H I, CO, and Dust in the Perseus Cloud

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Abstract

Comparison analyses between the gas emission data (H I 21 cm line and CO 2.6 mm line) and the Planck/IRAS dust emission data (optical depth at 353 GHz $\tau_{353}$ and dust temperature $T_d$) allow us to estimate the amount and distribution of the hydrogen gas more accurately, and our previous studies revealed the existence of a large amount of optically thick H I gas in the solar neighborhood. Referring to this, we discuss the neutral hydrogen gas around the Perseus cloud in the present paper. By using the J-band extinction data, we found that $\tau_{353}$ increases as a function of the 1.3th power of column number density of the total hydrogen ($N_H$), and this implies dust evolution in high density regions. This calibrated $\tau_{353}$–$N_H$ relationship shows that the amount of the H I gas can be underestimated to be $\sim$60% if the optically thin H I method is used. Based on this relationship, we calculated the optical depth of the 21 cm line ($\tau_{21}$) and found that ($\tau_{21}$) $\sim$ 0.92 around the molecular cloud. The effect of $\tau_{21}$ is still significant, even if we take into account the dust evolution. We also estimated a spatial distribution of the CO-to-H$_2$ conversion factor ($X_{\text{CO}}$), and we found its average value is $X_{\text{CO}}$ $\sim$ 1.0 $\times$ 10$^{20}$ cm$^{-2}$ K$^{-1}$ km$^{-1}$ s. Although these results are inconsistent with some previous studies, these discrepancies can be well explained by the difference of the data and analyses methods.

Key words: ISM: atoms – ISM: individual objects (Perseus cloud) – ISM: molecules

1. Introduction

The neutral atomic hydrogen (H I) 21 cm emission was discovered in the Galaxy in 1951, and has been used in order to investigate the structure of the Galaxy. It was revealed that the Galaxy has a spiral structure and is rotating at a nearly uniform velocity of $\sim$200 km s$^{-1}$, except for within $\sim$2 pc from its center (e.g., Sofue 2013). The emission also brought advances in our understanding of the interstellar medium (ISM) and external galaxies. The role of hydrogen as the raw material of stars also attracted attention. In the 1970s, the interstellar carbon monoxide (CO) emission at 2.6 mm was discovered and has been used as a tracer of molecular hydrogen (H$_2$) clouds, and a picture of the phase transition from H I to H$_2$ that triggers the star formation emerged. The molecular emission lines in the H$_2$ gas are efficient in cooling the gas, which leads to the release of the cloud internal energy and subsequent gravitational collapse.

Hydrogen (either atomic or molecular) accounts for the majority of the mass of the ISM in the Galaxy, helium, which is abundant next to hydrogen, and heavier atoms account for $\sim$25% and $\sim$1% in mass, respectively. The volume number densities of the H I gas and the H$_2$ gas are estimated to be $\sim$1 cm$^{-3}$ and $\sim$1000 cm$^{-3}$, respectively, on average. The physical states of the neutral gas at the intermediate density around 100 cm$^{-3}$ are not understood in detail. In order to elucidate the evolution of the galaxies, it is an important task to better understand the behavior of the hydrogen gas, including the transition from H I to H$_2$ over a density range 1–1000 cm$^{-3}$. Planck is an astronomical satellite that aimed at observing the cosmic microwave background (CMB), and it observed the all sky at millimeter/sub-millimeter wavelengths (e.g., Planck Collaboration et al. 2011b). The data obtained by Planck necessarily include the emission from the ISM of the Galaxy as the foreground component of the CMB. By using the Planck data, physical parameters of the interstellar dust such as the optical depth at 353 GHz ($\tau_{353}$), the dust temperature ($T_d$), and so forth are obtained (the symbols used in the present study are summarized in Table 1), and they are available in the archival form (Planck Collaboration et al. 2014). These dust parameter data have relative uncertainties of $\lesssim$10%, and hence we can expect that they accurately reflect the properties and states of the ISM at an angular resolution of 5 arcmin. In particular, $\tau_{353}$ is much less than 1 for all over the sky, even toward the Galactic plane, and therefore the data offer a reliable tracer of the column density of the total hydrogen atom ($N_H$), if the dust-to-gas ratio (DGR) is a constant.

Fukui et al. (2014, 2015) compared the Planck dust data and the gas emission data such as H I and CO for the solar neighborhood. The H I 21 cm emission is generally assumed to be optically thin, as written in textbooks. If the dust properties are uniform and DGR is a constant, it is expected that the velocity-integrated intensity of the 21 cm spectrum ($W_{21}$) is proportional to $\tau_{353}$ for the data points where the CO emission is not detected. Fukui et al. (2014, 2015), however, found that the correlation between them is not so good. By introducing $T_d$ into the $\tau_{353}$–$W_{21}$ correlation plot, these authors discovered that the poor correlation in the $\tau_{353}$–$W_{21}$ plot is mainly due to the data points where the density is high and $T_d$ is low. There are two main possibilities to explain this bad correlation between $\tau_{353}$ and $W_{21}$: one is the presence of optically thick H I gas, and the other is the presence of “CO-dark H$_2$ gas,” which is H$_2$ gas without the CO emission (e.g., Wolfine et al. 2010; Planck Collaboration et al. 2011c; Langer et al. 2014). Fukui et al. (2014, 2015) investigated the H$_2$ fractions in the hydrogen gas by referring to the UV measurements (Gillmon et al. 2006), and found that the fractions are typically $\lesssim$10% toward the lines of sight whose column densities are up to at least 10$^{21}$ cm$^{-2}$. That

Note that in Figure 16 of Fukui et al. (2015), the H$_2$ fractions are somewhat larger than 10% toward two Galactic B-type stars, HD 210121 and HD 102065 (Rachford et al. 2002). These two stars may be contaminated by their own localized gas, and therefore the H$_2$ fractions for the local ISM are possibly not reliable toward them. For this reason, Fukui et al. (2017; see Section 4.3) did not use the results obtained in Rachford et al. (2002).
Table 1
List of Symbols Used in the Present Paper

| Symbol | Unit | Description | Note |
|--------|------|-------------|------|
| \(W_{\text{H}1}\) | (K km s\(^{-1}\)) | H I 21 cm line velocity-integrated intensity | (a) |
| \(N_{\text{H}1}\) | (cm\(^{-2}\)) | H I column number density | ... |
| \(N_{\text{H}1}^{\text{eff}}\) | (cm\(^{-2}\)) | H I column number density (optically thin limit), \(\equiv X_{\text{H}1} \times W_{\text{H}1}\) | ... |
| \(T_{\text{H}1}\) | (K) | H I brightness temperature | ... |
| \(\Delta V_{\text{H}1}\) | (km s\(^{-1}\)) | H I velocity width, \(\equiv W_{\text{H}1}/T_{\text{H}1}\) (peak) | ... |
| \(\gamma_{\text{H}1}\) | ... | H I optical depth | ... |
| \(L_{\text{H}2}\) | (K) | Theoretical conversion factor, \(= 1.823 \times 10^{10} \text{ cm}^{-2} \text{ K}^{-1} \text{ km}^{-1} \text{ s}\) | ... |
| \(X_{\text{H}2}\) | (cm\(^{-2}\)) | H2 column number density | ... |
| \(N_{\text{H}2}\) | (cm\(^{-2}\)) | Total hydrogen column number density, \(= N_{\text{H}1} + 2 N_{\text{H}2}\) | ... |
| \(W_{\text{CO}}\) | (K km s\(^{-1}\)) | ^12CO(\(J = 1–0\)) line velocity-integrated intensity | (b) |
| \(X_{\text{CO}}\) | (cm\(^{-2}\) K\(^{-1}\) km\(^{-1}\) s\(^{-1}\)) | Empirical CO-to-H\(_2\) conversion factor, \(\equiv N_{\text{H}2}/W_{\text{CO}}\) | ... |
| \(\tau_{353}\) | ... | Optical depth at 353 GHz derived by Planck/IRAS satellite | ... |
| \(\tau_{353,\text{ref}}\) | ... | J-band extinction derived by NICEST method | (c) |
| \(\Delta \tau\) | (K) | Cold dust temperature derived by Planck/IRAS satellite | ... |
| \(\tau_{b}\) | (K) | Background brightness temperature at 21 cm | (d) |
| \(\tau_{353,\text{ref}}\) | ... | Reference value of \(\tau_{353,\text{ref}}\), \(= 1.2 \times 10^{-6}\) | (e) |
| \(N_{\text{H}2,\text{ref}}\) | (cm\(^{-2}\)) | Reference value of \(N_{\text{H}2,\text{ref}}\), \(= 2.5 \times 10^{20} \text{ cm}^{-2}\) | (e) |
| \(\alpha\) | ... | Power index in Equation (2) | ... |

Notes.

1. Peck et al. (2011). The integrated range is from \(-188.4\) to \(+188.4\) km s\(^{-1}\).
2. Dame et al. (2001). The integrated range is from \(-4.9\) to \(+12.0\) km s\(^{-1}\).
3. Juvela & Montillaud (2016).
4. Reich (1982), Reich & Reich (1986).
5. Appendix.

is, H I dominates H2, and the “CO-dark H2 gas” would not be a dominant component in the local ISM. Therefore, these authors concluded that there exists a large amount of optically thick H I gas in the local ISM, whose typical optical depth is \(\sim 1\), and the amount of the H I gas is underestimated by \(\sim 50\%\) if a correction for the opacity effect is not applied. In Fukui et al. (2014, 2015), these analyses were made for the high Galactic latitude at \(|b| > 15^\circ\) where the gas density is low. An open issue discussed in Fukui et al. (2014, 2015) is if \(\tau_{353}\) obeys a simple linear relationship with the \(N_{\text{H}1}\) or not. A study in the Orion A molecular cloud (Roy et al. 2013) indicates that the dust optical depth is proportional to the 1.28th power of \(N_{\text{H}1}\), rather than a simple linear relationship. If correct, this nonlinearity may be ascribed to the dust evolution at high column density. This suggests that it is possible to apply a minor modification of the method of Fukui et al. (2014, 2015) in order to improve the accuracy in \(N_{\text{H}1}\).

The Perseus cloud is one of the most well-known molecular clouds in the solar neighborhood (\(d \sim 300\) pc) located at \((\ell, b) \sim (160^\circ, -20^\circ)\) (e.g., Bally et al. 2008). This region is a part of Gould’s belt, and the cloud includes some star-forming regions (SFRs), IC 348 and NGC 1333, for example. There are a few previous studies on the interstellar hydrogen gas in the Perseus region, such as see Lee et al. (2012, 2014) and Stanimirović et al. (2014). Lee et al. (2012, 2014) estimated a spatial distribution of the \(X_{\text{CO}}\) factor, which is a conversion factor between the velocity-integrated intensity of the ^12CO(\(J = 1–0\)) line (\(W_{\text{CO}}\)) and the column number density of the H\(_2\) gas (\(N_{\text{H}2}\)). They used the IRAS 60, 100 \(\mu\)m data, and concluded that the average value of \(X_{\text{CO}}\) is \(\sim 0.3 \times 10^{20} \text{ cm}^{-2} \text{ K}^{-1} \text{ km}^{-1} \text{ s}\). This average value is significantly smaller than the typical value for the Galaxy, \((1–2) \times 10^{20} \text{ cm}^{-2} \text{ K}^{-1} \text{ km}^{-1} \text{ s}\) (e.g., Bolatto et al. 2013). In Stanimirović et al. (2014), the measurements of the optical depth of the H I gas (\(\tau_{\text{H}1}\)) around the Perseus cloud were made. They observed the H I 21 cm absorption spectra toward 26 extra-Galactic radio continuum sources, and analyzed the data by using the method described in Heiles & Troland (2003). They concluded that optically thick H I gas was detected only toward \(\sim 15\%\) of the lines of sight, which disagrees with the results of Fukui et al. (2014, 2015), and casts doubt on the “optically thick H I gas.”

With these results in mind, the aims of the present study are as follows:

1. To investigate whether the arguments by Fukui et al. (2014, 2015) still hold in the region where the density is relatively high and the SFRs exist, and to explore if the \(\tau_{353}\)–\(N_{\text{H}1}\) relationship requires the nonlinear relationship, suggesting dust evolution.
2. To understand the cause for the difference between the previous results by Fukui et al. (2014, 2015), Lee et al. (2012, 2014), and Stanimirović et al. (2014) on \(X_{\text{CO}}\) and \(\tau_{\text{H}1}\), and to test the validity of usage of \(\tau_{353}\) in order to estimate the amount of the hydrogen gas.

The present paper is organized as follows. Section 2 introduces the data set we used in the present study, and Section 3 describes the analyses methods and the results. We present the discussions in Section 4. Finally, Section 5 summarizes the paper.

2. Observational Data Set

In the present paper, we used the following gas and dust maps in order to investigate relationships between them. These data were spatially smoothed to an effective HPBW (half power beam width) of 8.4 arcmin, which corresponds with that
of the CfA CO data, except for the 21 cm radio continuum map (35 arcmin). Then, they were converted to a 3.0 arcmin grid spacing in Right Ascension and Declination.

2.1. H I Data

Data sets of the GALFA H I survey (Data Release 1; Peek et al. 2011) are used in the present study. This survey was done with the Arecibo Observatory 305 m telescope, and its HPBW is ~4 arcmin. Note that we have linearly refitted the baseline of each spectrum using the velocity ranges of mainly $V_{lsr} \leq -161$ km s$^{-1}$ and $V_{lsr} \geq +112$ km s$^{-1}$, in order to correct the baseline offsets in this version of the raw GALFA data. Then the data were spatially smoothed to be a 8.4 arcmin effective beam size, and rms fluctuations of the smoothed data are ~0.06 K at a 0.18 km s$^{-1}$ velocity resolution.

2.2. CO Data

We used the $^{12}$CO($J = 1-0$) data cube by Dame et al. (2001) as a tracer of H$_2$ gas. The HPBW is 8.4 arcmin, and the rms noise fluctuations are ~0.25 K at a 0.65 km s$^{-1}$ velocity resolution (Dame et al. 2001). We downloaded this data cube from the website of the Harvard–Smithsonian Center for Astrophysics (CfA).  

2.3. Planck and IRAS Dust Emission Data

Archival data sets of dust optical depth at 353 GHz ($\tau_{353}$) and dust temperature ($T_d$) obtained by Planck and IRAS satellites are used. They were obtained by fitting intensities at 353, 545, and 857 GHz observed with Planck, and at 100 $\mu$m of IRIS (Improved Reprocessing of the IRAS Survey) with modified-blackbody functions (for details, see Planck Collaboration et al. 2011a). In the present study, we utilized version R1.20 of the Planck dust maps$^3$ and IRAS 60 and 100 $\mu$m maps$^4$ (Miville-Deschênes & Lagache 2005). We downloaded all-sky FITS data sets with a HEALPix$^5$ format (Górski et al. 2005).

2.4. J-band Extinction Data

An all-sky distribution of J-band extinction ($A_J$) was derived in Juvela & Montillaud (2016). They used “NICER” and “NICEST” methods in order to calculate the $A_J$ map based on the 2MASS (two micron all-sky survey) J, H, and K-band extinction data. We downloaded an all-sky FITS data$^6$ with a HEALPix format. The angular resolution of the raw map is 3 arcmin.

2.5. H$\alpha$ Data

For the purpose of identifying regions where ultraviolet (UV) emission locally affect the dust properties by heating up or destroying them, we used H$\alpha$ emission data. The H$\alpha$ map was obtained by Finkbeiner (2003), and it has an angular resolution of 6 arcmin.

2.6. 21 cm Radio Continuum Data

21 cm continuum brightness temperature map is used in order to obtain the background emission. This map was derived by Reich & Reich (1986) and includes the 2.7 K cosmic background radiation. Although it has a lower spatial resolution (~35 arcmin) than the other maps, we use this map as it is in the present study.

3. Analyses and Results

3.1. Spatial Distributions

Figure 1 shows spatial distributions of data sets used in the present study.

Figure 1(a) is the distribution of velocity-integrated intensity of the $^{12}$CO($J = 1 - 0$) line ($W_{CO}$) obtained by Dame et al. (2001). The integrated velocity range is from -4.9 to $+12.0$ km s$^{-1}$. We use this map as a tracer of column number densities of molecular hydrogen ($N_{H_2}$).

Figure 1(b) is a map of velocity-integrated intensity of the H I 21 cm line ($W_{HI}$). It was derived by the GALFA-H I survey (Peek et al. 2011). The integrated velocity range is from $-188.4$ to $+188.4$ km s$^{-1}$. Because we found some strong spike noises in the spectra in our region, we masked four areas to exclude these bad spectra. See Figure 2 for details on the mask.

Figures 1(c) and (d) show distributions of the dust emission parameters obtained from the Planck/IRAS observations. A map of dust optical depth at 353 GHz ($\tau_{353}$) is drawn in Figure 1(c). $\tau_{353}$ is obtained by using the data observed with the Planck satellite, which is aimed at accurately detecting the spatial distribution of the CMB. Therefore, it has high reliability with typical uncertainty of $\leq 10\%$. In addition, the value of $\tau_{353}$ is at most $\leq 10^{-3}$ even toward the Galactic plane, and hence we can expect that it perfectly reflects the distribution and amount of ISM. $\tau_{353}$ is considered as a high accuracy/precision tracer of column number density of total hydrogen atoms ($N_{H}$) if DGR is uniform.

Figure 1(d) shows cold dust temperature ($T_d$) obtained simultaneously with $\tau_{353}$. We can see a trend that $T_d$ becomes lower toward the molecular clouds detected by CO. It indicates that dust grains themselves shield the interstellar radiation field (ISRF) in the molecular clouds and grains are less heated in addition to radiative cooling (see also Figure 5). Note that $T_d$ is high around local heating sources, such as the California Nebula (NGC 1499), the Pleiades (M45), and the “ring-like feature” described in Lee et al. (2012). The $T_d$ image has a relatively low contrast compared with $\tau_{353}$; in particular the range of $T_d$ in this region is typically from 17 to 22 K. This is because $T_d$ is proportional to the one-sixth power of the total intensity radiated from thermal-equilibrium grains expressed as the modified-blackbody model. It reflects that the total radiation energy of the modified-blackbody is proportional to the fourth power of the temperature, and is in addition proportional to the emissivity spectral index (~2).

Figure 1(e) is an image of J-band extinction ($A_J$) derived by Juvela & Montillaud (2016) using 2MASS data and the “NICEST” method (Lombardi & Alves 2001). We use this map as another tracer of $N_{H_2}$.

A spatial distribution of IRIS 100 $\mu$m intensity ($I_{100}$) is drawn in Figure 1(f). This map is used for a comparison of the CO-to-H$_2$ conversion factor (see Section 4.1).
We show an intensity map of \( \text{H}_\alpha \) emission in Figure 1(g), overlaid with locations of young stellar object (YSO) candidates. \( \text{H}_\alpha \) emission indicates the presence of ionized hydrogen (H II), and thus indicates the presence of strong UV radiation. We use the data in order to identify the region where the dust may be destroyed by UV radiation. The red crosses are the location of YSO candidates cataloged by Tóth et al. (2014). From this catalog, we extracted the candidates under the condition that the “probability of being a YSO candidate” is greater than 0.997. It is based on AKARI Far-infrared Surveyor Bright Source Catalog.

Figure 1(h) shows a spatial distribution of brightness temperature of 21 cm continuum radiation. This map was derived by Reich & Reich (1986) and includes the 2.7 K cosmic background radiation, and so on.
3.2. Masking

Masks applied in the present study are shown in Figure 2.

(a) This mask is used in order to mask the data points in which molecular hydrogen can exist ($W_{\text{CO}} > 3\sigma$).

(b) There exist strong spike noises (equivalent to $I_\lambda (\sim 30 \text{ K})$) in some spectra of GALFA-H I DR1 data. This mask is used in order to exclude the data points within 8.4 arcmin (=1 HPBW) from these bad spectra.

(c) In Stanimirović et al. (2014), absorption spectra due to the local H I gas are detected toward extra-Galactic radio continuum sources. Since there is a total of 11 out of these sources in this region, this mask is used to exclude the data points within 8.4 arcmin (=1 HPBW) from them.

(d) This mask excludes the data points within 1.5 deg from the center of the Pleiades ($\alpha_{2000}, \delta_{2000} \sim (3^h 47^m, +24^\circ 07^\prime)$ (SIMBAD Astronomical Database; Wenger et al. 2000), because dust grains are locally heated up.

(e) Lee et al. (2012) describes the “ring-like feature,” which is formed by an H II region due to a B-type star named HD 278942 (Ridge et al. 2006). This “ring-like feature” is masked to exclude the data points within 56 arcmin from ($\alpha_{2000}, \delta_{2000} = (3^h 39^m 30^s, +32^\circ)$).

(f) Dust grains can be locally heated up or destroyed in regions where Hα emission is strong. We use this mask for the purpose of excluding the data points where $H\alpha \geq 10^7$.

Mask (a) is applied to Figures 6, 7(c), 8, and 9. Mask (b) and (c) are applied to the H I data, and masks (d)–(f) are applied to the dust data.

3.3. Velocity Structure

Figure 3(a) is an R.A.-velocity diagram of H I (image) and CO (contours, every 0.3 K from 0.3 K) in terms of decl.-averaged intensities. Figure 3(b) shows the mean H I spectrum of this region. Although there is an intermediate-velocity component (intermediate-velocity cloud; IVC) at $V_{\text{LSR}} \lesssim -30 \text{ km s}^{-1}$, its contribution to the column density is only up to ~6% of the total; we therefore use the data including all the velocity components.

3.4. Hydrogen Amount Estimation

Figure 4 is a double logarithmic correlation plot between $A_J$ and $\tau_{535}$. A linear regression in double logarithmic scale using the data of $A_J \geq 0.5$ mag and $\tau_{535} \geq 3 \times 10^{-5}$ yields the following relationship:

$$\tau_{535} = [(1.08 \pm 0.02) \times 10^{-4}] \times (A_J)^{1.32 \pm 0.04}.$$  \hfill (1)

We assume the uncertainties in the $A_J$ data are 0.5 mag, which is the typical fluctuation nearby the Perseus cloud. Considering $A_J$ as a linear tracer of $N_{\text{H}}$ along each line of sight, Equation (1) indicates that dust emission cross section per hydrogen atom increases with the ~1.3 power of $N_{\text{H}}$. A similar analysis was done in Roy et al. (2013) for the Orion A region, and they concluded that the power index is 1.28. Our result is consistent with this, and these results show dust evolution in high density regions. The grain size is typically up to ~0.2 μm (Jones et al. 2013), which is much smaller than the J-band wavelength, ~1.25 μm. In addition, the grain size can change by only ~0.02 μm (Ysard et al. 2015). Roy et al. (2013) and Forbrich et al. (2015) also argue that in the high density regions, it is mostly the sub-millimeter opacity that is changing, not the infrared extinction. Therefore, changes in the grain size have a small effect on the J-band extinction, and we can regard $A_J$ as a linear tracer of $N_{\text{H}}$ if DGR is uniform. In the present study, therefore, we adopted 1.3 as the power index ($\alpha$) from Equation (1).

In Fukui et al. (2014, 2015) we suggested an algorithm for estimating the amount of the hydrogen gas using $\tau_{535}$ as an accurate tracer of $N_{\text{H}}$. In Fukui et al. (2014), we assumed the relationship $\tau_{535} \propto N_{\text{H}}$. On the other hand, Fukui et al. (2015), considering the result of Roy et al. (2013), made discussion using the relationship of

$$\frac{\tau_{535}}{\tau_{535, \text{ref}}} = \left( \frac{N_{\text{H}}}{N_{\text{H}, \text{ref}}} \right)^\alpha.$$  \hfill (2)

In Fukui et al. (2014), the relationship $\tau_{535} \propto N_{\text{H}}$ was used. On the other hand, we used $\tau_{535} \propto N_{\text{H}}^{1.32 \pm 0.04}$ and $\tau_{535} \sim 1.3 \times 10^{-4}$ mag cm$^2$ (Roy et al. 2013).Considering this, we adopted $\alpha = 1.3$ for the present study.
Here $t_{353,\text{ref}}$ and $N_{H,\text{ref}}$ are normalization constants that satisfy the relationship of $N_{H,\text{ref}} = (1.15 \times 10^8) \times X_{HI} \times t_{353,\text{ref}}$ (Fukui et al. 2015). In the present study, we use Equation (2) by substituting $\alpha = 1.3$, $t_{353,\text{ref}} = 1.2 \times 10^{-6}$ and $N_{H,\text{ref}} = 2.5 \times 10^{20}$ cm$^{-2}$:

$$N_H = \left( \frac{\tau_{353}}{\tau_{353,\text{ref}}} \right)^{1/\alpha} N_{H,\text{ref}}$$

$$= (9.0 \times 10^{24}) \times (t_{353})^{1/1.3}.$$  (3)

See the Appendix for the details of the determination of $\tau_{353,\text{ref}}$ and $N_{H,\text{ref}}$.

Conventionally, the following equation is used to calculate the column number density of H I gas from an observable value, $W_{HI}$,

$$N_{H I}^\ast = X_{HI} \times W_{HI}.$$  (4)

Although widely used, this equation is obtained under the assumption that the H I gas is optically thin ($\tau_{HI} \ll 1$). The symbol $N_{H I}^\ast$ is the H I column number density in the optically thin limit. Therefore, when Equation (4) is used, the H I column number density can be underestimated if optically thick H I gas exists. Here we will show that H I optical depth has significant effects on the estimation of the H I amount in the Perseus region.

Figure 5 is a scatter plot between $\tau_{353}$ and $T_d$. It clearly shows a negative relationship, as with Fukui et al. (2014), for the MBM 53, 54, 55 region.
addition, in the latter case, the dust growth can increase $\tau_{353}$ in such high density areas.

Figure 6 is a correlation plot between $\tau_{353}$ and $W_{H\text{ I}}$, colored by $T_d$ in windows of 0.5 K intervals. Note that we applied the mask (a) (CO mask), and therefore $N_H = N_{H\text{ I}}$ for the data points plotted in Figure 6. Although the correlation is not so good as a whole, the distributions of the data points on the $\tau_{353}$–$W_{H\text{ I}}$ plane are clearly different when separated according to $T_d$. The scattering is small for the data points where $T_d$ is high, and it becomes large with decreasing $T_d$. In particular, the distribution of the high-$T_d$ points (such as $T_d > 19.5$ K) is elongated, and it seems to pass through the origin when it is extrapolated. On the other hand, the distribution of the low-$T_d$ points is broadened along the $\tau_{353}$ axis. As described previously, this indicates that for such low-$T_d$ points, the amount of the ISM is large, and hence $W_{H\text{ I}}$ is saturated against $\tau_{353}$ because of the effect of large optical depth (i.e., $\tau_{353} \gtrsim 0.3$). Therefore, for such data points, the amount of $H\text{ I}$ cannot be calculated by using Equation (4). It can be said that the reason for the low spatial correlation between $\tau_{353}$ and $W_{H\text{ I}}$ (Figures 1(b) and (c)) is the effect of $\tau_{353}$. Note that there is another possibility to explain the bad correlation between $\tau_{353}$ and $W_{H\text{ I}}$: the presence of “CO-dark $H_2$ gas,” which is not detectable by the CO line. In Fukui et al. (2015), however, the authors examined the fraction of $H_2$ in the hydrogen gas by referring to the results of the UV measurements (Rachford et al. 2002; Gillmon et al. 2006), and found that the fraction is at most $\sim 10\%$. This means that $H\text{ I}$ dominates $H_2$ in the typical hydrogen gas. In addition, Fukui et al. (2012) revealed that the total hydrogen column number density ($N_{H\text{ I}} + 2 N_{H_2}$) shows a good correlation with the TeV gamma-ray distribution (a reliable tracer of the total hydrogen) in the supernova remnant RX J1713.7−3946 when the $H\text{ I}$ optical depth is corrected. From these, the bad correlation between $\tau_{353}$ and $W_{H\text{ I}}$ can be explained by optically thick $H_2$ gas alone, without “CO-dark $H_2$ gas.” Therefore, in the present study, we did not consider “CO-dark $H_2$ gas.” The aspect of the $W_{H\text{ I}}$ saturation can be explained by using the radiation transfer equation, stated as follows.

Equations (5) and (6) are the radiation transfer equation of the $H\text{ I}$ 21 cm line and the equation of $H\text{ I}$ optical depth, respectively, and both of them are derived theoretically (e.g., Dickey & Lockman 1990; Draine 2011):

$$W_{H\text{ I}} = (T_e - T_{bg}) \Delta V_{H\text{ I}} \{1 - \exp(-\tau_{H\text{ I}})\}, \quad (5)$$

$$\tau_{H\text{ I}} = \frac{N_{H\text{ I}}}{X_{H\text{ I}}} \left( 1 - \frac{1}{\gamma_{H\text{ I}}} - \frac{1}{\Delta V_{H\text{ I}}} \right). \quad (6)$$

These equations are independent of each other, and are valid regardless of whether $\tau_{H\text{ I}}$ is negligible or not. We define $\Delta V_{H\text{ I}}$ as $W_{H\text{ I}}/T_{H\text{ I}}$(peak), and $\gamma_{H\text{ I}}$, in Equations (5) and (6) are regarded as the average values over the velocity range $\Delta V_{H\text{ I}}$. From the two and Equation (3), we derive the following relationship:

$$W_{H\text{ I}} = \left\{ \frac{\tau_{353}}{\tau_{353, \text{ref}}} \right\}^{3/2} \frac{N_{H\text{ I}, \text{ref}}}{X_{H\text{ I}}} \left( 1 - \frac{1}{\gamma_{H\text{ I}}} - \frac{1}{\Delta V_{H\text{ I}}} - T_{bg} \right) \times \Delta V_{H\text{ I}} \{1 - \exp(-\tau_{H\text{ I}})\}. \quad (7)$$

The lines/courses in Figure 6 show this relationship in cases of $\alpha = 1.0$ and 1.3 (light blue lines and red curves, respectively) when $\tau_{353} \ll 1$, $\gamma_{H\text{ I}} = 0.11, 1, 2, 3$ are substituted (from left to right). We applied $\Delta V_{H\text{ I}} = 13.7 \text{ km s}^{-1}$ and $T_{bg} = 3.7$ K, which are the mean values of the data points shown in Figure 6. The standard deviations of $\Delta V_{H\text{ I}}$ and $T_{bg}$ are 1.9 km s$^{-1}$ and 0.05 K, respectively. Note that $\gamma_{H\text{ I}} = 0.11$ is given in the Appendix. According to these curves, there is a trend that larger $\tau_{H\text{ I}}$ gives a smaller slope, which is consistent with the distribution of the low-$T_d$ points. Therefore, these equal-$\gamma_{H\text{ I}}$ curves should trace the distribution of the equal-$T_d$ points. As shown in Figure 6, the curves to which $\alpha = 1.3$ is applied show better correlations with the distributions of the data points, rather than $\alpha = 1.0$ for both high- and low-$T_d$. This also suggests that it is important to take into account the dust evolution. In addition, we can say that the small variances at high $T_d$ (small $\tau_{H\text{ I}}$) suggest the uniform DGR and the uniform grain size.

Figure 7(a) is a spatial distribution of $N_{H\text{ I}}$ calculated with Equation (3). Figure 7(b) shows a distribution of $N_{H\text{ I}}^{\text{ref}}$ derived with Equation (4), which is the $H\text{ I}$ column number density at.
Figure 7. (a) Map of $N_H$ calculated by Equation (3). Masks (d)-(f) are applied. (b) Spatial distribution of H I column density calculated under the assumption of the optically thin limit, $N_{H1}^* = W_{H1} \times X_{H1}$. Masks (b) and (c) are applied. (c) A pixel-to-pixel ratio map between (a) and (b) $(N_H/N_{H1}^*)$. We found the mean value as $\langle N_H/N_{H1}^* \rangle \sim 1.6$. In addition, mask (a) is applied.

Figure 8. Estimated spatial distributions of (a) $\tau_{H1}$ and (b) $T_s$, which are the solutions of the system of Equations (5) and (6). For the purpose of comparisons with the results of Stanimirović et al. (2014), we spatially interpolated the H I spectra toward the background sources using the bilinear interpolation method and computed $\tau_{H1}$ and $T_s$.

the optically thin limit. Note that in Figures 7(a) and (b), the scales of their color-bars are significantly different from each other. In Figure 7(c), we show a distribution of $N_H/N_{H1}^*$, which is the pixel-to-pixel ratio map of Figures 7(a) and (b). In this map, mask (a) is applied in order to exclude the data points where H$_2$ can exist. We found that the mean value of $N_H/N_{H1}^*$ is $\sim 1.8$ (see also Figure 9), and hence in this region, the amount of H I is underestimated to be $\sim 57\%$ if Equation (4) is used. From these, it turns out that H I optical depth has a significant effect in estimating the amount of H I gas in the ISM.

Using Equation (3), we can estimate the total (atomic and molecular) amount of the hydrogen gas in a high accuracy without being affected by H I optical depth. However, note that Equation (3) alone cannot separate atomic and molecular components, and also cannot separate individual components located along the same line of sight.

3.5. $\tau_{H1}$ and $T_s$ Estimation

Once $N_H$ is derived with Equation (3), $\tau_{H1}$ and $T_s$ can be calculated independently as solutions of a system of Equations (5) and (6) (Fukui et al. 2014, 2015). Since the solutions of the coupled equations cannot be expressed analytically, they are numerically calculated. We note that in the limit of $\tau_{H1} \ll 1$, the solutions are indeterminate. Figure 8 shows the spatial distributions of (a) $\tau_{H1}$ and (b) $T_s$, respectively. In order to compare with the result of $\tau_{H1}$ obtained based on H I absorption measurements in Stanimirović et al. (2014), we spatially interpolated (using the bilinear method) the H I spectra masked by mask (c) and calculated the solutions.

In Figure 9 we show mass-weighted histograms of (a) $N_H$, (b) $N_H/N_{H1}^*$, (c) $\tau_{H1}$, and (d) $T_s$, respectively, for the region shown in Figure 8. We assumed the distance to the Perseus cloud as 300 pc (Bally et al. 2008), and the mass is calculated by including hydrogen and helium. We found the mass-weighted mean values as $\langle N_H \rangle \sim 1.7 \times 10^{21}$ cm$^{-2}$, $\langle N_H/N_{H1}^* \rangle \sim 1.6$, $\langle \tau_{H1} \rangle \sim 0.92$, and $\langle T_s \rangle \sim 97$ K. The ratio of
the H I mass with $\tau_{\text{H}I} < 1$ is $\sim 37\%$ of the total mass, and as shown in Figure 6, optically thick H I cannot be ignored. In Fukui et al. (2014) we found that $\langle T_i \rangle \sim 30$ K around the MBM 53, 54, 55/HLCG 92–35 clouds, which is somewhat lower than that for the Perseus region. It is possible that the Perseus cloud is located in the Gould’s belt, which contains heat sources, including some SFRs and OB associations.

Figure 10 shows examples of the $\tau_{\text{H} I}$ and $T_i$ solutions. The curves of Equation (5) (blue) and Equation (6) (red), and the solutions of $\tau_{\text{H}I}$ and $T_i$ (purple), are drawn on the $\tau_{\text{H}I}$–$T_i$ plane. We show the solutions toward the background radio sources described in Stanimirović et al. (2014). As described previously, the H I spectra toward the directions are spatially interpolated. The blue and red dashed curves indicate 1σ uncertainties for each curve, and we defined the uncertainties in the solutions (purple lines) as the intersections of the dashed curves. Table 2 is the results of the calculations. For each data point, the solutions of $\tau_{\text{H}I}$ and $T_i$ are well determined.

### 3.6. $X_{\text{CO}}$ Estimation

The $X_{\text{CO}}$ factor, which is an empirical conversion factor, has been used in order to estimate H$_2$ column number density ($N_{\text{H}_2}$) from the velocity-integrated intensity of the CO line ($W_{\text{CO}}$). Conventionally, $X_{\text{CO}} \sim (1–2) \times 10^{20}$ cm$^{-2}$ K$^{-1}$ km$^{-1}$ s$^{-1}$ is assumed as a typical value for the Galaxy (e.g., Bolatto et al. 2013). Here, since $N_{\text{H}_2}$ is obtained with a higher accuracy, we are able to determine $X_{\text{CO}}$ by using the Planck data and $W_{\text{CO}}$ data.

Figure 11 indicates correlation plots between $W_{\text{CO}}$ (x-axis) and $N_{\text{H}_2}$ (y-axis). Fitting the distribution of the data points and calculating the slope and the intercept, we can separate the atomic component and the molecular component from $N_{\text{H}_2}$:

$$N_{\text{H}} = N_{\text{H}_2} + 2 N_{\text{H}_I}$$
$$N_{\text{H}_I} = X_{\text{CO}} \times W_{\text{CO}} - C$$

Thus we obtain the following:

$$N_{\text{H}} = (2 X_{\text{CO}}) W_{\text{CO}} + N_{\text{H}_I}$$
$$\equiv (\text{slope}) \times W_{\text{CO}} + (\text{intercept}).$$

The intercept gives the atomic component, and the slope gives the molecular component and the $X_{\text{CO}}$ factor ($=\text{slope}/2$). Note that the contribution of the atomic component is a mean value, and we assumed that it is constant against $W_{\text{CO}}$. We used an outlier-robust linear regression method in order to avoid the effect due to the data points where $W_{\text{CO}}$ is saturated against $N_{\text{H}_I}$. For this purpose, we utilized the ROBUST_LINEFIT routine provided in the IDL Astronomy User’s Library (Landsman 1993). In the present study, we estimated the spatial distribution of the $X_{\text{CO}}$ factor by the procedure described as follows.

1. We prepare a “window” that extracts the data points within a 1° radius from a certain point. This radius is determined in order to ensure a sufficient number of data points to be fitted.
2. By using the data points inside the window, we estimate the $X_{\text{CO}}$ factor from the $W_{\text{CO}}$–$N_{\text{H}_I}$ plot.
3. We regard the resulting $X_{\text{CO}}$ as the value of the center point of the window.
4. The $X_{\text{CO}}$ map can be obtained by iteratively calculating the $X_{\text{CO}}$ factor for all the data points, while moving the center of the window pixel by pixel (this process is similar to image convolution).

Figures 12(a) and (b) show the map of $W_{\text{CO}}$ and $N_{\text{H}}$ (already shown in Figures 1(a) and 7(a)), but only mask (d) and (e) are applied in order to compare with previous studies (Lee et al. 2012, 2014, described later). The four overlaid circles (A)–(D) indicate the examples of the “window,” corresponding with the panels (a)–(d) of Figure 11, respectively. The resulting $X_{\text{CO}}$ map is shown in Figure 12(c). We found the $X_{\text{CO}}$ factor significantly varies within the Perseus cloud, $X_{\text{CO}} \sim (0.3-2.0) \times 10^{20} \text{ cm}^{-2} \text{ K}^{-1} \text{ km}^{-1} \text{s}$, with a typical uncertainty of 10%–50%. The $X_{\text{CO}}$ variation within molecular clouds is discussed in some previous studies (e.g., Magnani et al. 1998; Cotten & Magnani 2013; Lee et al. 2014), and the present result agrees with these results. We also found the average value is $\langle X_{\text{CO}} \rangle \sim 1.0 \times 10^{20} \text{ cm}^{-2} \text{ K}^{-1} \text{ km}^{-1} \text{s}$ (Figure 11(e)), which is consistent with the empirical and typical value of the Galaxy, $\langle X_{\text{CO}} \rangle \sim 1.0 \times 10^{20} \text{ cm}^{-2} \text{ K}^{-1} \text{ km}^{-1} \text{s}$. On the other hand, Lee et al. (2012, 2014) also estimated a spatial distribution of the $X_{\text{CO}}$ factor in the Perseus molecular cloud. However, they obtained the average value of $\langle X_{\text{CO}} \rangle \sim 0.3 \times 10^{20} \text{ cm}^{-2} \text{ K}^{-1} \text{ km}^{-1} \text{s}$, which is $\sim 1/3$ of our result. We will explain the discrepancy between these two results on the $X_{\text{CO}}$ factor in the next section.

4. Discussions

4.1. $X_{\text{CO}}$

As mentioned previously, Lee et al. (2012, 2014) also estimated the spatial distribution of the $X_{\text{CO}}$ factor in the Perseus molecular cloud. Their procedure for the $X_{\text{CO}}$ estimation is briefly described here:

1. $N_\text{H}$ is estimated by using $A_v$ as a tracer of the total amount of hydrogen. They used the DGR as the conversion factor,

$$N_\text{H} = \frac{A_v}{\text{DGR}}, \quad \text{DGR} = 1.1 \times 10^{-21} \text{ mag}^{-1} \text{ cm}^2.$$

2. $N_{\text{H}_2}$ is calculated by subtracting $N_{\text{H}_1}$ from $N_\text{H}$,

$$N_{\text{H}_2} = \frac{1}{2}(N_\text{H} - N_{\text{H}_1}). \quad (9)$$

Note that in Lee et al. (2012, 2014), $\gamma_{\text{H}_1} \ll 1$ is assumed—that is, $N_{\text{H}_1} = 0$ is assumed.

3. The resulting $X_{\text{CO}}$ map is obtained by dividing $N_{\text{H}_2}$ by $W_{\text{CO}}$ for each data point.

However, the available $A_v$ map—“COMPLETE survey” (Lombardi & Alves 2001) based on the 2MASS data—covers only the central region of the cloud; hence they made a wide-area “simulated” $A_v$ map by using IRAS data:

1. The wide-area dust temperature map was estimated from the ratio of the intensities of the IRIS 60, 100 $\mu$m maps. The effect from very small grains was considered for the IRIS 60 $\mu$m map.

2. The wide-area map of optical depth at 100 $\mu$m ($\tau_{100}$) was derived from the ratio of the IRIS 100 $\mu$m map to the intensity at 100 $\mu$m of the blackbody radiation at derived dust temperature. The zero point offset in $\tau_{100}$ was also corrected.

3. The wide-area “simulated” $A_v$ map was obtained from the $\tau_{100}$ map by using the conversion factor obtained by the correlation between $\tau_{100}$ and the COMPLETE $A_v$ map.

Figure 13(a) shows histograms of $X_{\text{CO}}$ derived in Section 3.6 and $X_{\text{CO}}$ reproduced by the same procedure as Lee et al. (2012, 2014). Note that the data points used are the same as Figure 12, not the same as Lee et al. (2012, 2014). The average values are...
Table 2
List of Radio Continuum Sources in Table 1 of Stanimirović et al. (2014)

| Name              | Position | Present Study | Stanimirović et al. (2014) |
|-------------------|----------|---------------|-----------------------------|
|                   | $\alpha$| $\delta$| $\tau_{55}$ | $N_H$ | $T_e$ | $\eta_{HI}$ | $\eta_{HI} \times \Delta V_{HI}$ | $\int \eta_{HI} dV$ |
|                   | (b)     | (c)     | (d)    | (e)   | (f)   | (g)     | (h)               | (i)             |
| NV 0232 + 34      | 32:58   | 06:06  | 0.5   | 82   | 0.4   | 5.1    | 1.89             | 0.14            |
| 3C 068.2          | 34:23   | 17:16  | 0.9   | 71   | 0.9   | 9.0    | 4.77             | 0.14            |
| 4C +28.06         | 35:41   | 57:57  | 0.7   | 95   | 0.4   | 5.8    | 3.67             | 0.04            |
| 4C +28.07         | 37:46   | 09:16  | 1.1   | 50   | 1.2   | 15.7   | 4.43             | 0.15            |
| 4C +34.09         | 00:23   | 20:34  | 0.7   | 85   | 0.7   | 8.9    | 4.05             | 0.04            |
| 4C +30.04         | 11:35   | 20:40  | 2.0   | 2.2  | ...   | ...    | 7.62             | 0.08            |
| B 20326 + 27      | 29:57   | 15:54  | 1.2   | 97   | 0.6   | 8.1    | 4.50             | 0.04            |
| 3C 092            | 04:08   | 03:12  | 2.5   | 3.9  | ...   | ...    | 13.96            | 0.99            |
| 3C 093.1          | 48:46   | 15:41  | 2.2   | 2.4  | ...   | ...    | 8.93             | 0.23            |
| 4C +26.12         | 52:04   | 18:11  | 0.8   | 1.1  | 50   | 0.9    | 11.7             | 4.87            |

Notes.
(a), (b), and (c) Names and coordinates of the radio continuum sources listed in Table 1 of Stanimirović et al. (2014).
(d) $\tau_{55}$ values toward the sources.
(e) $N_H$ values toward the sources calculated by Equation (3).
(f) and (g) H I spin temperature and H I optical depth calculated by Equations (5) and (6).
(h) Velocity-integrated H I optical depth derived from column (g) and $\Delta V_{HI}$.
(i) Total velocity-integrated H I optical depth derived from the Gaussian parameters of $\eta_{HI}$ spectra of Stanimirović et al. (2014).

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\(\langle X_{CO} \rangle \sim 1.0 \times 10^{20} \text{ cm}^{-2} \text{ K}^{-1} \text{ km}^{-1} \text{ s} \) and \(\langle X_{CO} \rangle_{\text{Lee}} \sim 4.0 \times 10^{20} \text{ cm}^{-2} \text{ K}^{-1} \text{ km}^{-1} \text{ s} \) for the present study and Lee’s result, respectively, and the result of Lee et al. (2012, 2014) is well reproduced. In Figure 13(b) we show histograms of $N_H$ derived using Equation (3) and the same method as Lee et al. (2012). We found \(\langle N_H \rangle \sim 4.3 \times 10^{23} \text{ cm}^{-2} \) and \(\langle N_H \rangle_{\text{Lee}} \sim 1.4 \times 10^{23} \text{ cm}^{-2} \), hence Lee et al. (2012) underestimated $N_H$ to be \(\sim 40\% \).

Here we will quantitatively examine the difference in $X_{CO}$ between the present study and Lee et al. (2012, 2014). Since $X_{CO} = N_H / W_{CO}$, the underestimation of $X_{CO}$ in Lee et al. (2012, 2014) is caused by the underestimation of $N_H$ in Equation (9). Therefore we investigated the cause of the underestimation of $N_H$ and $N_{HI}$ in Equation (9). Figure 14(a) is a correlation plot between $\tau_{55}$ and $I_{200}$. The correlation coefficient is \(\sim 0.5\), and we found that $I_{200}$ is not a good tracer of $N_H$. Figure 14(b) shows a correlation between $N_H$ calculated by Equation (3) and $N_{HI}$ calculated by the same method as Lee et al. (2012). The dashed line indicates the 1:1 relationship. The latter is clearly underestimated (\(\sim 35\% \) on average) against the former. Separately from that, in Lee et al. (2012, 2014), the effect of H I optical depth was not considered. As shown in Section 3.4, the effect of $\eta_{HI}$ is $N_{HI} / N_{HI}^{*} \sim 1.6$. Therefore $N_{HI}$ is underestimated to be (at least) \(\sim 62\% \) on average. In addition, the integrated velocity range of H I spectra is from \(\sim 5\) to \(+15 \text{ km} \text{ s}^{-1} \) in Lee et al. (2012). This corresponds to \(\sim 76\% \) of the total integrated intensity of the mean spectrum shown in Figure 3(b). From these, $N_{HI}$ in Equation (9) is underestimated as at least \(62\% \times 76\% \sim 50\% \) or less on average. In Lee et al. (2012, 2014), the right side of Equation (9) is underestimated to be \(\sim 40\% \), hence $X_{CO}$ is underestimated to be \(\sim 40\% \) against our result.

Figure 15 shows a correlation between $W_{CO}$ and $X_{CO}$ maps. We spatially smoothed the $W_{CO}$ map to a 1 deg effective HPBW in order to compare with $X_{CO}$, and we plotted the data points where $X_{CO} \geq 3\sigma$. We also show the average and the standard deviation of $X_{CO}$ in each 1 K km s\(^{-1}\) bin as the white circles and the vertical bars. From this plot, we found an anticorrelation relationship between the two variables. This anticorrelation reflects that in the diffuse (low-$W_{CO}$) region, the CO molecule is photo-dissociated more effectively than H$_2$, and therefore $X_{CO}$ increases. This trend is consistent with the result in Cotten & Magnani (2013) and Schultheis et al. (2014), and we can say that the spatial distribution of $X_{CO}$ can be well calculated by using the present method.

4.2. Mass

The total mass of the hydrogen gas including H I, H$_2$, and helium is derived as $M_{HI} = 1.8 \times 10^5 M_{\odot}$ by using $N_H$ calculated by Equation (3). We assumed the distance to the Perseus cloud as 300 pc (Bally et al. 2008). On the other hand, the mass of the molecular hydrogen gas is calculated as $M_{H_2} = 2.5 \times 10^4 M_{\odot}$ by using $W_{CO}$ and the $X_{CO}$ map obtained in Section 3.6. From these masses, we calculate the mass of the atomic hydrogen gas as $M_{HI} = M_{HI} - M_{H_2} = 1.5 \times 10^5 M_{\odot}$. This indicates that the molecular cloud is surrounded by the atomic gas whose mass is by an order of magnitude larger than that of the molecular one, and it also indicates that the atomic gas is the principal component of the ISM. This is consistent with the result for the MBM 53, 54, 55/HILCG 92–35 region described in Fukui et al. (2014). Note that the virial mass of the H I gas around the Perseus cloud is calculated as \(\sim 2 \times 10^9 M_{\odot} \), if we assume that the gas around the Perseus cloud is a sphere with a radius of 50 pc and a velocity width of 15 km s\(^{-1}\). This is an order of magnitude larger than the estimated mass above (\(1.5 \times 10^5 M_{\odot} \)), and hence it is not gravitationally bound. The virial mass of the CO cloud is \(\sim 1 \times 10^5 M_{\odot} \), if we assume that its radius is 25 pc and its velocity width is 5 km s\(^{-1}\). The molecular mass estimated above (\(2.5 \times 10^4 M_{\odot} \)) is \(\sim 1/4\) of this virial mass, and the
cloud traced by $^{12}$CO($J = 1–0$) line is also not gravitationally bound. Since the molecular cloud is denser than the atomic cloud, the mass of the molecular cloud is relatively closer to its virial mass than that of the atomic cloud.

4.3. $\tau_{\text{HI}}$

As one of the previous studies on the atomic gas in the Perseus region, Stanimirović et al. (2014) calculated the HI optical depth toward 26 extra-Galactic radio continuum sources (such as quasars). They calculated $\tau_{\text{HI}}$ as a function of velocity toward each radio source by using the method described in Heiles & Troland (2003). The calculated $\tau_{\text{HI}}$ spectra were fitted with a sum of Gaussian functions, and the peak $\tau_{\text{HI}}$ values and the Gaussian FWHMs (full width at half maximum) of each velocity component were derived. However, they found the optically thick HI gas only toward $\sim 15\%$ of lines of sight. We test the results in Stanimirović et al. (2014) and Fukui et al. (2014, 2015), which differ by several factors. To do this, we compare $\tau_{\text{HI}}$ derived in Stanimirović et al. (2014) and that obtained in Section 3.5. Since our $\tau_{\text{HI}}$ corresponds to the average value within given velocity width ($D V_{\text{HI}}$; see Section 3.4), we compare the following two values toward each radio source located in the region we analyzed: (1) the sum of the areas of each Gaussian component of the $\tau_{\text{HI}}$ profiles calculated in Stanimirović et al. (2014), and (2) the products of our $\tau_{\text{HI}}$ and $D V_{\text{HI}}$. The results are listed in columns 8 and 9 of Table 2. Note that 4C +30.04, 3C 092, and 3C
093.1 are located at the masked area; therefore $T_H$ cannot be calculated by our method toward them. Although there is a rough positive correlation between them, they differ 2--4 times as a concrete numerical value. The correlation between them is plotted in Figure 16. The solid line indicates the one-to-one relationship ($\beta = 1$), and the dashed line is the best-fit regression line through the origin ($\beta = 2.1$). The results in Stanimirović et al. (2014) are systematically smaller than our results, and it is obvious that there is a discrepancy between these two results. This discrepancy can, however, be explained by characteristics of the data used to derive $T_H$ in the present study and Stanimirović et al. (2014).

In Stanimirović et al. (2014), $T_H$ is calculated based on the 21 cm absorption spectrum toward the extra-Galactic point sources. Since these point sources have infinitesimal apparent size, the absorption by the H I gas actually occurs toward the very direction of each source. However, Inoue & Inutsuka (2012) and McClure-Griffiths et al. (2006) revealed that the cold neutral medium (CNM), which is an optically thick component of the H I gas, has a highly filamentary and spatially

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**Figure 12.** (a) Map of $W_{\text{CO}}$ overlaid with $r = 1^\circ$ windows (A)--(D), (b) Map of $N_H$ overlaid with the windows (A)--(D). (c) Map of the estimated spatial distribution of the $X_{\text{CO}}$ factor. In Figures 11(a)--(d), we show examples of $W_{\text{CO}}$--$N_H$ correlation plots using the data points inside the windows (A)--(D) used to compute $X_{\text{CO}}$ at their center positions (X-points). The average value of $X_{\text{CO}}$ is $\langle X_{\text{CO}} \rangle = 1.0 \times 10^{20}$ cm$^{-2}$ K$^{-1}$ km s$^{-1}$ (Figure 11(e)).

**Figure 13.** Histograms of (a) $X_{\text{CO}}$ and (b) $N_H$ for the region shown in Figure 12. The orange ones are obtained in the present study, and the purple ones are obtained by replicating the procedures described in Lee et al. (2012, 2014). The dashed lines denote the average values of each histogram.
inhomogeneous structure. Based on the three-dimensional numerical simulation of magnetohydrodynamics (MHD; Inoue & Inutsuka 2012), we found that the CNM accounts for typically ~30% of the 2D-projected area (Fukui et al. 2017). Hence the probability with which the CNM affects the absorption toward the point sources is small. Therefore, unless the observational beam size is not infinitesimal, absorption measurements tend to detect only warm neutral medium (WNM) and tend to regard the optical depth of the WNM as the average value within the beam. On the other hand, we use the emission data of gas and dust, and they include information from both the CNM and the WNM within the large beam (≤4 arcmin). Therefore we can say that the discrepancy of $\tau_{HI}$ is due to the difference between the measurement methods (absorption toward point sources or emission). We independently confirm this result by using the numerical simulation (“synthetic” observations) separately in Fukui et al. (2017).

5. Conclusions

In the present paper, we discussed the amount of the interstellar hydrogen gas and H I optical depth in the Perseus region by using the dust emission parameters obtained in Planck, H I 21 cm line, and CO line data. The results are as follows:

1. The distributions of the data points on the $\tau_{353}$–$W_{HI}$ plot systematically vary by the change in $T_d$. This is consistent with the results in Fukui et al. (2014, 2015), which is that H I optical depth cannot be ignored for the low-$T_d$ points. However, since the distance to the Perseus region is larger than that to the region analyzed in Fukui et al. (2014, 2015) and there exist the SFRs, the $\tau_{353}$–$W_{HI}$ plot is somewhat complicated as compared with the local clouds. As described in Section 3.4, the previous studies (Fukui et al. 2012, 2015) showed that the total hydrogen amount can be explained without assuming the presence of “CO-dark H$_2$ gas.” Therefore we consider that the bad correlation between $\tau_{353}$ and $W_{HI}$ for the low-$T_d$ points is due to optically thick H I gas.

2. In order to consider the dust evolution at high density regions, we calibrated the $\tau_{353}$–$N_H$ relationship by using the extinction at J-band. As with Roy et al. (2013), we confirmed that $\tau_{353}$ becomes larger as a function of the 1.3th power of $N_H$ ($\alpha = 1.3$). In addition, we
reconsidered the reference values of $\tau_{353}$ and $N_H$ in Equation (2) by referring to the results in Fukui et al. (2014). The calibrated $\tau_{353} - N_H$ relationship (Equation (3)) yields $\sim 20\%$ smaller $N_H$ than that in the case of $\alpha = 1.0$. By using this relationship, we can calculate $N_H$ from $\tau_{353}$ more accurately, taking the dust evolution into account.

3. Compared with the present method, the conventional method, which assumes that the H I gas is optically thin, underestimates the amount of the hydrogen gas to be $\sim 62\%$ in the Perseus region. Optical depth of the H I gas ($\tau_{HI}$) and spin temperature ($T_s$) can be calculated, and we obtain $\langle \tau_{HI} \rangle \sim 0.92$. These results support that there exists a large amount of optically thick H I gas around the molecular clouds. The arguments by Fukui et al. (2014, 2015) still hold in the region where the density is relatively high and there exist the SFRs.

4. By using $N_H$ calculated from $\tau_{353}$ and the CO intensity ($W_{CO}$), we estimated the spatial distribution of $X_{CO}$. We obtained $(X_{CO}) \sim 1.0 \times 10^{20}$ cm$^{-2}$ K$^{-1}$ km s$^{-1}$, which is consistent with the conventional value in the Galaxy, $X_{CO} \sim (1-2) \times 10^{20}$ cm$^{-2}$ K$^{-1}$ km s$^{-1}$. The relative uncertainty in $X_{CO}$ is smaller than conventional estimation and that in previous studies—typically 10%–50%. Although the result in Lee et al. (2012, 2014) is underestimated to be $\sim 40\%$ compared with this result, this discrepancy in the $X_{CO}$ maps can be quantitatively explained by the difference of the data used in order to calculate $N_H$, the effect of the optical depth of H I, and the difference of the integrated velocity ranges of H I 21 cm spectra.

5. We compared our $\tau_{HI}$ with that obtained in Stanimirović et al. (2014). When the optical depth is calculated based on the absorption measurements toward the background point sources, it can be underestimated to be $\sim 40\%$ on average, compared with that obtained based on the gas/dust emission data. It is revealed that the cold H I gas (CNM) has highly filamentary distribution by numerical simulation studies (e.g., Inoue & Inutsuka 2012). Therefore the probability with which the optically thick H I filaments lie on the infinitesimal apparent-size sources is small, $\sim 30\%$. The underestimation of $\tau_{HI}$ in absorption measurements is consistent with this picture.

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Appendix
Determination of $\tau_{353,ref}$ and $N_{H,ref}$

$\tau_{353,ref}$ and $N_{H,ref}$ are the normalization constants conveniently introduced in order to nondimensionalize both sides of Equation (2). Although in Fukui et al. (2015) $\tau_{353,ref}$ and $N_{H,ref}$ are determined as $4.77 \times 10^{-6}$ and $1 \times 10^{21}$ cm$^{-2}$, respectively, we derive our $\tau_{353,ref}$ and $N_{H,ref}$ for the Perseus region by using Equation (7). By giving $\alpha$, $\tau_{HI}$, and using $N_{H,ref} = (1.15 \times 10^{6}) \times X_{HI} \times \tau_{353,ref}$ (Fukui et al. 2015), we make the free parameter in Equation (7) $\tau_{353,ref}$ alone, and determine it from the $\tau_{353}$–$W_{HI}$ plot. First, we describe the estimation of $\tau_{HI}$ for high-$T_d$ points in the Perseus region.

Figure 17 shows theoretical relationships between $N_{H,ref}$ and $W_{HI,ref}$ in the cases of the limit of $\tau_{HI} \ll 1$ and $\tau_{HI} = 1, 2, 3$ or $T_d = 20, 50, 100$ K. We assumed that $\Delta V_{HI} = 10$ km s$^{-1}$ and $T_{bg} = 2.7$ K. One can see that the variation width in $W_{HI,ref}$ becomes larger when $\tau_{HI}$ becomes higher, even if $T_d$ is a constant (orange curves).

Figure 18 is a $\tau_{353}$–$W_{HI}$ correlation plot (similar to Figure 6 in the present paper) for the MBM 53, 54, 55, and HLC G92–35 region (Yamamoto et al. 2003; Fukui et al. 2014). Although Figure 18 is almost the same as a figure in Fukui et al. (2014), the Planck dust data R1.20 are used, and we apply an additional mask that excludes the data points where intermediate-velocity clouds (Pegasus-Pisces Arch, Albert & Danly 2004) are detected in Figure 18. If we regard $\tau_{353}$ as a tracer of $N_{H,ref}$ and if there is a positive correlation relationship between $T_d$ and $T_s$, Figures 17 and 18 can roughly be considered.
as the same thing. Since it is thought that $\tau_{\text{H}1}$ is larger if $T_d$ is lower, the variation width in $W_{\text{H}1}$ for the low-$T_d$ points is relatively large in Figure 18, and vice versa. Accordingly, we performed linear fittings for each $T_d$ range and examined variances from each regression line. We used the reduced major axis regression method (e.g., Isobe et al. 1990), which minimizes the sum of the areas of the right-angled triangles delimited by each data point and the regression line, $\sum S_i$, and we defined the variance as the mean of the areas of the triangles, $\langle S \rangle$.

The results are shown in Table 3 and in Figure 19. In the MBM 53, 54, 55 region, an anticorrelation relationship between $T_d$ and $\langle S \rangle$, can obviously be seen (the columns 1 and 2 of Table 3 and Figure 19(a)). Column 3 of Table 3 shows the mean $\tau_{\text{H}1}$ values for each $T_d$ range, derived by using the method described in Fukui et al. (2014), and we can see a positive correlation relationship against $\langle S \rangle$ (see also Figure 19(b)). Therefore $\langle \tau_{\text{H}1} \rangle$ for $T_d \geq 20.0$ K for the Perseus region can be estimated by using the $\langle \tau_{\text{H}1} \rangle$-$\langle S \rangle$ relationship for the MBM 53, 54, 55 region as a template. The solid line in Figure 19(b) indicates the result of a linear fitting for the $\langle \tau_{\text{H}1} \rangle$-$\langle S \rangle$ relationship. By referring this line, we get $\langle \tau_{\text{H}1} \rangle$ for $T_d \geq 20.0$ K for the Perseus region as $\langle \tau_{\text{H}1} \rangle = 0.11$ from $\langle S \rangle = 0.5 \times 10^{-5}$ K km s$^{-1}$ (the dashed lines).

We apply $\langle \tau_{\text{H}1} \rangle$ to Equation (7), and with this function, fitting the data points of $T_d \geq 20.0$ K, $\tau_{\text{H}1,\text{ref}}$ for the Perseus region can be calculated. Note that $\alpha = 1.3$ was applied, and we used the relationship of $N_{\text{H}1,\text{ref}} = (1.15 \times 10^3) \times X_{\text{H}1} \times \tau_{\text{H}1,\text{ref}}$ (Fukui et al. 2015). The result of the fitting is plotted in

![Figure 18](image_url) **Figure 18.** $\tau_{\text{H}1}$–$W_{\text{H}1}$ correlation plot in the MBM 53, 54, 55/HLCG 92–35 region (Fukui et al. 2014) colored by $T_d$. We used the Planck dust data R1.20, unlike Fukui et al. (2014). The results of RMA (reduced major axis) regressions for each $T_d$ range are also plotted. We assumed that H1 gas is optically thin for the data points of $T_d > 21.5$ K (Fukui et al. 2014); therefore we make the regression line for $T_d > 21.5$ K pass through the origin.

![Figure 19](image_url) **Figure 19.** (a) Dispersions of the data points for each $T_d$ range. The open circles indicate the results for the MBM 53, 54, 55 region, and we use this as a template. The diamonds indicate the result for the Perseus region. The colors of the diamonds are the same as Figure 20. (b) The relationship between $\langle \tau_{\text{H}1} \rangle$ (average of $\tau_{\text{H}1}$ derived by the same method as Fukui et al. 2014) and the variance for each $T_d$ range (MBM 53, 54, 55 template). The solid line indicates the result of a linear fit. The horizontal dashed line denotes $\langle S \rangle$ for the range of $T_d > 20.0$ K, and the vertical dashed line the corresponding $\langle \tau_{\text{H}1} \rangle (=0.11)$.

### Table 3

| $T_d$ (K) | MBM 53, 54, 55 | Perseus |
|-----------|----------------|---------|
|           | $\langle S \rangle$ | $\langle \tau_{\text{H}1} \rangle$ |
|           | ($10^{-5}$ K km s$^{-1}$) | ($10^{-5}$ K km s$^{-1}$) |
| 21.5<     | 0.34            | 0.09    |
| 21.0–21.5 | 0.34            | 0.14    |
| 20.5–21.0 | 0.45            | 0.22    |
| 20.0–20.5 | 0.48            | 0.30    |
| 19.5–20.0 | 0.52            | 0.42    |
| 19.0–19.5 | 0.76            | 0.66    |
| 18.5–19.0 | 1.09            | 1.01    |
| 18.0–18.5 | 1.63            | 1.54    |
| 17.5–18.0 | 3.34            | 2.56    |
| <17.5     | 3.95            | 3.76    |

**Note.** The dispersions of the data points from the regression lines shown in Figure 18. (a) The $T_d$ range. (b) and (c) The dispersions of the data points defined in the text, and the mean value of $\tau_{\text{H}1}$ estimated in Fukui et al. (2014). We use the relationship between these two as a template. (d) The dispersions of the data points in the Perseus region.
Figure 20. $\tau_{353}$–$W_{{\rm HI}}$ plot in the Perseus region. The right-side y-axis indicates the column number density of H i in the optically thin limit ($N_{{\rm HI}}$). Fitting the data points where $T_d > 20.0$ K with the theoretical function fixing $\alpha = 1.3$ and $n_{{\rm H_2}} = 0.11$, we get $\tau_{353,\text{ref}} = 1.2 \times 10^{-6}$. Note that we use the relationship described in Fukui et al. (2015), $N_{{\rm HI,\text{ref}}} = (1.13 \times 10^8) \times n_{{\rm HI}} \times \tau_{353,\text{ref}}$. The left dotted curves indicate the case in which $\tau_{353,\text{ref}} = 4.77 \times 10^{-6}$, and the right curve indicates the case in which $\tau_{353,\text{ref}} = 8.7 \times 10^{-7}$. The dashed lines correspond to $\tau_{353,\text{ref}} = 1.2 \times 10^{-6}$ and $N_{{\rm HI,\text{ref}}} = 2.5 \times 10^{20}$ cm$^{-2}$.

From the provided results, we adopted $\alpha = 1.3$, $\tau_{353,\text{ref}} = 1.2 \times 10^{-6}$, and $N_{{\rm HI,\text{ref}}} = 2.5 \times 10^{20}$ cm$^{-2}$ for the Perseus region.

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