OPTICALLY THICK H I DOMINANT IN THE LOCAL INTERSTELLAR MEDIUM: AN ALTERNATIVE INTERPRETATION TO “DARK GAS”* 

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ABSTRACT
Dark gas in the interstellar medium (ISM) is believed to not be detectable either in CO or H I radio emission, but it is detectable by other means including γ rays, dust emission, and extinction traced outside the Galactic plane at |b| > 5°. In these analyses, the 21 cm H I emission is usually assumed to be completely optically thin. We have reanalyzed the H I emission from the whole sky at |b| > 15° by considering temperature stratification in the ISM inferred from the Planck/IRAS analysis of the dust properties. The results indicate that the H I emission is saturated with an optical depth ranging from 0.5 to 3 for 85% of the local H I gas. This optically thick H I is characterized by spin temperature in the range 10 K–60 K, significantly lower than previously postulated in the literature, whereas such low temperature is consistent with emission/absorption measurements of the cool H I toward radio continuum sources. The distribution and the column density of the H I are consistent with those of the dark gas suggested by γ rays, and it is possible that the dark gas in the Galaxy is dominated by optically thick cold H I gas. This result implies that the average density of H I is 2–2.5 times higher than that derived on the optically thin assumption in the local ISM.

Key words: infrared; ISM – ISM: atoms – ISM: clouds – radio lines: ISM

1. INTRODUCTION

It is important to quantify the constituents of the interstellar medium (ISM), which mainly consists of neutral, molecular, and ionized hydrogen H I, H2, and H II, in order to understand the role of the ISM in galactic evolution. The H I gas has density mainly in a range from 0.01 cm−3 to 100 cm−3, while the CO probes the molecular hydrogen gas at density higher than 1000 cm−3, so the intermediate density regime 100 cm−3–1000 cm−3 may possibly remain unrecognized. It has been discussed that “dark gas” may exist, which is undetectable in radio emission, either in the 21 cm H I or 2.6 mm CO transitions (Grenier et al. 2005; Planck Collaboration et al. 2011). Previous studies suggest that the dark gas probed by γ rays and dust emission has a density regime between the H I and H2 as inferred from its spatial distribution intermediate between H I and CO (Grenier et al. 2005; Planck Collaboration et al. 2011).

The physical properties of the CO emitting molecular gas are relatively well understood due to transitions of its different rotational states and isotopic species, which allow us to derive physical and chemical parameters of the CO gas. On the other hand, the physical parameters of the H I gas are more difficult to estimate, because the H I line intensity is the only measurable quantity for a combination of two unknown parameters, the spin temperature Tσ and optical depth τHI. The 21 cm transition is a transition characterized by the excitation temperature, called spin temperature, between the two spin-flip states in the electronic ground state. The H I consists of warm neutral medium (WNM) and cold neutral medium (CNM; for a review, see Dickey & Lockman 1990; Kalberla & Kerp 2009). The mass of the H I gas is measurable at a reasonably high accuracy under the optically thin approximation, while the cold components having Tσ of ≤80 K may not be easily measurable because of optical depth effects. Only a comparison of the absorption and emission H I profiles toward extragalactic radio continuum sources can be used to estimate Tσ and τHI (Dickey et al. 2003; Heiles & Troland 2003b), so the details of the cold H I are still not fully understood. The existence of optically thick H I in galaxies has been discussed based on line profiles, whereas a quantitative method to evaluate the physical properties has not yet been developed (Braun 2012).

A recent work on the high-latitude molecular clouds MBM 53, 54, 55, and HLCG 92–35 has shown that the H I emission is optically thick in the surroundings of the CO clouds (Fukui et al. 2014, Paper I). These authors compared the Planck/Infrared Astronomical Satellite (IRAS) dust opacity (Planck Collaboration et al. 2014a) with H I and CO, and estimated Tσ to be 20 K–40 K (average is 30 K) and τHI 0.3–5 (average is 2) by assuming that the dust opacity is proportional to the ISM proton column density. They suggest that the H I envelope is massive having more than 10 times the mass of the CO clouds, and that such optically thick H I may explain the origin of the dark gas, an alternative to CO-free H2. It is important to test if the H I shows similar high optical depth in a much larger portion of the sky.

In addition, it is notable that in three TeV γ-ray supernova remnants, RX J1713.7-3946, RX J0852.0-4622, and HESS J1731-347, it is found that spatially extended cold H I gas of Tσ ∼40 K, which has no CO emission, is responsible for the γ rays via the hadronic process between the cosmic ray protons and the interstellar protons (Fukui et al. 2012; Torii et al. 2012; Fukui 2013; Fukuda et al. 2014). The cold H I probably represents the compressed H I shell swept up by the stellar winds of the supernova progenitor. This finding raised independently a possibility that the cold H I gas may be more ubiquitous than previously thought.

It has been difficult to derive Tσ and τHI in general and our knowledge on the cold H I remains ambiguous at best. In order to better understand the relationship between the dust emission and H I over a significant portion of the sky, we have compared
the H\textsc{i} with the dust properties derived from the Planck and IRAS data beyond the area studied by Paper I. This comparison was made by using the H\textsc{i} data set at 33′ resolution from the Leiden/Argentine/Bonn (LAB) archive data and the Planck/IRAS dust properties. We present the results of the detailed comparison. Section 2 presents the observations, Section 3 the results, Section 4 the discussion, and Section 5 our conclusions.

2. OBSERVATIONAL DATA SETS

2.1. Data Sets

In this study, we used the all-sky maps of the dust model data measured by Planck/IRAS, the LAB H\textsc{i} data, the CfA CO data, 1.4 GHz radio continuum data, and H\textalpha data. All the data sets are smoothed to be a HPBW of 33′, which corresponds to the HPBW of the LAB H\textsc{i} data, and are then converted into the Mollweide projection with a grid spacing of 30′.

2.1.1. H\textsc{i} Data

The LAB H\textsc{i} 21 cm survey (Kalberla et al. 2005) is used in this study. It covers the entire sky at an effective angular resolution of 33′ (HPBW). The data is taken from the web page of the LAMBDA project with Healpix format\textsuperscript{4}. The rms noise fluctuations of the H\textsc{i} data are 0.07 K–0.09 K in $T_{mb}$ at 1 km s\textsuperscript{-1} velocity resolution (Kalberla et al. 2005). The effective velocity range of the present analysis is $\sim \pm 10$ km s\textsuperscript{-1} in $v_{LSR}$, where the H\textsc{i} is peaked at around 0 km s\textsuperscript{-1}, while the H\textsc{i} integrated intensity $W_{H\textsc{i}}$ is calculated using a radial velocity, $v_{LSR}$, range from $-150$ km s\textsuperscript{-1} to $+150$ km s\textsuperscript{-1}. More details on the velocity range are given in Section 2.2.

2.1.2. Planck/IRAS Data

Archival data sets of dust optical depth at 353 GHz, $\tau_{353}$, and dust temperature, $T_{\text{d}}$, are used to make comparisons with the H\textsc{i} data, where the 353, 545, and 857 GHz data of the first 15 months of observations with Planck and the 100 $\mu$m data obtained with IRAS are used to derive $\tau_{353}$ and $T_{\text{d}}$ (see Planck Collaboration et al. 2014\textsuperscript{a}, for details). Here we utilize version R1.20 of the Planck maps.

2.1.3. CO Data

We use the integrated intensity $^{12}$CO $J$ = 1–0 map over the full observed velocity range by Dame et al. (2001) as a molecular gas tracer. The HPBW is 8.7′, and the rms noise fluctuations are 0.1 K–0.35 K at 1.3 km s\textsuperscript{-1} velocity resolution (Dame et al. 2001). The data are also taken from the LAMBDA project page.

2.1.4. Background 21 cm Continuum Data

The 21 cm continuum emission is used as background emission of H\textsc{i}. We use the CHIPASS 21 cm radio continuum map with a sensitivity of $\sim$40 mK (Calabretta et al. 2014) for the southern sky and the Stockert 21 cm radio continuum map with a sensitivity of $\sim$50 mK (Reich & Reich 1986) for the northern sky. The original HPBWs are 14′/4 and 35′, respectively. This continuum emission includes the cosmic microwave background emission.

2.1.5. H\textalpha Data

In order to mask the region where dust is locally heated or destroyed by ultraviolet (UV) radiation, we use the all-sky H\textalpha data provided by Finkbeiner (2003). The angular resolution is 6′. Typical uncertainties in each pixel is estimated to be 0.3–1.3 Rayleigh for $|b| > 15^\circ$ and 1–5 Rayleigh for $|b| \leq 15^\circ$.

2.2. Masking

Figure 1 shows the distribution of $\tau_{353}$, which includes mainly local clouds like Taurus, Lupus, Aquila, Polaris flare, and Chameleon within 200 pc of the Sun. A correlation analysis between dust and gas must be done toward a single component of the ISM and regions that do not overlap along the line of sight are chosen for comparison. Otherwise, regions of different physical properties will be mixed up, reducing the correlation among the physical parameters. It is also important to avoid contamination so that local irradiation by high-mass stars does

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\textsuperscript{3} http://lambda.gsfc.nasa.gov
\textsuperscript{4} http://healpix.jpl.nasa.gov

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Figure 1. All-sky Mollweide projections of $\tau_{353}$ distribution in the galactic coordinate. The center of the map is $(l, b) = (0^\circ, 0^\circ)$, and the coverage of $l$ and $b$ is from $-180^\circ$ to $+180^\circ$ and from $-90^\circ$ to $+90^\circ$, respectively. Dashed lines are plotted every 60′ in $l$ and every 30′ in $b$. The masked region used in the present analysis is shown by shading.
not significantly affect the dust emission. Considering these, we selected the region for the present analysis according to the following five criteria.

1. The Galactic latitude $|b|$ is higher than 15° in order to eliminate contamination by different components in the Galactic plane along the line of sight. At intermediate latitudes, the assumption that the ISM emission in any given direction is dominated by a single structure (cloud or cloud complex) is a valid approximation over most of the sky. This approximation ignores the very diffuse gas (inter-cloud medium) that is present at some level in all directions. At high latitudes the diffuse gas (neutral and ionized) is sometimes the only form of interstellar matter on the line of sight, with column density below about $10^{18}$ cm$^{-2}$.

2. Extragalactic objects such as the Large Magellanic Cloud, Small Magellanic Cloud, and M 31 are removed from the present analysis. The points where the H$\alpha$ integrated intensities $W_{\alpha}$ at $|v_{\text{LSR}}| > 100$ km s$^{-1}$ are larger than 10% of those at $|v_{\text{LSR}}| < 70$ km s$^{-1}$ are masked. In addition, the low-velocity component of the Magellanic stream seen at $l \sim -60^\circ$ to $+60^\circ$ and $b < -60^\circ$ is masked by hand using the integrated intensity map at $|v_{\text{LSR}}| < 70$ km s$^{-1}$ to show a continuous distribution with the components seen at $|v_{\text{LSR}}| > 70$ km s$^{-1}$.

3. As seen in the H$\alpha$ longitude-velocity map in Figure 2(a), the H$\alpha$ components are concentrated around $|v_{\text{LSR}}| < 30$ km s$^{-1}$. We thus remove the points that have H$\alpha$ emission from $-70$ km s$^{-1}$ to $-35$ km s$^{-1}$; those are identified as the intermediate velocity clouds mainly distributed at $60^\circ < b < 80^\circ$ (Planck Collaboration et al. 2011, 2014a). The points where $W_{\alpha}$ are larger than 50 K km s$^{-1}$ at $35$ km s$^{-1} < |v_{\text{LSR}}| < 70$ km s$^{-1}$ are masked.

4. In order to eliminate locally heated components, the H$\alpha$ emission is restricted to be weaker than 5 Rayleigh (Finkbeiner 2003). This eliminates the dust in ionized regions (e.g., in Orion A, the Ophiuchus region, etc.), where the dust may be destroyed or heated by the UV photons, causing an anomalous dust to gas ratio and dust temperature.

5. CO gas has a different physical environment with higher density. Regions with detectable CO emission with integrated intensities of larger than 1 K km s$^{-1}$ are excluded by using the CO data provided by Dame et al. (2001). Individual regions of CO gas not included in the present study will be dealt with in detail at higher resolution in separate papers.

The entire masked region is shown in Figure 1, and Figure 2(a) shows the longitude-velocity map after masking by criteria 1, 2, 4, and 5. Figure 2(b) by all the criteria including the criterion 3. Figure 3 also shows the histograms of the peak velocities and velocity dispersions, $\sigma_v$, for the resulting H$\alpha$ data. The present analysis substantially excludes, by masking, components that are broad and separated by more than 35 km s$^{-1}$ from the main H$\alpha$ emission at around 0 km s$^{-1}$ (Figure 3). The fraction of $W_{\alpha}$ of $v_{\text{LSR}}$ between $-9$ km s$^{-1}$ and $+6$ km s$^{-1}$ accounts for 86% (Figure 3(a)) and that having $\sigma_v$ less than 10 km s$^{-1}$ is 81% (Figure 3(b)), while we otherwise estimate $W_{\alpha}$ by using a $v_{\text{LSR}}$ range from $-150$ km s$^{-1}$ to $+150$ km s$^{-1}$.

The main H$\alpha$ component corresponds to velocities showing CNM in general. On the other hand, the major part of the WNM has large line width of more than 20 km s$^{-1}$ and a peak velocity often shifted by more than 10 km s$^{-1}$ from the main H$\alpha$ peak (Heiles & Troland 2003a). A single $T_e$ for the present substantially narrow velocity range is a reasonable assumption as a first-order approximation, and is consistent with the results in the high-latitude clouds (Paper I).

3. RESULTS

3.1. $\tau_{353}$ Versus $N_{\alpha}$

Figure 4(a) shows a scatter plot between $W_{\alpha}$ and $\tau_{353}$ for the entire region analyzed. This plot has a correlation coefficient of 0.79. In the same manner in Paper I, in order to see the
due to the optical depth effect causes weaker \( W \) is moderately optically thick in general and that the saturation the same argument as in Paper I, we expect that the \( H \) density (1) (2) (3) (4) (5) fitting results. (5): correlation coefficients for the plot. dependence on dust temperature \( T_d \), we colored the data points in a window of 0.5 K in \( T_d \) every 1 K in Figures 4(b) and (c). We see clearly that points for each \( T_d \) show better correlation with a correlation coefficient higher than 0.9. We obtained best-fit straight regression lines by least-squares fitting (Table 1). Here, for the ranges 22.0 K \( \leq T_d \) \( < 22.5 \) K and 22.5 K \( \leq T_d \), the number of points is less than for the other ranges, and we thus assume that the intercept is zero and make fits only for slopes. The regression shows a trend that the slope of \( W_{\text{H}_i} \) with respect to \( T_{353} \) becomes smaller systematically with decreasing \( T_d \). This trend is similar to what is found in the case of high-latitude clouds (Paper I). Recent studies by the Planck Collaboration have also found that \( T_d \) increases with decreasing gas column density (Planck Collaboration et al. 2014a, 2014b). By following the same argument as in Paper I, we expect that the \( H \) emission is moderately optically thick in general and that the saturation due to the optical depth effect causes weaker \( W_{\text{H}_i} \) for lower \( T_d \) and higher \( T_{353} \). The optically thin limit is seen only for the highest \( T_d \), and the rest of the points with lower \( T_d \) and shallower slopes suffer from saturation in \( H \) intensity. We apply the optically thin relationship in Equation (1) in order to convert \( W_{\text{H}_i} \) into the \( H \) column density under the optically thin approximation \( N_{\text{H}_i}^* \),

\[
N_{\text{H}_i}^*[\text{cm}^{-2}] = 1.823 \times 10^{18} \cdot W_{\text{H}_i}[\text{K km s}^{-1}].
\]  

With the optically thin points at 22.5 K \( \leq T_d \) in Figures 4(b) and (c), we obtain a relationship between \( W_{\text{H}_i} \) and \( T_{353} \)

\[
W_{\text{H}_i}[\text{K km s}^{-1}] = k \cdot T_{353},
\]

where \( k = 1.15 \times 10^8 \text{ K km s}^{-1} \) is a constant. This relation will hold for any optically thin values of \( T_{353} \), even if the \( H \) emission is not optically thin, as long as the dust properties are uniform with no significant spatial variation. We tested the variation of \( k \) as a function of \( b \) and find that the peak-to-peak dispersion of \( k \) is less than 10% for \( |b| = 50^\circ - 90^\circ \). Finally, using Equations (1) and (2), we can convert \( T_{353} \) into the \( H \) column density, \( N_{\text{H}_i} \), using the following equation,

\[
\frac{N_{\text{H}_i}[\text{cm}^{-2}]}{N_0} = \frac{T_{353}}{T_0},
\]

where \( N_0 = 1 \times 10^{21} \text{ cm}^{-2} \) and \( T_0 = 4.77 \times 10^{-6} \) are typical values for intermediate latitude lines of sight (see Section 3.2 and Figure 9 below).

3.2. Temperature-dependent Analysis of \( H \text{ } \) 

The above results suggest that the \( H \) emission is partially saturated due to the optical depth effect for lower temperatures and the degree of saturation depends on the spin temperature, \( T_s \), of the \( H \) in a way similar to the high-latitude clouds (Paper I). \( W_{\text{H}_i} \) is expressed by a radiation transfer equation

\[
W_{\text{H}_i}[\text{K km s}^{-1}] = (T_s[K] - T_{bg}[K]) \cdot \Delta V_{\text{H}_i}[\text{K km s}^{-1}] \cdot [1 - \exp(-\tau_{\text{H}_i})].
\]

where \( T_s \) is assumed to be uniform on the line of sight, \( T_{bg} \) is the background radio continuum radiation, and \( \Delta V_{\text{H}_i} \) is the \( H \)  

![Figure 3](image-url) Intensity-weighted histograms of (a) the peak velocity and (b) \( \sigma_v \) for the \( H \) emission shown in Figure 2(b). The shaded areas in (a) and (b) show the velocity ranges that account for 86% and 81% of \( W_{\text{H}_i} \), respectively.

| \( T_d \) (K) | \( N_{\text{pixel}} \) | Slope (K km s\(^{-1}\)) | Intercept (K km s\(^{-1}\)) | C.C. |
|---|---|---|---|---|
| <18.5 | 9446 | 3.5 \times 10^7 | 67.6 | 0.80 |
| 18.5–19.0 | 8327 | 5.1 \times 10^7 | 27.9 | 0.85 |
| 19.0–19.5 | 12692 | 5.7 \times 10^7 | 22.3 | 0.92 |
| 19.5–20.0 | 17233 | 6.4 \times 10^7 | 13.8 | 0.93 |
| 20.0–20.5 | 17764 | 7.0 \times 10^7 | 7.3 | 0.94 |
| 20.5–21.0 | 11299 | 7.7 \times 10^7 | 4.1 | 0.94 |
| 21.0–21.5 | 5607 | 8.7 \times 10^7 | −1.3 | 0.93 |
| 21.5–22.0 | 3278 | 12.5 \times 10^7 | −14.3 | 0.88 |
| 22.0–22.5° | 1693 | 10.2 \times 10^7 | ... | 0.77 |
| 22.5 ≤ | 3278 | 11.5 \times 10^7 | ... | 0.70 |

Notes: Columns (1): \( T_d \) range. (2): number of pixels used for the fitting. (3) and (4): fitting results. (5): correlation coefficients for the plot.

*a* Represents the ranges in which the intercept is fixed to be zero.
line width ($\Delta V_{HI} = W_{HI}/T_{peak}$ for single-component spectra, where $T_{peak}$ is the peak temperature of the H$^i$ emission at each point). Equation (4) makes the assumption that all the H$^i$ in each velocity channel is at a single temperature, and $\tau_{HI}$ is the average in $\Delta V_{HI}$.

By assuming that $\tau_{353}$ is solely ascribed to the dust in the H$^i$ gas, we are able to estimate $T_d$ and $\tau_{HI}$. This assumption needs to be examined because molecular hydrogen with no detectable CO may account for some fraction of the total column density, $N_{HI}$, at space density, $n_{HI}$, above 100 cm$^{-3}$. It is also worth considering whether the spatial variation of dust properties may offer an alternative explanation. We shall discuss these possibilities later in Section 4.

Under the present assumption, $\tau_{353}$ is converted into $N_{HI}$ by Equation (3) or $N_{HI} \ [cm^{-2}] = 2.1 \times 10^{26} \cdot \tau_{353}$, and $W_{HI}$ into the H$^i$ column density under the optically thin approximation $N_{HI}^*$ by Equation (2). $N_{HI}^*$ gives an underestimate of the actual $N_{HI}$ if the H$^i$ emission is not optically thin, and the ratio $N_{HI}/N_{HI}^*$ is given as

$$N_{HI}/N_{HI}^* = \tau_{HI}/[1 - \exp(-\tau_{HI})], \quad (5)$$

where $\tau_{HI}$ is given by the following equation, which is valid for any positive optical depth;

$$\tau_{HI} = \frac{N_{HI} \ [K \ km \ s^{-1}]}{1.823 \times 10^{18} \cdot T_d \ [K]} \cdot \frac{1}{\Delta V_{HI} \ [km \ s^{-1}]} \cdot \frac{1}{\Delta V_{HI} \ [km \ s^{-1}]} \cdot (6)$$

Figure 5 shows a curve of Equation (5).

Along with the assumption that there is only one cloud structure that dominates the emission by dust and gas on any given line of sight, we further assume that there is a single $T_d$ for the H$^i$ gas in this structure. Relaxing this assumption to include warm and cool gas phases associated with the cloud would make Equations (4) and (6) more complicated and introduce more unknown quantities into the analysis. For the present paper, we keep the analysis simple by assuming that a single spin temperature dominates the H$^i$ on each line of sight. We here solve the two coupled Equations (4) and (6) to estimate $T_d$ and $\tau_{HI}$. Note that these two equations are independent as long as $\tau_{HI}$ is finite, although they become essentially a single equation in the optically thin limit. Discussion of optically thick H$^i$ is also found in the literature (Strasser & Taylor 2004; Dickey 2013). Examples for $T_d$ and $\tau_{HI}$ determination are shown in Figure 6, with the results summarized in Table 2. Figure 7 shows the distributions of $T_d$, $\tau_{HI}$, and $N_{HI}$ colored by their fractional errors. Here we estimate the error in $T_d$ and $\tau_{HI}$ as shown by thick lines in Figure 6 from the 1$\sigma$ uncertainties of $\tau_{353}$ and $W_{HI}$. The error in $N_{HI}$ is also calculated using Equation (3) from the error in $\tau_{353}$. It is
shown that the method cannot be applied with high accuracy when \( \tau_{\text{HI}} \) is smaller than \( \sim 0.2 \) because of the degeneracy of Equations (4) and (6). We therefore excluded the regions where \( \tau_{\text{HI}} \) is smaller than 0.2. Figure 7(c) indicates that \( N_{\text{HI}} \) is accurately determined within \( \pm 5\% \), while the errors in \( T_s \) and \( \tau_{\text{HI}} \) are not always small.

The spatial distributions of the derived \( T_s \), \( \tau_{\text{HI}} \), and \( N_{\text{HI}} \) are shown in Figure 8, and Figure 9 shows histograms of these three parameters. In Figures 8(a) and (b), the points with \( \tau_{\text{HI}} < 0.2 \) are shown in white, and we use \( N_{\text{HI}}^* \) instead of \( N_{\text{HI}} \) for these points in Figure 8(c), while these points are not included in Figure 9. The mass ratio of the points with \( \tau_{\text{HI}} < 0.2 \) to all the data points is only 3%. As seen in Figure 9, \( \tau_{\text{HI}} \) ranges from 0.5 to 3.0 for 85\% of the total \( \text{H}_1 \) gas, where the \( \text{H}_1 \) gas with \( \tau_{\text{HI}} \) larger than 0.5, accounts for 91\%. On the other hand, \( T_s \) ranges from 15 K to 35 K for 78\% and \( T_s \) is less than 35 K for 84\%. \( N_{\text{HI}} \) ranges from \( 5 \times 10^{20} \) cm\(^{-2} \) to \( 3 \times 10^{21} \) cm\(^{-2} \) for 73\%, where the peak is seen at \( 10^{21} \) cm\(^{-2} \).
There has been discussion that $T_s$ is generally higher than 80 K, with 130 K as the nominal value in the literature (e.g., Mohan et al. 2004). On the other hand, Dickey et al. (2003) and Heiles & Troland (2003b) showed that there exists cold H I gas (CNM) having $T_s$ of 20 K–50 K from H I emission/absorption profiles toward radio continuum background sources. This $T_s$ range is consistent with the current $T_s$ distribution.

The observed $W_{HI}$ as a function of the computed $N_{HI}$ from Equation (3) with colors showing the value of $T_s = 10$ K–100 K is shown in Figure 10. Generally, $W_{HI}$ begins to saturate at H I optical depth around 0.3. For lower $T_s$, saturation begins at lower $N_{HI}$, and for higher $T_s$ the correlation between $W_{HI}$ and $N_{HI}$ becomes better than for lower $T_s$. Since both $T_s$ and $T_d$ are determined by radiative heating and cooling (see Section 4 in Paper I), the qualitative trend of the $T_d$ dependence of $W_{HI}$ should be consistent with that found in Figure 4.

We shall estimate the total ISM mass in the solar vicinity in the unmasked area. The H I masses with optical depth correction and that without correction are $1.0 \times 10^6 M_\odot$ and $0.5 \times 10^6 M_\odot$, respectively, for an assumed distance of 150 pc (Paper I). This

Figure 8. All-sky distributions of the (a) $T_s$ and (b) $\tau_{HI}$ maps. The masked region is shown in gray. The black dots represent the region where $T_d > 22.5$ K. The white dots show the points where $T_s$ and $\tau_{HI}$ are not determined because $\tau_{HI} < 0.2$. In (c) we use $N_{HI}^*$ instead of $N_{HI}$ for the points colored in white or black in (a) and (b). The center of the map is ($l, b$) = (0°, 0°), and the coverage of $l$ and $b$ is from $-180°$ to $+180°$ and from $-90°$ to $+90°$, respectively. Dashed lines are plotted every $60°$ in $l$ and every $30°$ in $b$. 

- Figure 8.
Figure 9. Histograms of (a) $T_s$, (b) $\tau_{HI}$, and (c) $T_d$ weighted by $HI$ mass, where distance is assumed to be 150 pc. The gray area in (a) indicates the lower limit of $\tau_{HI}$. The area filled in pink in each panel is defined to contain about 70%–80% of the all points.

Table 2

| Region | $l$ | $b$ | $\tau_{353}$ | $T_d$ | $W_{HI}$ | $N_{HI}$ | $\tau_{HI}$ | $T_s$ |
|--------|----|----|------------|-----|---------|---------|----------|-----|
| (1)    | (2) | (3) | (4)         | (5) | (6)     | (7)     | (8)      | (9) |
| a      | 15.6 | 45.6 | 2.4       | 20.6 | 179.3   | 5.1     | 0.64$^{+0.08}_{-0.08}$ | 21$^{+2}_{-2}$ |
| b      | 102.4 | -64.5 | 1.8     | 20.5 | 180.8   | 3.9     | 0.25$^{+0.11}_{-0.11}$ | 54$^{+12}_{-12}$ |
| c      | 121.1 | -65.7 | 2.3     | 20.3 | 197.5   | 4.7     | 0.40$^{+0.08}_{-0.08}$ | 36$^{+7}_{-5}$ |
| d      | 162.6 | -56.3 | 1.7     | 21.2 | 146.1   | 3.7     | 0.43$^{+0.07}_{-0.07}$ | 25$^{+4}_{-4}$ |
| e      | 173.2 | -29.3 | 2.7     | 17.7 | 930.0   | 5.7     | 3.06$^{+0.12}_{-0.12}$ | 69$^{+1}_{-1}$ |
| f      | 183.4 | 17.7  | 5.1     | 19.8 | 375.4   | 6.3     | 0.23$^{+0.06}_{-0.06}$ | 69$^{+23}_{-13}$ |
| g      | 252.7 | 27.4  | 3.3     | 21.0 | 250.1   | 6.8     | 0.64$^{+0.06}_{-0.06}$ | 28$^{+2}_{-2}$ |
| h      | 323.5 | 16.3  | 6.8     | 20.4 | 386.7   | 14.3    | 1.25$^{+0.10}_{-0.11}$ | 20$^{+1}_{-1}$ |

Notes. Columns (1): name of region. (2) and (3): position in the Galactic coordinate. (4)–(6): $\tau_{353}$, $T_d$ and $W_{HI}$ of the target region. (7): $HI$ column density without optically thin assumption. (8) and (9): derived $\tau_{HI}$ and $T_s$ with errors.

implies the mass increase due to the optical depth correction amounts to $0.5 \times 10^6 M_\odot$, or a factor of $\sim 2.0$, similar to the high-latitude clouds in Paper I. We also estimate the total ISM mass for the entire sky including the masked area by extrapolating $\tau_{353}$ and $W_{HI}$. In Figure 11, we show the latitude distribution of $\tau_{353}$ and $W_{HI}$ averaged in Galactic longitude, where the two curves, dashed and solid lines, indicate the entire areas with and without masking, respectively. We fit the data by tentatively assuming a Lorentzian function as shown in Figure 11 to estimate the mass in the masked area. The estimated total masses with $N_{HI}$ and $N_{HI}^*$ are $2.9 \times 10^6 M_\odot$ and $1.2 \times 10^6 M_\odot$, respectively, suggesting the optical depth correction amounts of $1.7 \times 10^6 M_\odot$, or a factor of 2.5.

4. DISCUSSION: UBIQUITOUS OPTICALLY THICK H$_1$, AN ALTERNATIVE EXPLANATION FOR THE DARK GAS

The optically thick H$_1$ gas has been identified in the region of MBM 53, 54, 55, and HLCG 92–35, and the CO clouds are enveloped by massive H$_1$ gas having more than 10 times...
greater mass than the CO clouds (Paper I). The present study has shown that optically thick H\textsc{i} is common in interstellar space within 200 pc of the Sun. The typical parameters of the H\textsc{i} gas (≥70% of the total) are summarized as follows: $T_s = 15\text{ K} - 35\text{ K}$, $\tau_{\text{HI}} = 0.5 - 3.0$, and $N_{\text{HI}} = 5 \times 10^{20}\text{ cm}^{-2} - 3 \times 10^{21}\text{ cm}^{-2}$ (Figure 9). If we tentatively assume a typical line-of-sight depth of 5 pc for the cold H\textsc{i}, the average density is estimated to be $30\text{ cm}^{-3} - 190\text{ cm}^{-3}$. The ratio of the actual H\textsc{i} column density $N_{\text{HI}}$ to that obtained under the optically thin approximation $N_{\text{HI}}^\ast$ is estimated to be 2.0 over the region analyzed. The high density and low temperature of the cold H\textsc{i} gas are consistent with the temperature estimates in a model spherical cloud with the density range concerned, which is heated by the interstellar radiation field and cooled by the atomic lines including C\textsc{ii} (Goldsmith et al. 2007).

Grenier et al. (2005) presented the dark gas based on $\gamma$ ray observations by EGRET, which is not “detectable” either by H\textsc{i} or CO emission. Subsequently, Planck Collaboration et al. (2011) discussed that the dust emission includes the dark gas component which has a similar distribution to the excess $\gamma$ rays. Dark gas is also seen in visual extinction (Paradis et al. 2012). According to these studies, the distribution of the dark gas is largely similar to the CO gas, but it is spatially extended beyond the limit of CO detection. Its correlation with the H\textsc{i} gas distribution did not seem to be strong in these previous studies that assumed optically thin H\textsc{i}. The present analysis has shown that the H\textsc{i} gas is dominated by an optically thick component. The typical H\textsc{i} column density derived for the optically thick case, $\sim 10^{21}\text{ cm}^{-2}$, is consistent with that of the dark gas (Grenier et al. 2005). Figures 12 and 13 show $N_{\text{HI}} - N_{\text{HI}}^\ast$ and $N_{\text{HI}}/N_{\text{HI}}^\ast$ at 33’ resolution over the entire sky. These distributions are fairly similar to the dark gas distribution presented in Grenier et al. (2005) and Planck Collaboration et al. (2011). More quantitative comparison between the optically thick H\textsc{i} and $\gamma$ rays is a subject of a forthcoming paper.

For more detail, in Figure 14 we show the scatter plot between $N_{\text{HI}}$ and $T_{353}$, similar to Figure 6 in Planck Collaboration et al. (2011). Figures 14(a)–(c) show the relationship between $T_{353}$ and $N_{\text{HI}}^\ast$ with colors indicating the dependence of the relationship on $T_{\text{HI}}$, $T_s$, and $T_d$, respectively. These figures indicate that the apparent scatter in the plot reflects the difference in temperature ($T_d$ or $T_s$) or $T_{\text{HI}}$, and that the actual scatter is much smaller than that in the $N_{\text{HI}} - T_{353}$ correlation (Figure 14). According to the present analysis, $T_{\text{HI}}$ takes maximum values of around 6–7 at $N_{\text{HI}}^\ast \sim 10^{21}\text{ cm}^{-2}$ or $W_{\text{HI}} \sim 550\text{ K km s}^{-1}$, and this optical depth effect causes the apparent bump at $N_{\text{HI}}^\ast = 4 \times 10^{20}\text{ cm}^{-2} - 2 \times 10^{21}\text{ cm}^{-2}$ with a maximum at $N_{\text{HI}}^\ast \sim 9 \times 10^{20}\text{ cm}^{-2}$, as seen in Figure 14. The bump in the scatter plot is then interpreted in terms of the optical depth effect but not by the enhanced dispersion in the plot. We note that the bump is a natural outcome of the saturation effect in the

**Figure 10.** Correlation plot between $W_{\text{HI}}$ and $N_{\text{HI}}$. Color represents $T_s$ of each point. The dashed red lines and the dashed blue lines indicate $W_{\text{HI}}$ derived with Equations (4) and (6) for $T_s = 10\text{ K} - 100\text{ K}$ and for $T_{\text{HI}}$, 0.3, 1.0, 2.0, and 3.0, respectively. Here $\Delta V$ in Equations (4) and (6) is uniformly assumed to be $15\text{ km s}^{-1}$.

**Figure 11.** Curves of averaged (a) $T_{353}$ and (b) $W_{\text{HI}}$ along the Galactic latitude with mask (black solid line) and without mask (black dotted line). Vertical dashed lines indicate $|b| = 15\degree$. Red lines show the results of fitting with a Lorenzian function for the masked data. Half widths of the resulting curves are 28:8 and 36:1 for $T_{353}$ and $W_{\text{HI}}$, respectively.
optically thick H\textsc{i} with no ad-hoc assumption, whereas it was ascribed to the property of the unknown dark gas in the previous interpretation (Planck Collaboration et al. 2011). Figure 15 shows the correlation between the optical-depth-corrected H\textsc{i} column density $N_{\text{HI}}$ and $\tau_{353}$. Naturally, the scatter is small, on the order of 10% at maximum in Figure 14(c). We consider that Figure 15 shows the real correlation with much smaller errors between $N_{\text{HI}}$ and $\tau_{353}$.
Figure 14. Scatter plots between $N_{\text{HI}}^*$ and $\tau_{353}$. Color represents $\tau_{\text{HI}}$, $T_s$, and $T_d$ in panels (a), (b), and (c), respectively. The dashed lines indicate the relations for $k = 1.15 \times 10^8 \text{K km s}^{-1}$ and $1.5 \times 10^8 \text{K km s}^{-1}$.

In Figure 14(c), we find that the points below the optically thin limit in a range of $N_{\text{HI}}^*$ of $7 \times 10^{19} \text{cm}^{-2}$–$5 \times 10^{20} \text{cm}^{-2}$ are outside the regime where the present method has a solution. Most of these points are located at very high Galactic latitude higher than $60^\circ$ as shown by black dots in Figures 8(a) and (b), where $\tau_{353}$ in the sky is very low (like $10^{-6}$), and are characterized by the highest $T_d$ of larger than 23 K; a typical point has $W_{\text{HI}} \sim 80 \text{K km s}^{-1}$ and $\tau_{353} \sim 7 \times 10^{-7}$. We suggest that the coefficient $k$ around $10^8 \text{K km s}^{-1}$ in Equation (2) is larger in the higher $b$ (greater than $60^\circ$) than in the lower $b$ (less than $60^\circ$). If we adopt $k = 1.5 \times 10^8 \text{K km s}^{-1}$, for instance, 99.7% of all the data points are explained in the present scheme (Figure 14). This condition will be fulfilled if the dust optical depth is smaller by $\sim 30\%$ at such a low column density. Such a trend is qualitatively consistent with smaller dust grains in the extremely low column density condition and is worth further study.

In order to evaluate the effect of the dust opacity which may depend on hydrogen column density, we shall test the following Equation (7) instead of Equation (3):

$$
\left( \frac{N_{\text{HI}} \text{[cm}^{-2}\]}{N_0} \right)^{1.28} = \frac{\tau_{353}}{\tau_0}. 
$$

Figure 15. Correlation between $N_{\text{HI}}$ and $\tau_{353}$ is shown by the thick line, where $N_{\text{HI}} = 2.1 \times 10^{26} \text{cm}^{-2}$. Representative values of the $\tau_{353}$ error are also plotted by bars. The area colored in light blue shows variation of the correlation provided by Equation (7) (see Section 4 for details). Histograms show $N_{\text{HI}}$ weighted by the $\text{H}_1$ mass at various $T_d$: black ($T_d < 18 \text{K}$), blue ($18 \text{K} \leq T_d < 19 \text{K}$), green ($19 \text{K} \leq T_d < 20 \text{K}$), yellow ($20 \text{K} \leq T_d < 21 \text{K}$), and red ($21 \text{K} \leq T_d$). Gray includes all points. Here vertical dashed lines indicate the range of typical $N_{\text{HI}}$ defined in Figure 9(c).
This relation is derived by assuming the dependence of sub-millimeter dust optical depth, which is proportional to $N_{\text{H}_1}^{0.28}$ for the total hydrogen column density $N_{\text{H}_1}$ above $10^{22}$ cm$^{-2}$ in Orion A (Roy et al. 2013). A trend of dust opacity evolution with column density is also recognized for clouds with column density of $(3–7) \times 10^{21}$ cm$^{-2}$ in the Vela Molecular Ridge (Martin et al. 2012) and in the Taurus filaments (Ysard et al. 2013). We made the same analysis of the cold H$^i$ by using Equation (7) instead of Equation (3) and have naturally found similar results to those above with some minor changes of physical quantities. Equation (7) can alter the $N_{\text{H}_1}$ by $-20\%$ to $+30\%$ at a typical range $5 \times 10^{20}$ cm$^{-2}$ to $3 \times 10^{21}$ cm$^{-2}$ as compared with the uniform dust opacity assumption, and the increase of the total H$^i$ mass due to the H$^i$ optical depth effect becomes slightly less by a factor of 2.1 instead of 2.0 for the unmasked area and 2.2 instead of 2.5 for the entire sky, including the masked area (see Section 3.2). Thus, it is not necessary to make a substantial change in the parameters of the cold H$^i$, even when the possibility of non-uniform dust opacity is taken into account. Equation (7) also suggests that the dust opacity variation is not the major cause of the observed poor correlation in Figure 4(a). If the dust opacity variation is assumed to be substantial, the dust cross section must be increased to more than 300\% for $\tau_{\text{H}_1} = 3$, which is not consistent with Equation (7).

The present analysis has shown that cold H$^i$ is a viable interpretation of the dark gas. It, however, does not exclude the possibility that H$_2$ is dominant instead of H$^i$ in the dark gas. In order to explain the dark gas origin, a possibility of molecular hydrogen with no CO emission has been discussed (e.g., Planck Collaboration et al. 2011). We here make a comparison with the results of direct UV absorption measurements of H$_2$ by FUSE and Copernicus (Gillmon et al. 2006; Rachford et al. 2002, 2009). They observed about 80 lines of sight toward active galactic nuclei and Galactic OB stars, and 21 of them are included in the present analysis. The 21 sources are taken from Gillmon et al. (2006) and Rachford et al. (2002), and are summarized in Table 3. The H$_2$ abundance ratio is estimated by these authors as

$$f_{H_2} = \frac{2N_{H_2}}{2N_{H_1} + N_{H_1}}.$$  \hspace{1cm} (8)

where $N_{H_1}$ is the column density of H$_2$, and $N_{H_1}$ is the H$_1$ column density. Note that the $N_{H_1}$ in Table 3 is derived under optically thin approximation measured with the 21 cm observations taken with multiple telescopes but not by the UV observations, except for HD 102065 whose H$_1$ column density was measured with $E(B-V)$. The beam sizes (HPBWs) of the 21 cm observations were $9.7'–35'$, as listed in Table 3. To make correction for the H$_1$ optical depth, we replaced $N_{H_1}^*$ in Equation (8) by the present $N_{H_1}$ as

$$f_{H_2} = \frac{2N_{H_2}}{2N_{H_1} + N_{H_1}}.$$  \hspace{1cm} (9)

$f_{H_1}$ at each point is typically reduced by 30%--80% from those in Gillmon et al. (2006) and Rachford et al. (2002), and the results are shown in Figure 16 and in Table 3. Figure 16 shows that molecular hydrogen is typically only $10^{-2}–10^{-1}$ or less of the total in the column density regime, $N_{H_1} \leq 1 \times 10^{21}$ cm$^{-2}$, whereas there are only a few observations for $N_{H_1} > 10^{21}$ cm$^{-2}$.

It is worthwhile to note that the minimum H$_1$ column density is calculated from the H$_1$ integrated intensity $W_{H_1}$ for the optically thin limit and is used to constrain the maximum $f_{H_2}$ by assuming that Equation (3) holds for H$_2$. For instance, at a data point having $W_{H_1} = 280$ K km s$^{-1}$ and $\tau_{353} = 5.0 \times 10^{-6}$ in Figure 4 the minimum $N_{H_1}$ is calculated to be $5.1 \times 10^{20}$ cm$^{-2}$ by Equation (1). This H$_1$ column density corresponds to $\tau_{353} = 2.4 \times 10^{-6}$ and the remaining $\tau_{353} = 2.6 \times 10^{-5}$ gives the possible contribution of H$_2$ at maximum when only neutral hydrogen either atomic or molecular forms are considered. The upper limit for $f_{H_1}$, $f_{H_2}$ (upper limit) is then calculated to be 0.52. In this way, we have calculated $f_{H_2}$ (upper limit) as a function of $\tau_{353}$ as shown in Figure 17. This provides a secure upper limit for $f_{H_1}$, because a mixture of H$_1$ and H$_2$ is more natural in the transition region between them, making the real $f_{H_1}$ smaller than shown in Figure 17. Figure 17 shows $f_{H_1}$ (upper limit) is
the timescale of $H_2$ formation is considerably larger than the timescale of the local ISM as described below. We shall here discuss theoretical aspects of the $H_2$ formation. It may be worthwhile to remark that Clark et al. 's paper presents "CO-free $H_2$", but their results actually show that $H_2$ is a minor component, corresponding to only $\sim 0.1$ of $H_1$ in mass (see their Figure 6). These results suggest that $H_2$ may not be the dominant form of neutral hydrogen, while direct observations of $H_2$ to confirm this trend are not yet made at $N_{HI}$ larger than $10^{21}$ cm$^{-2}$.

The dark gas in the Milky Way is observationally identified in the local space outside the Galactic plane where the line of sight contamination is not significant (Grenier et al. 2005; Planck Collaboration et al. 2011). Therefore, the dark gas in the Milky Way is distributed within $\sim 200$ pc of the Sun in the Galactic latitude higher than $5^\circ$. Wolfire et al. (2010) presented numerical simulations of a giant molecular cloud with a lower density envelope and argued that a $H_2$ layer without CO surrounding a CO cloud may be significant in mass, providing a possible origin of the dark gas. The cloud size of a giant molecular cloud in Wolfire et al. (2010) is much larger than that of the local clouds, and the timescale for a giant molecular cloud is as large as a few 10 Myr (Fukui et al. 1999; Kawamura et al. 2009; Fukui & Kawamura 2010). These model simulations therefore do not apply to the local ISM having a much smaller timescale where the dark gas is identified. Recent Herschel observations of C$^+$ toward the disk clouds at $|b|$ less than $1^\circ$ suggest that CO-free $H_2$ gas may be dominant in the disk outside the nearby

typically $\sim 0.5$, and the upper limit for the mass ratio of $H_2$ to $H_1$ is 58% in $N_{HI} = 10^{20}$ cm$^{-2}$−$10^{22}$ cm$^{-2}$. For $N_{HI} < 1 \times 10^{21}$ cm$^{-2}$ ($A_V < 0.5$ mag), $f_{H_2}$(upper limit) is mostly less than 0.5 and the upper limit for the mass ratio of $H_2$ to $H_1$ is estimated to be 48% on average. As such, $H_2$ is nearly equal to or less than $H_1$ in this regime with low extinction of $A_V < 0.5$ mag. This is consistent with Figure 16, which indicates that $f_{H_2}$ is less than $10^{-2}$−$10^{-1}$. On the other hand, for $N_{HI} > 1 \times 10^{21}$ cm$^{-2}$ ($A_V > 0.5$ mag) $f_{H_2}$(upper limit) is 0.6 on average, suggesting that $H_2$ may dominate $H_1$, whereas $H_1$ is still significant at a level of at least 10% of the total hydrogen. The upper limit for the mass ratio of $H_1$ to $H_2$ is estimated to be 64% for $A_V > 0.5$ mag.

A recent study of the $H_1$ at high latitude concluded that additional column density is provided by $H_2$ and that the $H_1$ is not optically thick (Liszt 2014). This author found $H_1$ intensity decreases as found in the present work, but the author rejected $T_e$ around 30 K for $E(B-V) \sim 0.1$ mag to explain the intensity decrease. $E(B-V) \sim 0.1$ mag corresponds to $6 \times 10^{20}$ cm$^{-2}$ in $N_{HI}$. This reasoning is not justified because $T_e$ can be as low as 30 K even for $E(B-V) = 0.1$ mag, as shown by theoretical calculations of $T_e$ as a function of visual extinction in a model cloud (see, e.g., Figure 2 of Goldsmith et al. 2007; also, for more extensive calculations, see Wolfire et al. 1995). The study by Liszt (2014) is therefore not justified as a counterargument for the optically thick $H_1$. It is also to be considered that the timescale of $H_2$ formation is considerably larger than the timescale of the local ISM as described below.

We shall here discuss theoretical aspects of the $H_1$−$H_2$ transition. The $H_2$ molecules are formed on the dust surface catalysis in the present-day universe and the $H_2$ formation timescale is given as $\sim 10 \times (n_{HI} \text{ cm}^{-3})/100$ Myr (Hollenbach & Natta 1995). The current local clouds within 200 pc of the Sun have a crossing timescale of $\lesssim 1$ Myr, which is too short to make $H_2$ as the major form by converting $H_1$, suggesting that $H_1$ is generally overabundant relative to $H_2$. More detailed numerical simulations of $H_2$ formation from $H_1$ gas have been undertaken by incorporating the $H_2$ formation reaction from purely $H_1$ gas and it is shown for a density range of $10^{21}$−$10^{23}$ cm$^{-3}$ that in $\sim 1$ Myr of cloud evolution the $H_2$ mass is about an order of magnitude smaller than the $H_1$ mass and that even in $\sim 10$ Myr the $H_2$ mass is still dominated by the $H_1$ mass (e.g., Inoue & Inutsuka 2012; Clark et al. 2012).
regions analyzed in the present work (Langer et al. 2014). These observations also observed the giant molecular clouds that have ages of more than 10 Myr and they do not apply to the local dark gas either.

As a future direction, an independent test of the H\textsc{i} optical depth and \( T_d \) is possible by using the H\textsc{i} absorption measurements toward extragalactic radio numerous continuum sources (Heiles & Troland 2003a, 2003b; Dickey et al. 2003). We are able to extend this method to more continuum sources with a higher sensitivity and to compare the results with the present paper. Such measurements are also to be compared with numerical simulations of the H\textsc{i}-H\textsubscript{2} transition, allowing us to have a deeper insight into the H\textsubscript{2} formation and the physical states of the hydrogen gas.

Another possibility that was not discussed in depth above is that the dust properties may be considerably different from the usual properties in the local space, as has been explored by the Planck collaboration (Planck Collaboration et al. 2014a). We shall defer to discuss this possibility until a full account of the Planck study is opened to the community.

5. CONCLUSIONS

We have carried out a study of the H\textsc{i} gas properties in the local ISM by using dust properties derived from the Planck/IRAS all sky survey at sub-millimeter/far-infrared wavelengths. The H\textsc{i} gas is in local regions within a few hundred parsecs of the Sun out of the Galactic plane, where giant molecular clouds do not exist. We find the H\textsc{i} integrated intensity \( W_{\text{HI}} \) shows poor correlation with the sub-millimeter dust optical depth \( \tau_{353} \), whereas the correlation becomes significantly better if the dust temperature \( T_d \), ranging from 13 K to 23 K, is analyzed in several small ranges of width 0.5 K. We hypothesize that the H\textsc{i} is optically thick and the saturation of the H\textsc{i} intensity is significant. We have shown that the H\textsc{i} emission associated with the highest \( T_d \) shows a good correlation expressed by a linear regression and hence derive a relationship, \( W_{\text{HI}} = 1.15 \times 10^8 \cdot \tau_{353} \). An analysis of \( W_{\text{HI}} \) and \( N_{\text{H}} \) based on coupled equations of radiative transfer and the H\textsc{i} optical depth yields both \( T_d \) and \( \tau_{353} \), \( T_d \) typically in the range from 15 K to 35 K and \( \tau_{353} \) from 0.5 to 3.0. The cold H\textsc{i} gas typically has density of \( 30 \text{ cm}^{-3} \sim 190 \text{ cm}^{-3} \), \( N_{\text{H}} \sim 5 \times 10^{19} \text{ cm}^{-2} \sim 3 \times 10^{21} \text{ cm}^{-2} \), and \( \Delta V_{\text{HI}} = 15 \text{ km s}^{-1} \). We argue that the “dark gas” is explained by cold H\textsc{i} gas, which is 2–2.5 times more massive than the H\textsc{i} gas derived under the optically thin approximation. We consider two alternative interpretations: one is that H\textsc{2} is dominant instead of H\textsc{i}, and the other that variation of the dust opacity relative to the gas column density is significant. The fraction of \( H_2 \) \( f_{\text{HI}} \), measured in the UV observations is consistent with that most of the hydrogen is atomic for \( N_{\text{H}} \) less than \( 1 \times 10^{21} \text{ cm}^{-2} \), while for \( N_{\text{H}} \) larger than \( 1 \times 10^{21} \text{ cm}^{-2} \), UV observations are only a few, insufficient to constrain \( f_{\text{HI}} \). Minimum values of \( N_{\text{H}} \) estimated by the optically thin limit constrain \( f_{\text{HI}} \) to be less than \( 0.5 \), supporting that H\textsc{i} is at least comparable to \( H_2\). Theoretical studies of H\textsc{i}-\text{cloud} evolution indicate that \( f_{\text{HI}} \) is less than 0.1 for \( \sim 1-\text{Myr} \) timescale by numerical simulations, lending support for H\textsc{i} dominating \( H_2 \) at density \( 10 \text{ cm}^{-3} \sim 10^3 \text{ cm}^{-3} \) in the local ISM. The second one the dust opacity variation is not reconciled with the general dust properties either (Equation (7)).

The spin temperature \( T_s \) and optical depth \( \tau_{353} \) of the H\textsc{i} emission cannot be disentangled by H\textsc{i} intensity alone. This has been an obstacle in 21 cm H\textsc{i} astronomy. The Planck dust optical depth offers a potential tool to disentangle this issue for an ISM column density range \( 10^{20} \text{ cm}^{-2} \sim 10^{22} \text{ cm}^{-2} \). The opacity gives a measure of the H\textsc{i} column density \( N_{\text{HI}} \), for given \( T_d \), if CO is not detectable and the background H\textsc{i} gas is negligible. The present study suggests that the cold H\textsc{i} is dominant in the local ISM and such cold H\textsc{i} has important implications on related subjects, i.e., dust properties (in particular grain size evolution), the structure of molecular and atomic clouds, the interaction of H\textsc{i} with cosmic rays, and the derivation of the CO factor. These issues will be subjects to be pursued in follow-up studies.

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