Estimating kinetic temperature from H I 21 cm absorption studies: correction for the turbulence broadening

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ABSTRACT

Neutral hydrogen 21 cm transition is a useful tracer of the neutral interstellar medium. However, inferring physical condition from the observed 21 cm absorption and/or emission spectra is often not straightforward. One complication in estimating the temperature of the atomic gas is that the line width may have significant contribution from non-thermal broadening. We propose a formalism here to separate the thermal and non-thermal broadening using a self-consistent model of turbulence broadening of the H I 21 cm absorption components. Applying this novel method, we have estimated the spin and the kinetic temperature of diffuse Galactic neutral hydrogen, and found that a large fraction of gas has temperature in the unstable range. The turbulence is found to be subsonic or transonic in nature, and the clouds seem to have a bimodal size distribution. Assuming that the turbulence is magnetohydrodynamic in nature, the estimated magnetic field strength is of μG order, and is found to be uncorrelated with the H I number density.

Key words: ISM:atoms – ISM:general – ISM:structure – radio line:ISM – turbulence

1 INTRODUCTION

In the thermal steady-state model for neutral hydrogen (H I) in Galactic interstellar medium (ISM), two stable phases, the cold neutral medium (CNM; kinetic temperature \( T_K \approx 40-200 \) K) and the warm neutral medium (WNM; \( T_K \geq 5000 \) K), coexist over a narrow range of pressures, \( P_{\text{min}} \leq P \leq P_{\text{max}} \approx 3P_{\text{min}} \) (Field 1965; Field et. al 1969; Wolfire et. al 1995, 2003). The temperature distribution of the CNM is in good agreement with theoretical predictions (Clark et. al 1962; Radhakrishnan et. al 1972; Dickey et. al 1978; Heiles & Troland 2003a; Roy et. al 2006), but, due to observational difficulties, little is yet known about the WNM (Heiles & Troland 2003b; Kanekar et. al 2003; Roy et. al 2013b). In the CNM, due to higher density (\( n \approx 10 - 100 \text{ cm}^{-3} \)), collision is sufficient to thermalize the H I 21 cm hyperfine line; thus, the spin temperature (\( T_s \)), which basically measures the relative population of the two hyperfine levels, is equal to kinetic temperature \( T_K \). In the WNM, due to low density (\( n \approx 0.1 - 1 \text{ cm}^{-3} \)), collision is not so strong to thermalize the levels, and hence \( T_s \) is generally less than \( T_K \) (Liszt 2001), unless strong Galactic Lyman-α photons thermalize the line (Field 1958). In this simple two phase model, H I at any intermediate temperature is expected to be unstable, and drift to either CNM by cooling or WNM by heating. But, recently it has been found, both from direct observations and realistic simulations, that a significant fraction of the Galactic H I has kinetic temperature in the unstable range, 200 – 5000 K (Heiles & Troland 2003b; Kanekar et. al 2003; Roy, Peedikakkandy & Chengalur 2008; Roy et. al 2013b; Murray et. al 2015, 2018). Numerical simulations of the ISM suggest that turbulence and star formation feedback may play a role in redistributing the H I from stable CNM or WNM phase to the thermally unstable phase, and the fraction of the unstable gas is strongly correlated with the nature of feedback and the strength of the turbulence (Audit & Hennebelle 2005; Kim et. al 2014).

Indeed, measuring the temperature of the diffuse ISM using H I 21 cm line has many uncertainties and challenges. Even if the natural width of the line is negligible, the broadening has significant non-thermal contribution, and the observed linewidth provides only an upper limit to the kinetic temperature \( T_{K_{\text{max}}} \). Further, a given line of sight will have multiple components, generally though to be isothermal “clouds”. So, the classical method of determining the temperature is to compare the emission and the absorption spectra after decomposing them into multiple Gaussian components. Absorption spectra are taken towards compact bright continuum sources, whereas emission spectra are from nearby lines of sight by assuming that the physical conditions are same for both of them (Dickey et. al 1978; Payne et. al 1982; Kulkarni & Heiles 1988; Heiles & Troland 2003b; Saha et. al 2018). Note that for the emission spectrum, distribution of

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gas clouds along the line of sight is not known independently, hence it is difficult to decompose the spectrum into multiple components including the effect of absorption of background components due to optical depth of the foreground ones (Heiles & Troland 2003a). Without multi-Gaussian decomposition, we would only infer the column density weighted harmonic mean spin temperature of multiple components in a given sightline which is biased towards CNM (Roy et. al 2013b). Moreover, using this method one gets only the spin temperature of individual components, not the kinetic temperature. As mentioned earlier, even if $T_s$ is coupled to $T_K$ in the CNM, for the WNM it provides only a lower limit to the kinetic temperature.

Emission-absorption studies may suffer from further systematic effects if either the emission spectra, or both absorption and emission spectra, are from single-dish observations. Although we assume that the physical conditions are same between the emission and the absorption sightlines, in reality there may be small scale variation of H I distribution between the sightlines. The analysis will also be affected by sidelobe contamination, spectral baseline stability and uncertainty in separating emission and absorption using position switching (Heiles & Troland 2003b). Note that, with an interferometer, it is easier to reduce or eliminate these systematics, and to measure the absorption spectra with high dynamic range to detect the WNM (Carilli et. al 1998; Dwarakanath et. al 2002; Roy et. al 2013b). Of course, the spin temperature measurement will still require observing the emission spectra, which is more conveniently done with a single dish telescope.

One way of solving this problem is to use only the more reliable absorption spectra to estimate the temperature by separating the thermal and non-thermal broadening of the components. To do that, one may use a simple model with some scaling relation between the turbulent velocity dispersion ($\sigma_{th}$) and length scale ($l$). For example, incompressible hydrodynamic turbulence follow Kolmogorov scaling relation ($\sigma_{th} \propto l^{1/3}$) (Kolmogorov 1941). Of course, the ISM is compressible as well as magnetized, so the power law index may be different (Goldreich & Sridhar 1995). However, for the diffuse neutral ISM, it is found from observations (Roy, Peedikakkandy & Chengalur 2008; Larson 1979; Dutta et.al 2013), as well as numerical simulation (Hennebelle & Audit 2007), that even if the power law is somewhat steeper, it is not very different from a Kolmogorov-like scaling.

In this paper, we have used 21 cm absorption spectra for a sample of Galactic lines of sight, and modelled the spectra using a Kolmogorov-like scaling of $\sigma_{th}$ with $l$. Apart from the scaling relation, the method takes into consideration the rough thermal pressure equilibrium, and a relation between $T_s$ and $T_K$. In §2, we have outlined the formalism of how one may derive self consistent temperature, density, length scale and column density from only the absorption spectra assuming such a scaling law (Larson 1979; Wolfire et. al 2003) and a model dependent relation between $T_s$ and $T_K$ (Liszt 2001). For a consistency check, the derived column densities are compared to the column density estimated from the corresponding emission spectra. The analysis and the results are described in §3, and our main conclusions are summarized in §4.
2 THE FORMALISM

Natural line width of H $\, 21$ cm hyperfine line is negligibly small. So the line broadening mainly come from the thermal and non-thermal Doppler broadening with Gaussian profile. As a result, the observed absorption profile for a isothermal component is a Gaussian function with total variance of

$$
\sigma_{\text{total}} = (\sigma_{\text{th}}^2 + \sigma_{\text{nth}}^2)^{1/2}. 
$$

(1)

If an observed absorption profile is fitted with multiple Gaussian components with parameters $\tau_{\text{peak}}$ (peak optical depth), $\sigma_{\text{total}}$ (total variance), and $v_c$ (center line of sight velocity) for each component, these can then be converted to column density under the assumption mentioned above. For this, first we separate the thermal and the non-thermal broadening in the following way. We start assuming an initial fraction ($0 < f < 1$) of total variance is due to $\sigma_{\text{nth}}$, and the rest, from equation (1) is $\sigma_{\text{th}}$. We then get the kinetic temperature for each component

$$
T_k = 121 \sigma_{\text{th}}^2. 
$$

(2)

We assume that the gas is in rough thermal pressure equilibrium, and for a constant value of the pressure and typical ISM condition, estimate the corresponding $T_k$ for each component using results from numerical simulations (Liszt 2001). Note that this relation depends crucially on the assumed value of the thermal pressure too. This then allows us to compute the column densities of the components

$$
N(\text{HI})_{ \text{abs}} = 1.823 \times 10^{18} \times T_k \sqrt{\pi} \tau_{\text{peak}} b. 
$$

(3)

From the column density, the kinetic temperature and the assumed value for the pressure, we can then estimate the representative length scale of the “cloud”

$$
l = \frac{N(\text{HI})_{ \text{abs}} T_k}{P}. 
$$

(4)

which can, then, be used to compute the value of $\sigma_{\text{nth}}$ using a scaling relation of the form

$$
\sigma_{\text{nth}} = A l^{\alpha}. 
$$

(5)

These calculations are done for an adopted value of $P = 3700$ K$\text{cm}^{-3}$, $A = 0.64$ and $\alpha = 0.37$ (Larson 1979; Wolfire et. al 2003). The estimated $\sigma_{\text{nth}}$ is compared with the initial assumed value, and the fraction $f$ is iteratively adjusted until a consistent solution is reached. Once the convergence is achieved, we get the temperature, density, size and column density for each of the components along a line of sight. We then calculate the total column density for the line of sight, and, as a consistency check, compare it with the total line of sight column density estimated from the emission spectrum. Finally, we vary the model parameters $A$ and $\alpha$, and repeat the procedure for different values of $P$ to probe how the results are affected by the choice of these parameters, and to show that the observed column densities matches more or less well for the adopted fiducial values of the parameters.

3 DATA ANALYSIS AND RESULTS

All the absorption spectra are taken from the ongoing Galactic H $\, 21$ cm absorption line survey (Roy et. al 2013a) carried out with the Giant Metrewave Radio Telescope (GMRT), the Westerbrook Synthesis Radio Telescope (WSRT), and the Australia Telescope Compact Array (ATCA) towards compact radio-loud quasars. These 30 lines of sight with 214 components in absorption are used for our analysis. The details of the survey and the reduction techniques are discussed in details in Roy et. al (2013a). The corresponding emission spectra for overall consistency checks are taken from the LAB (Leiden-Argentine Bonn) survey 1 (Bajaja et. al 2005; Hartmann & Burton 1997; Kalberla et. al 2005). Emission column densities were calculated from these spectra using the “isothermal estimation” - a statistically unbiased and more accurate estimate (compared to optically thin estimate) of the H $\, 1$ column density - by using the measured brightness temperature from LAB survey data and the optical depth from the absorption survey data (Chengalur, Kanekar & Roy 2013; Roy et. al 2013b). The best fit parameters of the Gaussian components (peak optical depth, line width and central velocity) are taken from Roy et. al (2013b).

We implement the analysis outlined in the previous section for this sample through numerical computation. In Figure 1, we show the result of our modeling to separate the thermal and the non-thermal width for an example case. The best fit model Gaussian components for the absorption spectra towards the source B0407-658 are shown in the figure with the full width half maxima (FWHM) and the thermal width as black and red horizontal lines respectively. Note that for showing the deep and weak components clearly, the optical depth is plotted using logarithmic scale. Clearly, a self-consistent model requires non-thermal broadening to explain the observed line width, and this is more clearly visible for the wider components.

Figure 2 shows a comparison of the column density using the emission and the absorption spectra for the lines of sight of our sample. This is for representative values of $P = 3700$ K$\text{cm}^{-3}$, $A = 0.64$ and $\alpha = 0.37$. In general, there is a good match between these two estimations, but for six sources, namely B1641+399, B1328+254, B1611+343, 1 http://www.astro.uni-bonn.de/en/download/data/lab-survey/
Figure 5. Absorption column density as a function of inferred length scale of 214 components. The colours are for different temperature range, and the lines are constant density curves with $n = 50, 5$ and $0.5\,\text{cm}^{-3}$ ($P = 3700\,\text{Kcm}^{-3}$, $A = 0.64$ and $\alpha = 0.37$).

Figure 6. H$\alpha$ column density distribution in the cold, warm and unstable phase for $P = 3700\,\text{Kcm}^{-3}$, $A = 0.64$ and $\alpha = 0.37$.

B0117-155, B0023-263, B0114-211, the emission column density is significantly higher. We note that the absorption spectra for these sources at the low H$\alpha$ column density end have higher rms noise (Roy et. al 2013b). Also, four out of these six are lines of sight at very high Galactic latitude. It is hence possible that a large fraction of the gas is at higher temperature below the detection limit of the absorption survey. However, this consistency check indicates that the fiducial parameter values adopted allow one to more or less accurately estimate the total line of sight column density for this sample solely from the absorption spectra. Next, we check the effect of changing various parameters of our model. This is quantified by the change in the estimated column density from the absorption spectra when $P$, $A$ or $\alpha$ is changed from the adopted values. The estimated column density varies significantly when the parameter values deviate from the adopted fiducial values, and the deviation is larger for a larger variation of the parameter values. This may arguably be an independent validation of the assumed models, but here we take this as indicative of the fact that the fiducial values adopted for the modeling are more or less the correct values. Hence, for the rest of the analysis, we confined ourselves to these fiducial values only. However, we compute the rms variation of the estimated column density for simultaneous variation of $P$, $A$ and $\alpha$ uniformly over the range of 750 - 6000 K/cm$^3$, 0.30 - 1.20, and 0.23 - 0.50 respectively. This is shown as error bars for each source in Figure 2. Note that the mean variation of the estimated column density for the choice of range of the parameters is $\sim 25\%$.

It is assuring that the total column density estimated from only the absorption spectra matches well with the one derived from the emission and absorption spectra ("isothermal" estimate) for each of these lines of sight. But, a more robust method of cross-checking will be a comparison of the estimated spin temperature from this method with the one classically derived from emission-absorption spectra for each individual components. However, that will require joint fitting of the emission and absorption spectra using multiple Gaussian components. Whereas this is already done for the sample of absorption spectra, due to complications mentioned earlier (e.g. uncertain radiative transfer due to self-absorption, relative position of components being unknown, possible stray radiation contamination and relatively unreliable spectral baseline for shallow and wide components), multi-Gaussian decomposition of emission spectrum is not straightforward. Modeling the emission spectra with multiple components for the full sample is beyond the scope of this work, and will be presented for the complete survey (with almost double sample size) in future work. However, for the purpose of comparing the spin temperature of individual components, we have done the fitting for a sub-sample of 10 emission line spectra using data from the LAB survey. These are lines of sight with relatively simpler profile with five or less number of components detected in absorption with low peak optical depth (so that the issue of self absorption is less problematic, and multi-component decomposition is relatively easier and reliable). The fitting of the emission spectra was done with constraints from the absorption spectra in terms of the central velocity of the components, but keeping the amplitude and width as free parameters. Some time, additional weak and wide components were necessary to achieve a good fit to the data. For those components, all three parameters were kept as free parameters without constraints. For the 25 absorption components along these 10 lines of sight, we derived the spin temperature based on the multi-Gaussian fitting of the emission and absorption spectra. The result is shown in Figure 3 that compares the spin temperature from this emission-absorption model with that estimated from the absorption spectra only. The match of these two estimation of spin temperature is quite good, and this indicates that the method used for column density estimation is self-consistent and reliable and the adopted fiducial values are more or less the correct values. Hence, for the rest of the analysis, we confined ourselves to these fiducial values only.

It is interesting to note that the inferred length scales from our analysis, shown in Figure 4 have a clear two-component distribution. Fitting the observed histogram, we get two log-normal distribution with one peaking at about 0.1 pc and another at 3 pc with the tail extending as large as few hundred pc. The components with smaller length scales have systematically lower kinetic temperature and higher density. This is shown in Figure 5 where we have overplotted three constant density curves corresponding to $n = 50$, 5 and $0.5\,\text{cm}^{-3}$, and the temperature of the components are colour coded accordingly.
In Figure 6, we show the temperature distribution of the gas based on this analysis. We would like to emphasize here, unlike other studies that deal with spin temperature (from absorption-emission study) or only the upper limit to the kinetic temperature (based on line width), this shows the estimated kinetic temperature, albeit certain reasonable assumption, from a self-consistent model using only the absorption spectra. The temperature of the individual components are shown in Figure 7. Considering column density fraction, we find that about 15% gas is in the cold phase, ~ 10% gas is in the warm phase, and as large as 75% gas has temperature in the intermediate range corresponding to the so called unstable phase. Note that the mean kinetic temperature of the cold, warm and intermediate phases are 88, ~ 8300 and ~ 940 K respectively. Interestingly, there are quite a few components where the temperature is too low (16 components below $T_K \leq 40$ K). H i with such low temperature has been reported earlier (Heiles & Troland 2003b; Roy et al 2013a), and may be indicative of the absence of small dust grains and polycyclic aromatic hydrocarbon, making heating inefficient in some of the compact clouds.

Next we investigate the strength of turbulence in various phases by computing the turbulence Mach number using the estimated temperature, density and the turbulent dispersion. Figure 8 shows the estimated Mach number as a function of length scale for the different phases.

It is found that the turbulence is subsonic (and at most transonic) at all scales and all different phases. Finally, we estimate the magnetic field for these components under the assumption that the turbulence in consideration is magnetohydrodynamic (MHD) in nature where Alfvén wave is the major energy transfer mode. In that condition, the non-thermal velocity dispersion and the magnetic field perturbation amplitude are related as $\delta v = \delta B / \mu G$, where $\mu$ (mean molecular weight) is 1.4 for H+He and $\delta B \approx B$ (Arons & Max 1975; Roshi 2007). Earlier, Roy, Peedikakkandy & Chengalur (2008) estimated magnetic field using this argument, and the values match with typical diffuse ISM magnetic field measured from the Zeeman splitting observations (Heiles & Troland 2005). For the current sample also, the magnetic field strength is found to be of the order of $\mu$G. Figure 9 shows that the inferred magnetic field values and column densities have a power law relation with a power law index of ~ 0.32, but, as shown in Figure 10, there is no strong correlation of magnetic field and density. This suggests that at densities under consideration, field-strength is not increasing significantly due to flux freezing.
4 CONCLUSIONS

Measurement of temperature from H i 21 cm emission and absorption spectra is challenging, and has various uncertainties. In this paper, we have outlined a method to consistently derive the gas column density and temperature from only the absorption spectra, by using a model dependent correction for turbulence broadening. This novel formalism is applied to high quality Galactic H i absorption spectra for a subsample of 30 lines of sight from an ongoing absorption line survey. We found that our model, with fiducial scaling relation between non-thermal velocity dispersion and length scale, can be used to estimate column density, and to infer the column density fraction in different thermal phases. This careful analysis establishes, beyond reasonable doubt, the existence of a large fraction of gas with the kinetic temperature in the so called unstable range. We also find a bi-modal distribution of length scale of the absorbing clouds. The non-thermal broadening indicates subsonic or, at most, transonic, nature of the turbulence for diffuse neutral ISM. Interestingly, the inferred magnetic field strength seems to be increasing monotonically with the column density but found to be mostly uncorrelated with the density. We plan to apply this analysis for a larger sample from the ongoing absorption survey in near future.

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