Properties of atomic hydrogen gas in the Galactic plane from THOR 21-cm absorption spectra: a comparison with the high latitude gas

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ABSTRACT
The neutral hydrogen 21 cm line is an excellent tracer of the atomic interstellar medium in the cold and the warm phases. Combined 21 cm emission and absorption observations are very useful to study the properties of the gas over a wide range of density and temperature. In this work, we have used 21 cm absorption spectra from recent interferometric surveys, along with the corresponding emission spectra from earlier single dish surveys to study the properties of the atomic gas in the Milky Way. In particular, we focus on a comparison of properties between lines of sight through the gas disk in the Galactic plane and high Galactic latitude lines of sight through more diffuse gas. As expected, the analysis shows a lower average temperature for the gas in the Galactic plane compared to that along the high latitude lines of sight. The gas in the plane also has a higher molecular fraction, showing a sharp transition and flattening in the dust - gas correlation. On the other hand, the observed correlation between 21 cm brightness temperature and optical depth indicates some intrinsic difference in spin temperature distribution and a fraction of gas in the Galactic plane having intermediate optical depth (for $0.02 < \tau < 0.2$) but higher spin temperature, compared to that of the diffuse gas at high latitude with the same optical depth. This may be due to a small fraction of cold gas with slightly higher temperature and lower density present on the Galactic plane.

Key words: ISM: kinematics and dynamics – ISM: clouds – ISM: dust, extinction – Galaxy: halo – ISM: general – radio lines: ISM

1 INTRODUCTION
The interstellar medium (ISM) consists mostly of hydrogen gas, in ionized, neutral atomic and molecular form. The 21 cm transition, originating from the hyperfine splitting due to spin-spin coupling in the neutral hydrogen atom ($H\alpha$) in its ground state, is thus very useful in in studying the ISM of the Milky Way and of nearby galaxies, as well as probing the distant universe through the redshifted 21 cm line (Clark et al. 1962; Field 1965; Walter et al. 2008). For the Galactic $H\alpha$, the 21 cm signal can be detected either as emission line from the gas, or absorption line towards suitable background continuum sources. The line of sight column density ($N_{HI}$) and the number density distribution in the hyperfine (triplet and singlet) energy levels, specified by the spin temperature ($T_s$), determine the strength of emission and absorption. Furthermore, the linewidth of emission/absorption spectra is determined by the kinetic temperature ($T_K$) and non-thermal broadening. Thus, $H\alpha$ 21 cm observations can be used to determine various physical properties of the gas.

Galactic $H\alpha$ can have a wide range of temperature, $\sim 20 - 10^4$ K (Field 1965; Field et al. 1969), with cold gas having higher density and smaller filling factor while the warm gas has lower density and is more diffuse and widespread. Different heating and cooling processes along with self-shielding of the gas yield a temperature of the stable cold neutral medium (CNM) to be $\sim 20 - 400$ K and of the stable warm neutral medium (WNM) to be $\sim 4000 - 10000$ K. Gas with intermediate temperatures is difficult to detect as this phase is expected to be unstable and easily moves to one of the stable phases via runaway heating or cooling (but also see Heiles &
The formation of hydrogen molecules in H I clouds by contributing to the self-shielding. Another important component of the ISM coexisting with the gas in different phases is dust. Dust takes part in heating and cooling processes of the ISM. It also plays a crucial role in the atomic gas transition and the atomic interstellar medium using the H I 21-cm emission-estimation of the atomic interstellar medium using the H I 21-cm absorption line as a function of either frequency (\( \nu \)) or Doppler velocity (\( \nu \)). The 21 cm optical depth \( \tau(v) \) can be computed from the absorption spectra \( I_\nu \) and the continuum intensity \( I_c \) of the background source. The quantity \( \tau = \int adl \) is the line of sight integral of the linear absorption coefficient \( a \), which depends on \( T_e \) and the density of H I (n(HI)). For an isothermal “cloud” with known \( T_e \), the H I column density \( N_{H I} \) can be determined from the observed absorption spectrum by integrating \( \tau(v) \) over the velocity range of the absorption,\[ N_{H I} = 1.823 \times 10^{18} \int T_e \tau dv \quad \ldots (1) \]

where \( N_{H I} \) is in cm\(^{-2}\), \( T_e \) is in Kelvin and the velocity interval \( dv \) is in km s\(^{-1}\) (Kulkarni & Heiles 1988; Dickey & Lockman 1990). The quantities \( T_e \) and \( T_B \) are connected through the radiative transfer relation \[ T_B = T_e \left[ 1 - \exp(-\tau) \right] \quad \ldots (2) \]
Combining equation (1) and (2), $N_{HI}$ for an isothermal cloud can be written as

$$N_{HI} = 1.823 \times 10^{18} \int \frac{\tau_T B}{[1 - \exp(-\tau)]} dv;$$

in terms of direct observables $T_B$ and $\tau$ (Dickey & Benson 1982). For the optically thin limit ($\tau \ll 1$), equation (3) can be simplified to

$$N_{HI} = 1.823 \times 10^{18} \int T_B dv .$$

Please note, although the observed quantities for the absorption (emission) spectra are $\tau$ ($T_B$) as a function of velocity in each spectral channel, here the velocity dependence of $T_B(v)$, $\tau(v)$ and also $T_x(v)$ (from equation (2)) are not shown explicitly. On the other hand, the line of sight average $T_x$ can be defined as

$$\langle T_x \rangle = \frac{N_{HI} }{1.823 \times 10^{18} \int \tau dv} ;$$

where $N_{HI}$ may be computed from observed spectra using equation (3).

For studies aiming to understand the properties of the Milky Way ISM, it is relatively easy to have high sensitivity and high spectral resolution $H_\text{I}$ emission data covering a large area or the full sky from (mostly) single dish or interferometric surveys. But availability of deep $H_\text{I}$ absorption spectra is limited as suitable bright background sources required for such studies are sparse. One way of estimating, without any bias, the $H_\text{I}$ column density from only the 21 cm emission spectra has been developed earlier by Saha et al. (2018); Chengalur et al. (2013), and has been applied to data for high Galactic latitude lines of sight.

For this work, we have taken $H_\text{I}$ absorption spectra from the H/αOH/Recombination line survey of the Milky Way (THOR, Beuther et al. 2016; Wang et al. 2020). This is a emission-absorption combined survey that covers part of the Galactic plane ($15^\circ < l < 67^\circ$ and $|b| < \pm 1^\circ$), observed with the Karl G. Jansky Very Large Array (VLA) in a C+D+single dish configuration (i.e. an angular resolution of $\approx 40''$). The emission data is taken from the VLA Galactic Plane Survey (VGPS) (Stil et al. 2006) in D and single dish configuration (angular resolution of $\approx 60''$), whereas, the absorption part is from THOR-only survey done in C-configuration with an angular resolution of $\approx 20''$ in L-band. The $H_\text{I}$ data have a spectral resolution of 1.5 km s$^{-1}$. Along with the $H_\text{I}$ emission signal, the THOR data also provide $H_\text{I}$ absorption spectra towards a large number of background sources. We have used these absorption spectra for the current study. For each $H_\text{I}$ absorption spectra, the optical depth towards the continuum source has been calculated following the prescription described by Bihr, S. et al. (2015). We refer the readers to the original THOR papers for a detailed analysis in deriving the $\tau$ values from the $H_\text{I}$ absorption spectra. We note that the optical depth RMS for these spectra has a wide range. The spectra with very large optical depth RMS are not of much use as these correspond to the weaker background sources and data from only a few spectral channels will be usable. On the other hand, if we use an RMS cutoff too small, the available number of lines of sight for the analysis will be very small. We have hence used a moderate cutoff and included all spectra with $\tau_{\text{RMS}} \leq 0.05$ (i.e., 75 lines of sight) for our analysis. We note that as the $\tau_{\text{RMS}}$ is mostly determined by the flux density of the background sources, this cutoff does not introduce any additional bias.

For comparison, we have used absorption spectra from the high spectral resolution and high sensitivity $H_\text{I}$ absorption survey by Roy et al. (2013a). This survey uses data from the Giant Metrewave Radio Telescope (GMRT) the Westerbork Synthesis Radio Telescope (WSRT), and the Australia Telescope Compact Array (ATCA), with an optical depth RMS sensitivity of $\sim 10^{-3}$ per 1 km s$^{-1}$ channel, for 32 lines of sight (excluding the Galactic plane). We have also used complementary 21 cm emission spectra from the Leiden/Argentina/Bonn (LAB) survey (Hartmann & Burton 1997; Arnaud et al. 2000; Bajaja et al. 2005; Kalberla et al. 2005) covering $v_{\text{LSR}} = -450$ to $+400$ km s$^{-1}$, at a resolution of 1.3 km s$^{-1}$ (angular resolution $\sim 36''$). We have used spatial interpolation and spectral resampling to get $\tau(v)$ and $T_B(v)$ at the corresponding velocity from the absorption and the emission spectra, respectively.

3 RESULTS

For the subsample of 75 lines of sight with reasonable S/N from THOR, we show the distribution of $T_B(v)$ and $\tau(v)$ from individual channels in Figure 1. The plotted density contours in the left panel
The correlation of $E(B-V)$ with $N_{HI}$ (left panel) and $\int \tau dv$ (right panel). Brown circles with green errorbars (3σ) are lines of sight on the Galactic plane from THOR (this work), and black circles with magenta errorbars (3σ) are high latitude lines of sight (Roy et al. 2013a). Solid lines (in the left panel) indicate $N_{HI} = E(B-V)$ relation (Liszt 2014b), $N_{HI} = 8.3 \times 10^{21} E(B-V) (1 - f_{HI})$, for different $H_2$ fraction ($f_{HI}$). Dashed grey line is drawn at $E(B-V)=1$ where the transition is happening.

The THOR data point on the Galactic plane sample is at higher optical depth. We note here that there is a small fraction of data points from THOR with optical depth saturation, where we only have a lower limit to the optical depth. However, this does not change the $T_B - \tau$ relation shown in Figure 1, apart from extending the flat part to even higher optical depth. This concentration of data points at the high $\tau$ end of the distribution is consistent with a large fraction of cold, dense gas in the Galactic plane. This is evident from the top right panel of Figure 1, which shows the median $T_B - \tau$ for both samples along with the constant $T_0$ lines (from equation (2)), with the high $\tau$ end having lower $T_0$. However, at the intermediate $\tau$ range (0.02 $\leq \tau \leq 0.2$), we found the two distributions to deviate, showing relatively higher $T_B$ (i.e. higher $T_0$ as well) for the lines of sight on the Galactic plane from THOR. To establish this deviation, we have performed a least square fitting (shown in Figure 1 left panel) in both the samples considering a linear function in the log-log scale and fitted models (corresponding parameters for high latitude sample: slope = 0.509 $\pm$ 0.020 and intercept = 1.871 $\pm$ 0.019 ; for THOR sample: slope = 0.260 $\pm$ 0.007 and intercept = 1.854 $\pm$ 0.004 )

do not match within their respective errors. The trend remains the same when we carried out the similar parametric least square fitting with an extra quadratic term in the function (i.e. the fitted slope terms are well beyond their individual uncertainties). In addition to that, we have also performed the non-parametric Kolmogorov-Smirnov (K-S) test for different bins in optical depth (in log scale) and shown the results (D-statistics and p-value) in the bottom right panel in Figure 1. Clearly, below $\tau < 1.0$ the two samples are very unlikely to be drawn from the same underlying distribution. Both of these parametric and non-parametric tests strongly support the inference of a statistically significant difference between the two samples. There are almost 15% (precisely 14.89%) channels that show optical depth saturation, but they are above $\tau \sim 1.3$ , and should not affect the K-S statistics or the slope of the $T_B - \tau$ relation below $\tau < 1.0$.

It is interesting to note that even if the channels with intermediate $\tau$ have a higher $T_0$ for the THOR sample, the line of sight average spin temperature ($\langle T_s \rangle$) is lower than that of the high latitude lines of sight (Saha et al. 2018; Roy et al. 2013a). In fact, as shown in Figure 2, the THOR data points on the $N_{HI} - \int \tau dv$ plot follow the same trend of lower ($T_s$) for higher $N_{HI}$ (Kanekar et al. 2011; Roy et al. 2013a), even in the zoomed scale. Note that NHI from LAB emission spectra is computed for the matching velocity range over which THOR absorption spectra are also integrated. The errors for the THOR sample have been calculated with a simple prescription considering the optical thin approximation in a 3σ limit and the er-
errors for the high latitude sample are taken from Kanekar et al. (2011) (see Table 1 in that paper). The contributions for the saturation points are incorporated by including an extra uncertainty, corresponding to a typical factor of two higher optical depth for those channels, in the upper limits of the errorbars (which are more readily visible in the zoomed plot in the right panel). For $N_{HI} > 10^{22} \text{cm}^{-2}$ we find $\langle T_i \rangle \lesssim 100 \text{ K}$, whereas for $N_{HI} < 2 \times 10^{20} \text{cm}^{-2}$, as reported in Kanekar et al. (2011), $\langle T_i \rangle \gtrsim 600 \text{ K}$.

Apart from the lower average temperature for the atomic gas, we also expect the molecular gas fraction to be significantly higher in the Galactic plane. One way to explore this is to check the correlation between the $I$ column density and the so-called error excess $E(B - V)$. Earlier observations have revealed a tight linear relation between $E(B - V)$ and $\tau$ (Bohlin et al. 1978; Savage et al. 1977; Liszt et al. 2010; Liszt 2014a,b; Heiles 1976; Burstein & Heiles 1982; Schlegel et al. 1998; Kalberla et al. 2005). A tight correlation between $E(B - V)$ and the integrated optical depth is also reported by Liszt (2014b). For the lines of sight in both the samples, we have taken the $E(B - V)$ values (angular resolution ~ $6'$) derived from the recalibrated infrared dust maps, from the NASA/IPAC Extinction calculator (Schlegel et al. 1998; Schlafly & Finkbeiner 2011). In Figure 3, these correlations are shown for both the THOR sample and the high Galactic latitude sample. The straight lines in the left panel are $N_{HI} - E(B - V)$ relation from different molecular gas fractions ($f_B$) taken from Liszt (2014b). In both cases, we see a clear flattening with a sharp transition of the relations at about $E(B - V) = 1$ (marked with dashed grey line), incidentally coinciding with the separating $E(B - V)$ for the two samples. The observed high $E(B - V)$ is expected due to the abundance of large amount of dust on the Galactic plane. Even if the $I$ column density can be somewhat underestimated due to the high optical depth and absorption saturation of some spectral channels, the sharp break and the flattening must be primarily due to the atomic-to-molecular transition of the ISM and a higher molecular gas fraction on the Galactic plane at $E(B - V) > 1$. Unlike Liszt (2014b) & Kanekar et al. (2011), we see the flattening at $\int \tau dv > 100$. The plausible reason behind this trend is that the column density here is already corrected for the optical depth using the isothermal estimator of $N_{HI}$. Note that, we see this flattening in $N_{HI} \sim 10^{22} \text{cm}^{-2}$, which is consistent with the understanding that the molecular fraction is significant for $N_{HI} > 10^{22} \text{cm}^{-2}$ (Schaye 2001; Krumholz et al. 2009).

To reconcile these two apparently contradictory results, viz. lower $T_i$ but higher $T_s(v)$ for intermediate $\tau$ range data points coming from the low Galactic latitude lines of sight of THOR, we have looked at the distribution of $T_s(v)$ for the two samples more closely. This is done by computing the $T_i$ and the $I$ column density for each individual channel, and determining the $N_{HI}$ fraction for different $T_i$ bins. As expected, for both samples, most of the gas has low $T_s (< 400 \text{ K})$. For the THOR sample, the fractions of $N_{HI}$ for $T_s < 200 \text{ K}$, $200 \text{ K} < T_s < 1000 \text{ K}$ and $T_s > 1000 \text{ K}$ are ~ 74%, 25% and 1%, respectively. For the high latitude sample, Roy et al. (2013a) reported the corresponding fractions to be 46%, 37% and 9%. As shown in the left panel of Figure 4, the high latitude sample indeed shows a larger fraction of warm gas compared to that for the Galactic plane data, increasing $T_s$ for those lines of sight. This is, however, considering all the data points including the very low optical depth channels for the high latitude sample. Instead, if we use an optical depth cutoff of $\tau > 0.02$ (Figure 4, middle panel) or $0.2 > \tau > 0.02$ (right panel), we see a clear excess of warmer gas in the low Galactic latitude data from THOR compared to the high latitude data from the earlier absorption survey. The similar trend in

Figure 5. Comparison of inferred $T_i$ and $T_s$ from the THOR data with models from Liszt (2001). Solid lines are model $T_k - T_i$ relation for different thermal pressure. Line with filled circles is from this analysis, for $P_{th} = 3000 \text{K} \text{cm}^{-3}$ and $I_c = 6 \text{ pc}$. Dashed lines are for $I_c = 6 \text{ pc}$ and $I_c = 12 \text{ pc}$. Line with empty squares is based on data from Saha et al. (2018) for $I_c = 2 \text{ pc}$ for a comparison with the low latitude sample.

the spin temperature is also in the other works by Heiles & Troland (2003); Nguyen et al. (2019); Murray et al. (2021).

### 4 DISCUSSION AND CONCLUSIONS

We want to emphasize the important point here that the $T_s$ distribution shown here comes from measured $T_B$ and $\tau$ in individual channels; the inferred $T_s$ for a channel is an average of multiple components with different individual $T_s$ blended at that particular Doppler velocity, and may not be spatially coexisting. Hence, an observed intermediate value of $T_s$ does not necessarily imply the presence of gas in the thermally unstable phase. However, this is true for both the samples, and the observed higher $T_s(v)$ at intermediate $\tau$ for the THOR sample indicates a real difference in physical properties for the gas on the Galactic plane compared to that along high latitude lines of sight.

For a single spectral channel, $T_s(v) = T_B(v)/\tau(v)$ can be expressed as $[(f_C/T_{s,C}) + (f_W/T_{s,W})]^{-1}$ in terms of the column density fraction of cold ($f_C$) and warm gas ($f_W = 1 - f_C$) for that channel, and the spin temperature of cold and warm gas, $T_{s,C}$ and $T_{s,W}$, respectively. For a given $\tau$, higher $T_B$ (i.e. higher $T_s$) can be due to higher $T_{s,C}$, $T_{s,W}$ and/or lower $f_C$. However, as the average $T_s$ for the channel is heavily biased to that of the cold phase [For eg. even for a 50% – 50% mixture of cold gas (~100K) and warm (~5000K), average $T_s$ remains in the colder phase (< 200 K)], explaining higher observed $T_s$ requires either significantly higher $T_{s,W}$ or very small $f_C$ – both of which seem unlikely for the Galactic plane gas. Alternatively, somewhat higher $T_{s,C}$ for a small fraction of gas can easily result in a higher average $T_s$ for a velocity channel, and that seems to be a more plausible scenario.

To understand the small fraction of high $T_s$ gas with relatively high optical depth, we further convert the observed $T_B - \tau$ relation to $T_s - T_i$ relation under some simplifying assumption, and compare it with theoretical expectations. From the binned $T_B$ and $\tau$, we get the corresponding $T_s$ for the bin using equation (2). We can also compute $T_k$ assuming a thermal pressure $P_{th}$ and characteristic length scale $I_c$ (corresponding to the spectral resolution) as

$$
T_k = P_{th}/n_{HI} = P_{th}I_c/N_{HI}
$$

(MNRAS 000, 1–6 (2022))
where \( N_{HI} \) is given by equation (3). Here, \( P_{th} \) and \( l_c \) (or, more appropriately \( P_{th}l_c \)) are parameters that may be adjusted to see if the observed \( T_k - T_{th} \) relation can be matched with the theoretical one (e.g. Liszt 2001). As shown in Fig 5, for a nominal choice of \( P_{th} = 3000 \text{ K cm}^{-2} \), if we set \( l_c = 2 \text{ pc} \) (per 1 km s\(^{-1} \) velocity width), the high latitude data match well with the theoretical curve, except for very low \( T_k \) end. The deviation of the low \( T_k \) end can be explained either by a higher pressure or a larger value of \( l_c \). However, for the Galactic plane sample, we need a slightly higher \( l_c = 3 \text{ pc} \) to match the data with expected models for 100 K < \( T_k \) < 300 K, and significantly higher values (up to 12 pc per 1 km s\(^{-1} \) velocity width) for \( T_k > 300 \text{ K} \). As there is a degeneracy between \( P_{th} \) and \( l_c \) in this analysis, part of the discrepancy may be explained as originating from higher thermal pressure in the Galactic plane compared to the high latitude sight lines; however, particularly for the high \( T_k \) end, there is clear indication of a larger length scale (equivalently, a lower number density) to account for the deviation.

In summary, we have carried out a systematic comparison of the THOR H \( i \) absorption spectra with the comparable data for a high Galactic latitude sample. As expected, the gas in the Galactic plane has lower average spin temperature, higher dust extinction and higher molecular gas fraction. There is an excess, compared to the high latitude lines of sight, of gas at relatively higher spin temperature at intermediate optical depth range. This is likely to be a small fraction of cold gas at slightly higher temperature and lower density on the Galactic plane. It will be interesting to further explore the origin and properties of this high \( T_k \) gas with future high sensitive measurements of optical depth for low latitude lines of sight passing through the Galactic plane.

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DATA AVAILABILITY

The data used for this study is available from the Leiden/Argentina/Bonn Galactic H \( i \) survey, THOR survey, and the ATCA/GMRT/WSRT H \( i \) absorption survey. The final data products from this study will be shared on reasonable request to the corresponding author.

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