \sim 1 \) Myr. These structures can survive if either the ambient pressure around the clouds is much higher than the standard ISM pressure or they are formed continuously with a comparable time-scale. While we have presented plausible arguments for the break that we see not corresponding to a physical phenomena, the lack of detailed understanding of these tiny HI structures means that we cannot rule out the possibility of some physical phenomenon being responsible for the break.

### 2.1 A new indicator of the temperature

For a multiphase medium if the turbulent velocity dispersion scaling is similar for coexisting phases, then this scaling relation can be exploited to get a handle on the physical temperature of the gas, that is, detected only in HI emission but not in absorption. Since only one has a lower limit on \( T_{S} \) for these components, they lie, as expected, systematically on the top left-hand side of the fit to the components detected in both emission and absorption (Fig. 3). For these components, we define a proxy temperature \( T_{L} \) that will restore the component back to this power-law correlation. Given the measured \( N_{\text{HI}} \) and \( T_{\text{Kmax}} \) from the emission spectra, one can uniquely compute this proxy temperature. Since \( T_{L} \) corresponds to the velocity width after correction for the turbulent velocity, it is a better estimate of the actual physical temperature of the cloud than that of \( T_{\text{Kmax}} \). Note that since most of the components in Fig. 3 line beyond the break in the fitted function, the derived \( T_{L} \) is consistent with the observed magnetic field in the diffuse neutral ISM and matches, within a factor of 2, with the median magnetic field estimated for a subsample of these components using Zeeman splitting measurements (Heiles & Troland 2005).
independent of whether the break arises due to some underlying physical reason.

For all except two of the 165 components detected only in emission, $T_L$ was calculated as described above. For two components, no meaningful solution for $T_L$ could be found, and they are hence not included in the further analysis. For the components detected both in emission and absorption, $T_S$ is taken to be same as $T_L$. With this, we have $T_L$ and $T_{Kmax}$ for a total of 351 Gaussian components.

Fig. 4 shows the histogram of $T_L$ and $T_{Kmax}$ in terms of both number of ‘clouds’ and HI column density. The top two panels give the number of Gaussian components and the bottom panels give the HI column density. From the histograms, it is evident that our results qualitatively confirm the earlier detection of a significant fraction of gas in the thermally unstable region.

Quantitatively, however, a significant fraction of the gas with high $T_{Kmax}$ after correction for turbulent broadening corresponds to gas in the stable phase. This quantitative difference is illustrated in Fig. 5 which shows the $N_{HI}$ fraction for both the population (components detected both in emission and absorption, and components detected only in emission) in different temperature range using $T_L$ instead of $T_{Kmax}$ as the proxy for the actual physical temperature.

A closer examination of the components with $T_L < 500$ shows a clear peak near $T_L \sim 50$ K in the number distribution and that the major fraction of the gas is below $T_L \sim 100$ K as shown in Fig. 6. Fig. 7 shows the histogram of scalelength $L \sim N_{HI}T_S$. This clearly shows a bimodal statistical distribution of the ‘cloud’ size for the neutral ISM. As expected, the dominant contribution to the peak at lower $L$ is from the cold components, and to the peak at higher $L$ is mostly from the warm components. If $N$ is number of clouds along the lines of sight, $R$ is typical size of the clouds and $n$ is HI number density, then $N(HI) \propto N_{HI}R_X n_X$ where $X$ stands for CNM or WNM. From the observed $N(HI)$ and $N$ for all the components...
used for this analysis we find, using this relation, $R_{\text{WNM}}/R_{\text{CNM}} \sim 110$ for typical $n_{\text{CNM}}/n_{\text{WNM}} \sim 100$. This is consistent with the ratio of the length-scale corresponding to two peaks in the bimodal distribution.

3 CONCLUSIONS

In this work, we present a new phenomenology-based technique to address the issue of non-thermal linewidth and the temperature of the diffuse neutral hydrogen of our Galaxy assuming a rough pressure equilibrium between different phases of the ISM. A possible connection between the observed Kolmogorov-like scaling of the non-thermal velocity dispersion in the Galactic HI and the turbulence of the interstellar medium is discussed. This scaling relation is used to re-examine the issue of the temperature of the Galactic ISM with the help of the millennium Arecibo 21-cm absorption-line survey measurements. The distribution of the derived temperature is found to be significantly different from the distribution of the upper limits of the kinetic temperature. A considerable fraction (~29 per cent) of the gas is found to be in the thermally unstable phase, qualitatively confirming earlier results. However, about 60 per cent of all the neutral diffuse gas, a much higher fraction than that of reported earlier, has temperature below 500 K. The CNM temperature distribution shows a clear peak near $T \sim 50$ K and the cloud size for the neutral ISM shows a bimodal statistical distribution. Derived magnetic field from the non-thermal velocity dispersion measurements, within a factor of 2, with the magnetic field value estimated from the Zeeman splitting measurements. The Kolmogorov-like scaling is consistent with the existing theoretical prediction, numerical simulations and earlier observational results.

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