Gas and Dust Properties in the Chamaeleon Molecular Cloud Complex Based on the Optically Thick H\textsc{i}

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Abstract

Gas and dust properties in the Chamaeleon molecular cloud complex have been investigated with emission lines from the atomic hydrogen (H\textsc{i}) and \textsuperscript{12}CO molecules, dust optical depth at 353 GHz (\(\tau_{353}\)), and J-band infrared extinction (A\textsubscript{J}). We have found a scatter correlation between the H\textsc{i} integrated intensity (\(W_{\text{H\textsc{i}}}\)) and \(\tau_{353}\) in the Chamaeleon region. The scattering has been examined in terms of a possible large optical depth in H\textsc{i}, the model curve reproduces well the \(W_{\text{H\textsc{i}}} - \tau_{353}\) scatter correlation, suggesting optically thick H\textsc{i} (\(\tau_{\text{H\textsc{i}}} \sim 1.3\)) extended around the molecular clouds.

Based on the correlations between the CO integrated intensity and the dust optical depth \(\tau_{353}\), the model curve reproduces well the \(W_{\text{H\textsc{i}}} - \tau_{353}\) scatter correlation, suggesting optically thick H\textsc{i} (\(\tau_{\text{H\textsc{i}}} \sim 1.3\)) extended around the molecular clouds.

Key words: ISM: atoms – ISM: individual objects (Chamaeleon Molecular Cloud) – ISM: molecules

1. Introduction

The neutral hydrogen on the atomic and molecular forms occupies the major mass of the interstellar medium (ISM) and is a fundamental constituent of the ISM. In the electronic ground state, neutral atomic hydrogen (H\textsc{i}) has two spin states where the spin angular momenta of a proton and an electron are parallel or antiparallel. The energy separation between the two states is small (5.9 × 10^{-6} eV) and corresponds to a wavelength of 21 cm. The 21 cm H\textsc{i} transition is used to calculate the H\textsc{i} column density (\(N_{\text{H\textsc{i}}}\)), usually by assuming that the emission is completely optically thin (e.g., Boulanger & Perault 1988).

The interstellar H\textsc{i} gas, however, has a density and temperature that range over an order of magnitude: density is distributed from 1 to 10\(^6\) cm\(^{-3}\) and temperature from 10 to 10\(^7\) K (e.g., Draine 2011). The gas consists of two distinct phases, the cold neutral medium (CNM) and the warm neutral medium (WNM). The CNM is dense and cool (∼30 cm\(^{-3}\)) and ∼60 K, while the WNM is diffuse and warm (∼0.6 cm\(^{-3}\)) and ∼2000 K; e.g., Heiles & Troland 2003b; Draine 2011). The H\textsc{i} gas is highly turbulent and transient because it is continuously shocked by supernovae every million years.

To precisely measure the local H\textsc{i} gas with the large variations of the optical depth, Fukui et al. (2014, 2015, hereafter F14, F15) proposed a method to calculate \(N_{\text{H\textsc{i}}}\) based on dust optical depth at 353 GHz (\(\tau_{353}\)), which is estimated from modified blackbody spectra fitted to the fluxes at submillimeter wavelengths measured by the Planck and IRAS satellites (Planck Collaboration XI 2014). Here \(\tau_{353}\) is measured to be very small, on the order of ∼10\(^{-3}\), toward the Galactic midplane, and we are able to use \(\tau_{353}\) as a tracer of \(N_{\text{H\textsc{i}}}\) if the gas-to-dust ratio is uniform. The results of F14 and F15 suggest that the H\textsc{i} emission can be optically thick, on the order of 1.0, with low spin temperature (\(T_{\text{S}} \lesssim 100\) K), and the considerable amount of atomic hydrogen is underestimated by the optically thin assumption often adopted in studies of the local ISM.

Stanimirović et al. (2014) carried out H\textsc{i} absorption observations toward 26 radio continuum sources behind Perseus using the Arecibo 305 m telescope. These authors showed that the H\textsc{i} optical depth (\(\tau_{\text{H\textsc{i}}}\)) in the emission–absorption measurements is significantly smaller than that derived by F14 and F15; the peak optical depth of \(\tau_{\text{H\textsc{i}}} > 0.5\) for only 21 out of 107 individual Gaussian components, as opposed to F14, who found \(\tau_{\text{H\textsc{i}}} > 0.5\) for 85% of the lines of sight at high Galactic latitudes. The results by Stanimirović et al. (2014) are consistent with those by Heiles & Troland (2003a, 2003b) toward 79 extragalactic sources and raised a question on F14 and F15.

Recently, Fukui et al. (2018) made synthetic observations of 21 cm emission and absorption by using the magnetohydrodynamic simulations performed by Inoue & Inutsuka (2012) and presented that the synthetic observations are consistent with the optically thick H\textsc{i} and the \(T_{\text{S}}\)-dependent relationship between \(N_{\text{H\textsc{i}}}\) and the H\textsc{i} integrated intensity (\(W_{\text{H\textsc{i}}}\)) suggested by F14 and F15. In addition, Fukui et al. (2018) found that the WNM with \(\tau_{\text{H\textsc{i}}} < 0.5\) and \(T_{\text{S}}\) higher than 300 K is extended by ∼70% in the sky and the radio absorption toward extragalactic continuum sources is biased toward WNM. These results give an estimate that the optically thin approximation for the H\textsc{i} emission underestimates the H\textsc{i} mass by a factor of ∼1.3. Okamoto et al. (2017) showed that the H\textsc{i} distribution in the Perseus molecular cloud can be reproduced well by the total...
column density ($N_{\text{HI}}$) model as a function of $\sim$1/1.3rd power of $\tau_{353}$. The authors derived that the H I column density is 1.6 times higher than that of the optically thin case, suggesting a large amount of the optically thick H I around the molecular clouds. The nonlinear behavior between $\tau_{353}$ and $N_{\text{HI}}$ indicates a dust evolution effect, as suggested from measurements of dust opacity in local molecular clouds (e.g., Roy et al. 2013 for the Orion A molecular cloud).

Among other local molecular cloud complexes, the Chamaeleon complex is known as a nearby low-mass star-forming region at a distance of $\sim$150 pc whose molecular cloud mass is estimated to be $\sim$5000–8000 $M_{\odot}$ (e.g., Mizuno et al. 2001; Ackermann et al. 2012; Planck Collaboration XXVIII 2015). The cloud properties and moderate star formation activities are reviewed by Luhman (2008). Planck Collaboration XXVIII (2015) attempted to model the gas distribution in the Chamaeleon region with a linear combination of H I, CO, and “dark gas,” a neutral gas component that cannot be traced by standard H I and CO observations, and estimated the gas column density by fitting these gas model maps to $\gamma$-rays and thermal dust emission models (dust extinction, $\tau_{353}$, and radiances). The dark-gas template is constructed through alternately iterating fittings to the $\gamma$-rays and dust data. The $T_e$ in the H I emission is assumed to be uniform, and the optically thin approximation is adopted because it gives a better fit to the $\gamma$-ray data as compared to other H I maps with several uniform $T_e$ from 125 to 800 K. Although gas properties in the cloud complex are discussed under the assumption of CO-dark H$_2$ (e.g., Wolfire et al. 2010; Smith et al. 2014) as a candidate of the dark gas, a quantitative estimate of the optically thick H I is not performed in their studies. The assumption of a uniform $T_e$ makes it difficult to examine the H I gas with low $T_e$ present in the CNM (e.g., Heiles & Troland 2003b).

On the other hand, F14 and F15 have attempted to examine a total column density model as a function of $\tau_{353}$. The $N_{\text{HI}}$ model not relying on a uniform $T_e$ allows accurate measurements of the H I gas. F14 and F15 found that the $N_{\text{HI}}$ model reproduces the scatter correlation in the $\tau_{353}$–H I $N_{\text{HI}}$ relationship, suggesting a large amount of the optically thick H I around molecular clouds. Okamoto et al. (2017) demonstrated that the $N_{\text{HI}}$ model is applicable in the Perseus molecular clouds and suggested that the average H I optical depth is up to $\sim$0.9. Using the obtained $N_{\text{HI}}$ model, the authors also derived a spatial distribution of the CO-to-H$_2$ conversion factor ($X_{\text{CO}}$) with the average value $\sim$1.0 × 10$^{20}$ cm$^{-2}$ K$^{-1}$ km$^{-1}$ s, which is comparable to past measurements of the Galactic interstellar clouds (e.g., Bolatto et al. 2013).

In this paper, we aim to investigate gas properties in the Chamaeleon region, focusing on the optically thick H I, by attempting the method applied in Okamoto et al. (2017). The aim of the present paper is summarized below.

1. Applying the $\tau_{353}$-based $N_{\text{HI}}$ model to the Chamaeleon complex to understand the physical states of the H I gas through a comparison with F14 (MBM 53, 54, 55 and HLC G9235, hereafter MBM 53–55), F15 ($|b| > 15^\circ$ in the all sky), and Okamoto et al. (2017; Perseus) and derive the distribution of $X_{\text{CO}}$ factor.

2. To test dust evolution found in the Orion A (Roy et al. 2013) and Perseus (Okamoto et al. 2017) regions. This will bring a better understanding of dust properties in the local ISM.

This paper is organized as follows. Section 2 shows observational data sets. Section 3 summarizes the gas properties in the Chamaeleon region. Section 4 describes the $N_{\text{HI}}$ model applied in this study. In Section 5, we discuss the possibility of the optically thick H I and these gas properties in comparison with other local molecular clouds. A summary is given in Section 6. All velocity information in the present paper is represented by local standard of rest (denoted as $V_{\text{LSR}}$).

### 2. Observational Data Sets

To investigate the gas and dust properties in the Chamaeleon region, we have used the following data sets.

#### 2.1. H I Data

The Galactic All-sky Survey (GASS) conducted with the Parkes 64 m radio telescope has provided the most sensitive and highest-resolution data of the H I 21 cm line emission for the southern sky (McClure-Griffiths et al. 2009; Kalberla et al. 2010, 2014; Kalberla & Haud 2015). In this study, we have used the second released GASS data, in which the effects of stray radiation received by the antenna diagram have been corrected (Kalberla et al. 2010). We have kept the half-power beam width (HPBW) of 16$'$ and velocity resolution of 0.82 km s$^{-1}$ in the original data. A typical noise level for the analysis region in rms is $\sim$0.05 K channel$^{-1}$. The measured velocity range for the Chamaeleon region is $-500$ to $+400$ km s$^{-1}$, but most of the H I line velocities span $-40$ km s$^{-1} \lesssim V_{\text{LSR}} \lesssim +20$ km s$^{-1}$, except for possible contributions from the Large Magellanic Cloud (LMC) at $+200$ km s$^{-1} \lesssim V_{\text{LSR}} \lesssim +300$ km s$^{-1}$.

#### 2.2. CO Data

To trace the distribution of molecular hydrogen, we have used the $^{12}$CO J = 1–0 emission line observed by the NANTEN 4 m telescope located at Las Campanas, Chile. NANTEN observations toward the Chamaeleon region were performed during two periods, from 1999 July to September and from 2000 October to December (Mizuno et al. 2001). The HPBW of the data is 2$'$ at 115 GHz with grid spacing of 8$'$, and the typical noise fluctuation is $\sim$0.3 K at a velocity resolution of 0.1 km s$^{-1}$.

#### 2.3. Planck and IRAS Dust Emission Data

The IRAS and Planck satellites performed the all-sky survey in millimeter/submillimeter wavelength, providing high-quality data of the thermal dust emission. The measured intensities of the Planck 353, 545, and 857 GHz data and the Improved Reprocessing of the IRAS Survey (IRIS) 100 µm data were fitted by modified blackbody intensity spectra (Planck Collaboration et al. 2011), which reveal dust properties down to 5$'$ spatial resolution in HPBW with a relative accuracy of $\sim$10%. In this analysis, we have used the dust optical depth at 353 GHz ($\tau_{353}$) and the dust temperature ($T_d$) to model/evaluate the total gas column density. The data with HEALPix format (Górski et al. 2005) released version R1.10$^3$ are used.

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3. The H I 4$\alpha$ (HI4PI) survey (Bekhti et al. 2016) adopting the third revision of GASS data (Kalberla & Haud 2015) was released in 2016. Instrumental effects that remained in the past GASS data are corrected. We confirmed that our results do not change significantly even if we use these revised data.

4. http://irsa.ipac.caltech.edu/data/Planck/release_1/all-sky-maps/
2.4. J-band Extinction Data

Using the Two Micron All Sky Survey (2MASS) infrared extinction data measured at the J, H, and K bands, Juvela & Montillaud (2016) derived an interstellar extinction map at the J band (A_J) over the whole sky, with optimal techniques to map the dust column density ("NICER," Lombardi & Alves 2001; "NICEST," Lombardi 2009). In the present study, we have used the A_J map constructed with the "NICEST" method to investigate the correlation with the dust optical depth for the Chamaeleon complex. An all-sky map given in magnitude at a spatial resolution of 3′ (FWHM) with the HEALPix format was downloaded from the archival page.5 The typical noise fluctuation for the Chamaeleon region is ∼0.08 mag in rms.

2.5. Hα Data

We have used the optical Hα data obtained from Finkbeiner (2003) in order to identify the bright H II regions, where dust grains are heated up or destroyed by ultraviolet (UV) radiation, and the neutral hydrogen is ionized as well. In the present study, these regions are masked to avoid mixing different gas properties in local specific environments (e.g., faint diffuse gas exposed by the strong radiation near the Galactic plane). The typical sensitivity for the Chamaeleon region is estimated to be ∼0.3 R, and the spatial resolution is 6′ in HPBW.

2.6. 21 cm Radio Continuum Data

Radio continuum data have been used to estimate the contribution from the background radiation, including the 2.7 K cosmic microwave background. We have used the 21 cm (1.4 GHz) "CHIPASS" continuum map (Calabretta et al. 2014), which was constructed by a combination of HI data obtained from the Parkes All-sky Survey and Zone of Avoidance survey. The typical sensitivity is ∼40 mK, and the spatial resolution is 14′/4 in HPBW.

3. Gas and Dust Properties in the Chamaeleon Region

3.1. Gas and Dust Spatial Distributions

Using the data sets described in Section 2, we have made maps showing the spatial distributions of the gas and dust properties in the Chamaeleon region, which are summarized in Figure 1. Each map in panels (a)–(g) is described below.

(a) Velocity-integrated intensity map of the ^12CO J = 1–0 line (hereafter denoted as W_{CO}) obtained by the NANTEN 4 m telescope. The integrated velocity range is from −16 to +16 km s−1, where most of the emission is included. The peak intensity in W_{CO} ~ 25 K km s−1 is intermediate between those measured from the MBM 53–55 (Yamamoto et al. 2003) and Perseus (Okamoto et al. 2017) molecular clouds.

(b) Velocity-integrated intensity map of the H I 21 cm line (W_{HI}) obtained from the GASS data (McClure-Griffiths et al. 2009; Kalberla et al. 2010). The integrated velocity range is from −500 to +400 km s−1 in the original data. Although scanning effects are found in 300° ≤ l ≤ 310°, −20° ≤ b ≤ −12° (see also Figure 8 in Kalberla & Haud 2015), we confirmed that they do not affect the result of this study. The gas along the line of sight within the region is mainly separated into three components on the basis of the velocity line profile (see Section 3.3).

(c) The T_{353} map obtained from the thermal dust emission model based on the Planck/IRAS data.

(d) Dust temperature map obtained from the thermal dust emission model based on the Planck/IRAS data.

(e) The J-band extinction (A_J; Juvela & Montillaud 2016) obtained with the "NICEST" method (Lombardi & Alves 2001) using the 2MASS near-infrared data.

(f) The Hα intensity map to search the H II regions.

(g) Brightness temperature at 21 cm wavelength derived by Calabretta et al. (2014). The map has been used to estimate the background brightness temperature at 21 cm (T_{bg}; see Section 4).

3.2. Masking Areas

In the present study, when focusing on the atomic gas data, we have masked the molecular gas regions to remove data points with possible contamination from the high-density regions. We also applied the mask to several areas having velocity profiles different from the local clouds with the peaks at V_{LSR} ~ 0 km s−1 (see also Section 3.3) and regions heated by the interstellar radiation field (ISRF), which may change the local gas-to-dust ratio. The areas including the LMC components are also masked, since their gas-to-dust ratios are much different from the local ISM. Figures 2(a)–(f) show the masked regions applied in this analysis.

(a) The areas with significant CO emission (W_{CO} > 1.2 K km s−1 (∼3σ)), where H_2 is dominant compared to H I.

(b) Intermediate-velocity clouds (IVCs) observed in the negative velocity range. The areas with W_{HI} > 50 K km s−1 at V_{LSR} < −30 km s−1 are masked.

(c) The areas including outskirts and streams around the LMC, which are seen around the bottom right part of the analysis region (see the gas and dust distributions in Figures 1(b)–(g)).

(d) Intermediate-velocity arc (IVA) consisting of H I-dominated clouds characterized by an elongated gas structure across the whole longitude direction at −15 km s−1 ≤ V_{LSR} ≤ −5 km s−1 (Planck Collaboration XXVIII 2015). We masked areas where the contribution from IVA is more dominant (l < 290° and b < −22°) compared to the local H I clouds (see details in Section 3.3).

(e) The position around a Be star, HIP 70248, located at (l, b) ~ (306°9.187°).

(f) The region with Hα > 10 R, where the dust grains are heated up or destroyed and hydrogen gas is ionized.

Mask (a) is applied to Figures 5(a), 7, 9(a), 10 (except for the N_{HI} histogram in panel (c)), 15(c), and 18. The other masks are applied to Figures 4–11, 13, 15(c), and 19.

3.3. Velocity Structure in the Neutral Gas

Line profiles obtained from the H I and CO data allow kinematical separation of the gas distribution. Figure 3(a) indicates an H I intensity spectrum showing the brightness temperature (T_{H I}) averaged in the analysis region. Figure 3(b) is an average longitude–velocity diagram, which overlays the CO intensity represented by the black contours. We have found three components separated by the dashed vertical lines in the

5 http://www.interstellarmedium.org
spectrum, whose gas structures are seen in the longitude–velocity diagram and a velocity channel map shown in Figure 16: (i) local clouds with an intensity peak around $V_{\text{LSR}} = 0\text{ km s}^{-1}$, at which most of the CO emission is detected; (ii) winglike structure at the intermediate velocity range spanning $-15\text{ km s}^{-1} \lesssim V_{\text{LSR}} \lesssim -5\text{ km s}^{-1}$, which corresponds to the IVA (Planck Collaboration XXVIII 2015), characterized by a mild gradient in the velocity toward the negative longitude direction, with comparatively bright H I emission at $280^\circ \lesssim l \lesssim 290^\circ$; and (iii) a high-velocity component with a long tail at $V_{\text{LSR}} \lesssim -20\text{ km s}^{-1}$, which corresponds to faint diffuse emission observed at $302^\circ \lesssim l \lesssim 314^\circ$, exhibiting a bridging feature connected to the intermediate clouds. To more clearly show that the H I spectrum can be separated into the three components, we give examples of the spectra in Figure 17 for restricted regions with a size of $1^\circ.0 \times 1^\circ.0$. Planck Collaboration XXVIII (2015) also showed that the similar spectral separation can be applied in the Chamaeleon region. In order to remove contamination from clouds other than the local Chamaeleon complex, we have
masked the region at $(280^\circ \lesssim l \lesssim 290^\circ, b \lesssim -22^\circ)$, where the contribution from the IVA is relatively large, and the regions with strong emission from the high-velocity component. Although the IVA component is extended toward $l \gtrsim 290^\circ$, from which the faint diffuse emission at the high-velocity range is observed, these contributions are not significant compared to that from the local H I clouds lying at the same line of sight. We therefore do not mask this area.

3.4. Correlation between Gas and Dust Properties

We have investigated gas and dust properties using measurements of the Planck dust emission model and the near-infrared extinction, $A_J$. The $J$-band wavelength ($\sim 1.25 \mu m$) is much larger than the typical size of a dust particle ($\lesssim 0.2 \mu m$; Jones et al. 2013), even if we take into account changing the size of a dust particle in its evolution (within $\sim 0.02 \mu m$; Ysard et al. 2015). Martin et al. (2012) suggested that the ratios of near-infrared color excess to $N_{HI}$ change less significantly in the evolutionary process of the dust grains. These results expect that the ratio of $A_J/N_{HI}$ does not change significantly, indicating that $A_J$ can be a tracer to measure the total gas column density.

Figure 4 shows a correlation plot between $\tau_{353}$ and $A_J$ for the Chamaeleon region. Whereas most of the data are saturated in low $A_J$, data above a few 0.1 mag show a tight correlation with $\tau_{353}$. The correlation between the two quantities above 0.32 mag ($\sim 4 \sigma$ in $A_J$) is expressed by a regression line as follows,

\[ \tau_{353} = [(1.35 \pm 0.05) \times 10^{-4}] \times A_J^{2.1\pm0.04}, \]

which is shown by the dashed line in the figure. This correlation between $\tau_{353}$ and $A_J$ indicates that $\tau_{353}$ increases as equivalent to $\sim 1.2$nd power of $N_{HI}$. Similar studies for the Orion A cloud (Roy et al. 2013) and Perseus cloud (Okamoto et al. 2017) found nonlinear relations between dust optical depth and $N_{HI}$, whose power-law exponents are $1.28 \pm 0.01$ and $1.32 \pm 0.04$, respectively. These authors made a point that the nonlinear relation is due to dust evolution effects. Although the correlation between gas and dust properties exhibits variations among the different regions, dust growth in the Chamaeleon region is also traced as a similar nonlinear relation with a power-law exponent of $\sim 1.2$.

Figures 5(a) and (b) show correlation plots of $\tau_{353}$ with $W_{HI}$ and $W_{CO}$, respectively, which are sorted by several $T_d$ in 0.5 K intervals represented by different colors. To more clearly show the data points, the same density distribution plotted in different panels sorted by $T_d$ is given in Figures 18 ($\tau_{353}$–$W_{HI}$) and 19 ($\tau_{353}$–$W_{CO}$). Although the correlation between $\tau_{353}$ and $W_{HI}$ is poor overall, the data points sorted by $T_d$ exhibit clearly different correlations depending on $T_d$: the scattering is small in high-$T_d$ areas, and it becomes larger with decreasing $T_d$. The relationship with $W_{CO}$ does not show a tight correlation either, even if we exclude noisy signals in $W_{CO}$ below $1.2$ K km s$^{-1}$ ($\sim 3\sigma$) and saturated ones above $\sim 8$ K km s$^{-1}$. However, the contrast in the dispersion among the different $T_d$ is not large compared to the relation with $W_{HI}$. As shown in Figure 6, we have found an anticorrelation between $\tau_{353}$ and $T_d$ that is probably related to feedback from the ISRF: in low-density regions with lower $\tau_{353}$, the ISRF heats up dust grains and leads to higher $T_d$. Conversely, in high-density regions where $\tau_{353}$ is large, the ISRF is shielded by dust grains, which leads to lower $T_d$. Similar gas and dust properties are also found in other local molecular cloud

Figure 2. Masked areas (shown by the shaded regions) applied in the present analysis. (a) Molecular gas with $W_{CO} > 3\sigma$. (b) IVCs with $W_{HI} > 50$ K km s$^{-1}$ at $V_{LSR} \leq -30$ km s$^{-1}$. (c) LMC- and (d) IVA-dominated regions. (e) Position of a Be star, HIP 70248. (f) Ionized gas with Hα $> 10$ R. Details are described in the text.
complexes, such as the MBM 53–55 (F14) or Perseus (Okamoto et al. 2017) regions.

4. Modeling the Gas Column Density

The H I column density usually adopted as the optically thin limit ($N_{H1}^*$) is calculated from $W_{H1}$ as follows,

$$N_{H1}^* = X_{H1} \times W_{H1},$$  

(2)

where $X_{H1} = 1.823 \times 10^{18}$ cm$^{-2}$ K$^{-1}$ km$^{-1}$ s. If the H I optical depth, $\tau_{H1}$, does not satisfy $\tau_{H1} \ll 1$, this approximation underestimates the true H I column density. F14 and F15 adopted $\tau_{353}$ as an accurate tracer of $N_{H1}$ and suggested a possible large amount of the optically thick H I in the local ISM. F14 analyzed a molecular cloud region, MBM 53–55, whose gas density and star-forming activities are relatively lower compared to other local molecular cloud regions (e.g., Yamamoto et al. 2003). The tight correlation between $\tau_{353}$ and $W_{H1}$ in high $T_d$ areas can be approximated well by a linear regression with small dispersion. The best-fit linear line is applied to the H I column density in the optically thin case (see Figure 3 in F14). Subsequently, F15 examined an $N_{H}$ model with a nonlinear relation with $\tau_{353}$ to consider the dust evolution effect suggested by Roy et al. (2013).

The model is expressed as

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

(3)

where $\tau_{353, ref}$ and $N_{H, ref}$ are reference points satisfying the relationship $N_{H, ref} = (1.15 \times 10^8) \times X_{H1} \times \tau_{353, ref}$ (Equation (2) in F15). Okamoto et al. (2017) applied the nonlinear $N_{H}$ model to further investigate gas properties in Perseus molecular clouds and revealed that the $N_{H}$ model with the $\sim 1.3$rd power more accurately traces the gaseous components from the diffuse medium to dense cores in the cloud complex.

Following the above studies, we have applied the nonlinear $N_{H}$ model and examined the possibility of optically thick H I in the Chamaeleon region. Based on an assumption of uniform gas-to-dust ratio in the local ISM, we have adopted the power-law index, $\alpha = 1.2$, which is derived from the $\tau_{353}$--$A_J$ relationship found in the opaque region (see Section 3.4). Although this gas-to-dust relation is not obtained from the diffuse H I medium, the similar nonlinearity is confirmed in Roy et al. (2013) down to $N_{HI} \sim 1 \times 10^{21}$ cm$^{-2}$, which corresponds to the typical $N_{HI}$ discussed in F15 and Okamoto et al. (2017). If we take into account that the gas column density significantly affects the dust properties, this assumption is compatible as a first approximation to consider the dust evolution effect. The reference points in the $N_{H}$ model are determined to be $\tau_{353, ref} = 7.8 \times 10^{-7}$ and $N_{H, ref} = 1.6 \times 10^{20}$ cm$^{-2}$, with an analytical method described in Appendix C. The $N_{H}$ model is thus expressed as

$$N_{H} = \left( \frac{\tau_{353}}{\tau_{353, ref}} \right)^{1/\alpha} \times N_{H, ref} = (2.0 \times 10^{25})$$ \times \tau_{353}^{-1/1.2}.  

(4)

Using the $N_{H}$ model, we have modeled the scatter correlation between $\tau_{353}$ and $W_{H1}$ with the following independent two equations (e.g., Dickey & Lockman 1990; Draine 2011): the radiative transfer equation of the H I 21 cm line emission,

$$W_{H1} = (T_s - T_{bg}) \times \Delta V_{H1} \times \{1 - \exp(-\tau_{H1})\},$$  

(5)
Applying average values in the analysis region, $\Delta V_{HI}$ and the $HI$ optical depth derived from the $HI$ spin flip transition,

$$\tau_{HI} = \frac{N_{HI}}{X_{HI}} \times \frac{1}{T_i} \times \frac{1}{\Delta V_{HI}},$$

(6)

where $\Delta V_{HI}$ is the spectral width in velocity, which can be defined as $W_{HI}/T_{HI}$.

Although $T_i$ is not uniform on the line of sight, it can be approximated to a single component with a density-weighted harmonic mean in the line of sight (e.g., Dickey et al. 1979; Heiles & Troland 2003b; Fukui et al. 2018). By applying the $N_{HI}$ model in Equation (4) to the $HI$-dominated region (i.e., $N_{HI} = N_{HI,ref}$), a coupled equation between Equations (5) and (6) gives a theoretical model curve of $W_{HI}$ as a function of $\tau_{353}$,

$$W_{HI} = \left( \frac{\tau_{353}}{\tau_{353,ref}} \right)^{1/\alpha} \times \frac{N_{HI,ref}}{X_{HI}} \times \frac{1}{\tau_{HI}} \times \frac{1}{\Delta V_{HI}} - T_{bg} \times \Delta V_{HI} \times \{1 - \exp(-\tau_{HI})\}.$$  

(7)

Applying average values in the analysis region, $\Delta V_{HI} = 13$ km s$^{-1}$ and $T_{bg} = 3.7$ K, which is estimated from the 21 cm radio continuum data, model curves with $\tau_{HI} \ll 1$ and $\tau_{HI} = 0.34$, 1.0, and 2.0 are represented by the solid lines (from left to right) in Figure 7. For comparison, model curves with $\alpha = 1.0$ for the same $\tau_{HI}$ are also shown. The model curves with high $\tau_{HI}$ allow one to reproduce the scatter correlation in high $\tau_{353}$ areas. The model with the nonlinear relation, $\alpha = 1.2$, traces the mildly curved shape better than $\alpha = 1.0$. This indicates that the $N_{HI}$ model in Equation (4) can approximately reproduce the gas distribution in the $HI$-dominated region. One can see a trend that $\tau_{HI}$ becomes larger with decreasing $T_{HI}$, which indicates that there is a positive correlation between $T_{HI}$ and $T_{bg}$. The contrast of the correlation strength among the different $T_{HI}$ in the $\tau_{353}$–$W_{HI}$ relationship (Figures 5(b) and 19) is not significant compared to the $\tau_{353}$–$W_{HI}$ relationship (Figures 5(a) and 18). The different correlation strength in the $\tau_{353}$–$W_{HI}$ relationship among $T_{HI}$ suggests the existence of the atomic gas with low $T_s$ (optically thick $HI$) around the molecular clouds.

5. Discussion

5.1. Constituent of the Dark Gas

Our study of the Chamaeleon region showed that the optically thick $HI$ is important around the molecular clouds. However, the previous $\gamma$-ray study (Planck Collaboration XXVIII 2015) disagrees with the large amount of optically thick $HI$. We discuss the cause of the contradiction below.

First, it is to be recognized that the $\gamma$-ray study assumes a uniform and high $HI$ spin temperature above 100 K, which is a strong assumption that pre-excludes the high $HI$ optical depth.
It has already been shown by H I emission–absorption measurements (Heiles & Troland 2003b) that $T_s$, the harmonic mean $T_s$ in a line of sight, is as low as 40 K and that low $T_s$ is appreciable in the CNM. Further, $T_s$ varies significantly from 30 K to more than 500 K, indicating that uniform high $T_s$ is not supported. For a realistic low $T_s$ less than 100 K, the H I optical depth is high, more than $\sim 1.0$; $\tau_{\text{HI}}$ derived from Equation (6) is $\sim 1.1$ at $N_{\text{HI}} = 1.0 \times 10^{21} \text{cm}^{-2}$, close to the peak of the $N_{\text{HI}}$ distribution, and $\Delta V_{\text{HI}} = 5 \text{ km s}^{-1}$, a typical line width of the CNM (see F15). We note if $\tau_{\text{HI}}$ is greater than 0.3 and 0.5, an optical depth correction by a factor of 1.2 and 1.3, respectively, is required in calculating $N_{\text{HI}}$. In this sense, the boundary between optically thick or thin H I lines at $\tau_{\text{HI}}$ is 0.3–0.5, depending on the accuracy needed, and the optically thin case is for $\tau_{\text{HI}}$ less than 0.2 in the practical H I sensitivity. We expect that optically thick H I is suggested by a $\gamma$-ray study if the unrealistic assumption of the uniform high $T_s$ is not adopted.

It is discussed in the literature, both observational and theoretical, that there exists a significant amount of CO-dark H$_2$ gas (e.g., Wolfire et al. 2010; Liszt et al. 2018). We discuss these works critically below and look into the cause of the apparent discrepancy.

1. Observations of molecular abundance are often used to estimate the molecular fraction in low-density molecular gas. Since absorption measurements toward radio continuum sources like quasars are more sensitive than emission line measurements, compact continuum sources are used to measure molecular absorption of HCO$^+$, HCN, etc. (e.g., Liszt & Gerin 2016; Liszt et al. 2018; Gerin et al. 2019). Detection of such molecular absorption shows that such rare molecules do exist in the low-density gas where the gas may not be detectable in CO emission due to low density. Liszt et al. (2018) assumed that the abundance ratio between HCO$^+$ and H$_2$ is uniform at $3 \times 10^{-9}$ to derive the H$_2$ density and argued that CO-dark H$_2$ gas may contribute significantly as the dark gas. These authors derived a high CO intensity by assuming $X_{\text{CO}} = 2 \times 10^{-20} \text{ cm}^{-2} \text{ K}^{-1} \text{ km s}^{-1}$, which is about two times higher than those obtained by recent studies of the Chamaeleon region (Ackermann et al. 2012; Planck Collaboration XXVIII 2015), and showed that the predicted CO intensity disagrees with the nondetection of CO by NANTEN by a factor of more than 2 at several points in these clouds. It is probable that their method is not accurate on the order of 10%, because the molecular abundance varies significantly from place to place; Gerin et al. (2019) showed that the HCO$^+$ abundance from ALMA observations, for instance, varies by an order of magnitude for a density around $N_{\text{H}}$ of $10^{20} \text{ cm}^{-2}$ (see their Figure 4), and the assumption of a uniform HCO$^+$ abundance by Liszt et al. (2018) is not supported. The large discrepancy above in the expected CO intensity is explained as due to the unrealistic assumption of uniform HCO$^+$ abundance. In summary, the HCO$^+$ absorption is not an accurate method to calculate H$_2$ abundance because of the small and variable abundance, and the mass estimate of CO-dark gas is uncertain by a factor of 2–3 at best. Accordingly, the molecular absorption is not accurate enough to constrain the dark molecular gas.

Figure 8. Examples of the $\tau_{\text{HI}}$ and $T_s$ calculations. The blue and red solid lines indicate Equations (5) and (6), respectively. The purple solid lines show the solution of $\tau_{\text{HI}}$ and $T_s$. The dashed lines of each color indicate the 1$\sigma$ error limit.
2. Wolfire et al. (2010) made a theoretical study of CO-dark H$_2$ by using calculations of molecular abundance in a model cloud and concluded that CO-dark gas is significant. This study assumes as the initial condition that the gas density is as high as $10^3$ cm$^{-3}$, where hydrogen exists mostly as H$_2$. It is a question if the initial condition is justified. Inoue & Inutsuka (2012) showed how molecular gas is formed in interstellar space by taking H$_1$ gas as the initial condition. This is a more general assumption, and their results show that H$_1$ gas remains significant even after the convergence of H$_1$ flows after 10 Myr. The results suggest a mixture of H$_1$ and H$_2$ gas as the state of the realistic interstellar molecular gas. Therefore, the fraction of H$_2$ is highly dependent on the initial condition. Since molecular gas is formed from atomic gas, any simulations assuming pure H$_2$ as the initial condition need justification before confronting with observations.

Fukui et al. (2018) performed a synthetic observation of the interstellar gas based on the results of Inoue & Inutsuka (2012). They applied the molecular fraction measured by UV absorption (Gillmon et al. 2006) to that of the simulated interstellar gas, whose $N_{H_1}$ is peaked at $\sim 1 \times 10^{21}$ cm$^{-2}$ in a range from $5 \times 10^{20}$ to $2 \times 10^{21}$ cm$^{-2}$, which is consistent with the $N_{H_1}$ distribution obtained by the $\tau_{553}$-based $N_{H_1}$ model (see Figure 4 in Fukui et al. 2018). The results showed that the CNM has clumpy gas distribution with a volume filling factor ($\sim 5\%$) and gas density ($10^2$–$10^3$ cm$^{-3}$), which are consistent with the generally suggested gas properties of the ISM; the gas masses of the CNM and WNM are comparable, while their density fraction is estimated to be 30:1, and thus the ratio of the volume filling factor is 1:30 (e.g., Doppita & Sutherland 2003). The fraction of the CNM in $\int \tau_{H_1} dv$ does not contradict the H$_1$ emission–absorption measurements by Heiles & Troland (2003a; see Figure 13 in Fukui et al. 2018). The simulation showed that the fraction of H$_2$ is only $\sim 5\%$.

From the above discussions, we conclude that in the Chamaeleon region, optically thick H$_1$ is more important than CO-dark H$_2$ and thus a dominant constituent of the dark gas. Hereafter, we discuss the gas properties and distribution, focusing on the optically thick H$_1$.

5.2. Gas Distribution and Mass Fraction

With the $N_{H_1}$ model in Equation (4), we discuss the H$_1$ gas properties and mass fractions in the cloud complex. We have solved the coupled equations between Equations (5) and (6) and derived $\tau_{H_1}$ and $T_s$ values by numerical solution. Figures 8(a)–(d) show examples of the solution for the corresponding positions. The blue and red lines indicate Equations (5) and (6), respectively, and the obtained $\tau_{H_1}$ and $T_s$ are shown by the purple solid lines. The dashed lines indicate 1σ error limits. The errors in the obtained $\tau_{H_1}$ and $T_s$ are given by the dashed crossing points. These examples give solutions ($\tau_{H_1}$, $T_s$ (K)) ~ (1.9, 40), (1.2, 60), (0.6, 80), and (0.3, 100).

Figures 9(a) and (b), respectively, show the distributions of $N_{H_1}$ generated with the $\tau_{H_1}$ and $T_s$ values and $N_{H_1}$ expressed by Equation (4). In the $N_{H_1}$ map, the CO-dominated region is masked. The high-column H$_1$ around the molecular clouds ($N_{H_1} \gtrsim 2 \times 10^{22}$ cm$^{-2}$) indicates a large amount and extent of the optically thick H$_1$. Its distribution is similar to that of high $\tau_{553}$ ($\gtrsim 1 \times 10^{-5}$) and low $T_s$ (≤18 K; see Figure 1). Physical associations between the H$_1$ gas and dust properties are confirmed in the spatial distribution.

Figures 10(a)–(c) show mass-weighted histograms of $\tau_{H_1}$, $T_s$, and $N_{H_1}$ in the analysis region, respectively. The obtained $N_{H_1}$ histogram is also plotted in panel (c). For the mass calculation, we have assumed a distance for the Chamaeleon region of 150 pc and adopted the mean atomic mass per H atom, $\mu = 1.41$ (Däppen 2000). Average values for $\tau_{H_1}$ and $T_s$ are ~1.3 and ~63 K, respectively, which suggests a large optical depth in the H$_1$–dominated region. The $N_{H_1}$ spans $\sim (0.5–4) \times 10^{21}$ cm$^{-2}$ with an average value of $\sim 1.8 \times 10^{21}$ cm$^{-2}$. The typical H$_2$ column density estimated from subtraction of $N_{H_1}$ from $N_{H_1}$ is $\sim 1.5 \times 10^{21}$ cm$^{-2}$, which is consistent with that obtained by the numerical simulation (Figure 4 in Fukui et al. 2018). Gas masses of atomic hydrogen excluding the CO-emitting region and total hydrogen including the molecular gas are $\sim 6.3 \times 10^4$ and $\sim 8.3 \times 10^4 M_\odot$, respectively. Our result indicates that the total mass is ~30% larger than the estimates in Planck Collaboration XXVIII (2015). The subtraction of the mass of the atomic gas component from the total mass, $\sim 2.0 \times 10^4 M_\odot$, is much larger than the molecular gas mass, $\sim 5000$–$8000 M_\odot$, estimated by previous studies (e.g., Mizuno et al. 2001; Ackermann et al. 2012; Planck Collaboration XXVIII 2015). This can be understood by the H$_1$ gas probably distributed in front of and behind the molecular clouds.

Planck Collaboration XXVIII (2015) and Remy et al. (2018) pointed out that the large gas column density inferred from the optically thick H$_1$ scenario should lower the local γ-ray emissivity and thus yield a cosmic-ray density different from the results of direct cosmic-ray measurements. However, our $\tau_{553}$-based $N_{H_1}$ model with the nonlinear effect lowered the column density.
compared to the linear relation with $\tau_{353}$ (F14; F15) and derived a total gas mass different from that of Planck Collaboration XXVIII (2015) by $\sim$30%, which is within the uncertainty of the measurements of the local $\gamma$-ray emissivity (see Table E.1 in Planck Collaboration XXVIII 2015). This result indicates that our $\tau_{353}$-based $N_{\text{HI}}$ model is acceptable in terms of the $\gamma$-ray studies.

Here we discuss an insight of the CO-dark H$_2$ in the case of our $\tau_{353}$-based $N_{\text{HI}}$ model. If we assume that all of the H I emission is optically thin, the mass of the atomic gas for the Chamaeleon region is derived to be $\sim$4.1 $\times$ 10$^4$ M$_\odot$. Given that the CO-dark H$_2$ contributes 50% of the dark gas, the molecular gas mass for our derived total gas mass is estimated to be $\sim$25% ($\sim$2 $\times$ 10$^4$ M$_\odot$), which is three to four times larger than the gas mass traced by CO. This fraction is much larger than those estimated in other observational studies (Planck Collaboration XXVIII 2015) and theoretical predictions (e.g., Levrier et al. 2012), where the CO-dark H$_2$ is a dominant component of the dark gas. Although the CO-dark H$_2$ increases the total gas budget, as suggested by many studies of molecular line surveys, we have not found evidence for the large mass of molecular gas as the dark-gas component.

Our results support the optically thick H I scenario, but we found a contradiction with previous studies of the local H I gas properties. Stanimirović et al. (2014) derived that a CNM fraction for the Perseus molecular cloud is $\lesssim$0.5 at the dark-gas medium where $N_{\text{HI}} \gtrsim 1 \times 10^{20}$ cm$^{-2}$ (see Figure 8 in that paper). This CNM fraction is almost consistent with Fukui et al. (2018). Meanwhile, our $N_{\text{HI}}$ model shows $\tau_{\text{HI}} \gtrsim 1$ at the dark-gas medium and thus suggests that the CNM is dominant there, which is not consistent with the slightly lower CNM fractions estimated by Stanimirović et al. (2014) and Fukui et al. (2018).

The cause of this discrepancy is not clear. To reveal the difference among these studies, further evaluations of our gas model (e.g., variations of $\tau_{\text{HI}}$ and $T_s$ due to uncertainty of the $N_{\text{HI}}$ model and $\Delta V_{\text{HI}}$) are required, as well as a number of H I emission–absorption measurements for the dark-gas medium of the Chamaeleon region.

5.3. $X_{\text{CO}}$ Distribution

The CO-to-H$_2$ conversion factor, $X_{\text{CO}}$, is usually estimated as $\sim$(1–2) $\times$ 10$^{20}$ cm$^{-2}$ K$^{-1}$ km$^{-1}$ s in the Milky Way disk.
Using our $\tau_{353}$-based $N_{\text{H}}$ model, we can calculate $X_{\text{CO}}$ from a correlation with $W_{\text{CO}}$ as described below. The total column density $N_{\text{H}}$ is expressed as the sum of the number of protons in $N_{\text{H}}$ I and $N_{\text{H}}$ II.

$$N_{\text{H}} = N_{\text{H}} \pm 2N_{\text{H}}.$$  \hspace{1cm} (8)

By substituting $X_{\text{CO}} (=N_{\text{H}}/W_{\text{CO}})$ into Equation (8), the correlation between $W_{\text{CO}}$ and $N_{\text{H}}$ is expressed as

$$N_{\text{H}} = (2X_{\text{CO}}) \times W_{\text{CO}} + N_{\text{H}} = (\text{slope}) \times W_{\text{CO}} + (\text{intercept}).$$  \hspace{1cm} (9)

The half value of the slope gives an $X_{\text{CO}}$ factor.

Figure 11 shows a relationship between $W_{\text{CO}}$ and $N_{\text{H}}$ for the entire analysis region. One can see a positive correlation, especially at low $W_{\text{CO}}$. However, significant deviation is seen at $W_{\text{CO}} \geq 8$ K km s$^{-1}$, probably due to saturation of the optically thick $^{12}\text{CO} J = 1\rightarrow0$ line often found in CO cores. In Figures 12(a)–(c), we make the same scatter plots whose data points are taken from the major clouds of the Chamaeleon region, Cha I, II, and III, which are covered by areas (a)–(c) as shown in Figure 13. The significant deviation is found at high $W_{\text{CO}}$ especially in areas (a) and (c), which yield the large scattering in the $W_{\text{CO}}$–$N_{\text{H}}$ relationship in Figure 11.

Recent studies of the ISM suggest that $X_{\text{CO}}$ has variations in a cloud complex depending on the surrounding interstellar environment (e.g., Bell et al. 2006; Lee et al. 2014; Okamoto et al. 2017). To derive a spatial distribution of $X_{\text{CO}}$ from the $W_{\text{CO}}$–$N_{\text{H}}$ relationship, we divided the analysis region into $1.5 \times 1.5$ regions and fit the data points with a linear function for each region that has a number of data points above 30 and a correlation coefficient above 0.7. At first, the fitting range in $W_{\text{CO}}$ is restricted to 1.2–5 K km s$^{-1}$ to exclude contamination in $W_{\text{CO}}$ lower than the detection limit and the saturation effect at high $W_{\text{CO}}$. Then we gradually raised the upper limit of the fitting range every 0.5 K km s$^{-1}$. The values of $X_{\text{CO}}$ derived with $W_{\text{CO}} < 7.5$ K km s$^{-1}$ are consistent with those of $<5$ K km s$^{-1}$ within the

Figure 12. The $W_{\text{CO}}$–$N_{\text{H}}$ correlation plots with the data points taken from areas (a)–(h) in Figure 13. The meaning of the lines in each panel is the same as in Figure 11.
statistical errors, except for the regions where the data points at high $W_{\text{CO}} (>8 \text{ K km s}^{-1})$ dominate. We therefore adopted the $X_{\text{CO}}$ obtained from the fitting range at $1.2 \text{ K km s}^{-1} < W_{\text{CO}} < 7.5 \text{ K km s}^{-1}$. The derived $1.5 \times 1.5$- based $X_{\text{CO}}$ map is shown in panel (a) of Figure 21, having some blanks in the diffuse medium where the value of $X_{\text{CO}}$ cannot be determined due to low statistics of the data and/or poor correlation of the $W_{\text{CO}}$-$N_{\text{H}_2}$ relationship. To compensate for the low data statistics, we extended the size of the fitting area to $2\times 2$ and $2.5 \times 2.5$ regions, whose results are shown in panels (b) and (c) of Figure 21, respectively. In these maps, the $X_{\text{CO}}$ for the blank regions found in the $1.5 \times 1.5$-based map is given owing to the increase of the data points. On the other hand, the larger pixelized map possibly overlooks a local variation of $X_{\text{CO}}$, such as a region at $(i, b) \sim (304^\circ, -14.5^\circ)$, where the $X_{\text{CO}}$ values of the $1.5 \times 1.5$-based map are significantly different from the other two maps. We therefore combined the three $X_{\text{CO}}$ maps, preferentially adopting the $X_{\text{CO}}$ from the $1.5 \times 1.5$- based map; the other two maps are used to compensate for the blank regions. The final obtained $X_{\text{CO}}$ map is shown in Figure 13. The $X_{\text{CO}}$ spans $\sim(0.5-3) \times 10^{20} \text{ cm}^{-2} \text{ K}^{-1} \text{ km}^{-1} \text{s}$ across the cloud complex, and the average one derived from Figure 11 is $1.4 \pm 0.1 \times 10^{20} \text{ cm}^{-2} \text{ K}^{-1} \text{ km}^{-1} \text{s}$. These values are consistent with the typical $X_{\text{CO}}$ measured for the Galactic interstellar clouds, $\sim(1-2) \times 10^{20} \text{ cm}^{-2} \text{ K}^{-1} \text{ km}^{-1} \text{s}$ (e.g., Bolatto et al. 2013). A study of the ISM of the Chamaeleon region, Planck Collaboration XXVIII (2015), also derives an $X_{\text{CO}}$ factor comparable to our result through their analysis using the dust optical depth, $\tau_{\text{dust}}$.

In Figures 12(d)-(h), we show the correlation plots for the regions, enclosed by the dashed lines, in the $X_{\text{CO}}$ map in Figure 13. These regions are selected to more clearly show and discuss possible relations between the $X_{\text{CO}}$ and the surrounding gas condition. We fit the data points with a linear function similar to Figure 11 and found that each region shows a good correlation, but their slopes vary depending on their positions. In addition to the $X_{\text{CO}}$, the fitting also gives the intercept values of $N_{\text{H}_2}$, as represented by the red dashed lines in Figure 12 (also in Figure 11 as an average value for the entire analysis region). These values correspond to the average H I column density in each fitted region and are comparable to the $N_{\text{H}_2}$ around the masked CO-dominated region shown in Figure 9(a).

The Chamaeleon complex consists of Cha I–III, Cha-East I, Cha-East II, and Major Filament, having different evolutionary history and star formation activity (Mizuno et al. 2001). We found $X_{\text{CO}}$ at $303^\circ \lesssim l \lesssim 304^\circ$ in Cha II and Cha III, and the whole cloud of Cha I shows relatively high values, $\sim(1.5-3) \times 10^{20} \text{ cm}^{-2} \text{ K}^{-1} \text{ km}^{-1} \text{s}$, as shown by the correlations for areas (d) and (f). Cha-East I, including area (g), also has a relatively high $X_{\text{CO}}$ ($\sim 1.5 \times 10^{20} \text{ cm}^{-2} \text{ K}^{-1} \text{ km}^{-1} \text{s}$). Conversely, the $X_{\text{CO}}$ at $300^\circ \lesssim l \lesssim 301^\circ$ in Cha II, where a part of area (e) is included, is relatively small ($\lesssim 1 \times 10^{20} \text{ cm}^{-2} \text{ K}^{-1} \text{ km}^{-1} \text{s}$). Cha-East II and Major Filament also show a similar low $X_{\text{CO}}$. The $N_{\text{H}_2}$ map in Figure 9(a) indicates that areas (d) and (g) are faced toward interstellar space with a relatively low column density $\sim(1.5 \times 10^{21} \text{ cm}^{-2})$, while the $N_{\text{H}_2}$ surrounding area (e) and Major Filament are rather high ($\sim 2-3.5 \times 10^{21} \text{ cm}^{-2}$). The large $X_{\text{CO}}$ in areas (d) and (g) is probably due to CO destruction in the low-density medium, while the small $X_{\text{CO}}$ in area (e) could be ascribed to sufficient dust shielding with the visual extinction, $A_v \gtrsim 1 \text{ mag}$ ($A_J \gtrsim 0.3 \text{ mag}$), preventing CO from photodissociation. The tendency toward high $X_{\text{CO}}$ in regions with low CO abundance outside molecular clouds is consistent with observational studies of molecular cloud regions (e.g., Cotten & Magnani 2013; Okamoto et al. 2017) and theoretical predictions of the formation of molecular clouds (e.g., Inoue & Inutsuka 2012).

Among the six cloudlets in the Chamaeleon complex, Cha I exhibits the highest star formation activity, represented by two Ae/Be stars located in the CO core (Luhman 2008). The relatively high $X_{\text{CO}}$ around the CO cores in Cha I, exemplified by area (f) ($X_{\text{CO}} \sim 1.7 \times 10^{20} \text{ cm}^{-2} \text{ K}^{-1} \text{ km}^{-1} \text{s}$), may be ascribed to the more intense radiation field and enhanced stellar feedback, suggesting preferential destruction of CO in the star-forming region. Cha II holds a few tens of young stellar objects at $303^\circ \lesssim l \lesssim 304^\circ$ and $-15^\circ \lesssim b \lesssim -13.5^\circ$ (Alcalá et al. 2008), which nearly corresponds to the positions with the highest $X_{\text{CO}} \sim 3.0 \times 10^{20} \text{ cm}^{-2} \text{ K}^{-1} \text{ km}^{-1} \text{s}$, possibly showing the gas properties related to an evolutionary step of the low-mass stars. On the other hand, Cha-East II has relatively lower $X_{\text{CO}}$, as seen in the correlation for area (h). This result makes sense in terms of no strong radiation field in the surrounding medium and a lack of star-forming activity in the CO cores of the clouds.

Finally, we note a peculiar correlation found in the CO core of Cha II. We found that the $W_{\text{CO}}$-$N_{\text{H}_2}$ relationship in area (e) shows a tight correlation without the $W_{\text{CO}}$ saturation, in spite of...
the inclusion of the data points at high $W_{\text{CO}} (>10\ \text{K}\ k\text{m} \text{s}^{-1})$. This trend is also confirmed in the $\tau_{353}$ vs. $W_{\text{CO}}$ relationship of Figures 5(b) and 19 as a scatter distribution at $\tau_{353} \sim 4 \times 10^{-5}$ and $W_{\text{CO}} > 10\ \text{K}\ k\text{m} \text{s}^{-1}$. One possibility for the high value of $W_{\text{CO}}$ is a high CO abundance in this region, suggesting a possible different age of the molecular gas and a different evolutionary history of the clouds in the Chamaeleon region. The other possibility for the lower saturation is the opacity effect of the CO line. Figure 14 shows CO spectra for the Cha I–III regions, whose intensities are summed for the pixels in areas (a)–(c). We confirmed that the spectrum of Cha II (area (a)) is broader than those of the others, which may suggest gas turbulence leading to a lower opacity of the cloud. A few tens of young stellar objects are included in the Cha II region (Alcalá et al. 2008); thus, possible outflows may contribute this effect, as similarly suggested in a star-forming region of the Perseus molecular cloud (Pineda et al. 2008).

### 5.4. Comparison with Other Molecular Cloud Regions

Finally, we compare gas properties among local molecular cloud complexes, the MBM 53–55 (F14), Perseus (Okamoto et al. 2017), and Chamaeleon (this study) regions, for which dedicated analyses have been performed with our $\tau_{353}$-based $N_{\text{H}}$ model. The $\tau_{353}$ vs. $W_{\text{HI}}$ correlation plots of each region are shown in Figures 15(a)–(c). For easier comparison, the horizontal and vertical ranges in panel (a) are shown in panels (b) and (c). Table 1 summarizes the physical quantities obtained by these studies.

In the MBM 53–55 region, $\tau_{353}$ is approximately 1 order of magnitude smaller than those in the other two regions, which yields relatively lower $N_{\text{H}}$. The large $\tau_{353}$ in the Perseus and Chamaeleon regions gives larger $N_{\text{H}}$, although it is unlikely to increase with a simple linear function of $\tau_{353}$. We have found a nonlinear relation with $\alpha \sim 1.2$–$1.3$ in the $\tau_{353}$ vs. $A_J$ relationship for the dense molecular clouds ($A_J \gtrsim 0.3$ mag) of the Perseus and Chamaeleon regions. This nonlinear relation also traces the mild curvature in the $\tau_{353}$ vs. $W_{\text{HI}}$ relationship for the H1-dominated medium, which is clearly different from the linear relation seen in the MBM 53–55 region (see Figure 15). These variations of dust opacity may arise from different grain evolution among the cloud complexes. Taking into account the dust evolution effect, the $N_{\text{H}}$ for the Perseus and Chamaeleon regions is found to be larger by a factor of $\sim 2$–$6$ than that for the MBM 53–55 region.

The total column density model as a function of $\tau_{353}$ allows us to investigate the atomic and molecular gas properties. The obtained ($T_{\text{a}}$) is highest in the Perseus region, and it becomes lower followed by the Chamaeleon and MBM 53–55 regions. The trend of dust evolution ($\alpha$) and the H1 gas properties ($T_{\text{a}}$ and $\tau_{\text{H1}}$) might be associated with current star-forming activities: less star formation in the MBM 53–55 clouds (e.g., Yamamoto et al. 2003), high-mass star formation in the Perseus region (e.g., Bally et al. 2008), and low-mass star formation in the Chamaeleon region (e.g., Luhman 2008). The Perseus molecular clouds are included in the Perseus OB2 association, which forms a part of the Gould Belt. Massive stars located in this region may heat the surrounding atomic gas and generate relatively higher $T_{\text{a}}$. The MBM 53–55 region shows the largest ($\tau_{\text{H1}}$), which indicates a large amount of dark gas between the H1 and CO transition. This is consistent with the large mass fraction of dark gas in this region suggested by a $\gamma$-ray analysis (Mizuno et al. 2016). The relatively lower $\alpha$ suggests less dust evolution, which may relate to the lower current star formation activity. The $X_{\text{CO}}$ becomes smaller in the MBM 53–55 region and larger in the Perseus region. According to recent studies of $X_{\text{CO}}$ in local interstellar clouds, the $X_{\text{CO}}$ in high-density regions tends to be lower (e.g., Cotten & Magnani 2013; Schultheis et al. 2014). A comparison with the $W_{\text{CO}}$ (peak) follows this tendency.

Among the three regions, the Chamaeleon region exhibits intermediate H1 and CO gas properties between those of the MBM 53–55 and Perseus regions. The lack of OB clusters in the Chamaeleon region yields relatively quiet environments, whereas the low-mass star formation found in the CO cores may affect gas properties in the opaque regions.

### 6. Conclusions

As part of an analysis of interstellar hydrogen gas based on the Planck data, we carried out a comparative study of H1, CO, and dust in the Chamaeleon molecular cloud complex. The main conclusions are summarized below.
1. A comparison of the J-band extinction $A_J$ and submillimeter dust optical depth $\tau_{353}$ shows a relationship that $\tau_{353}$ increases as the $\sim$1.2nd power of $A_J$. This indicates that the total column density $N_H$ is modeled by the $\sim$1/1.2nd power of $\tau_{353}$ and suggests dust growth in dense molecular clouds. Similar trends are found in the Perseus and Orion A clouds, whereas the index may vary within about $\pm 10\%$ from region to region.

2. We have found a scatter relation between $\tau_{353}$ and $W_{HI}$, similar to those found in the MBM 53–55 (F14) and Perseus (Okamoto et al. 2017) molecular cloud regions. Applying the nonlinear relation found in the $\tau_{353}$-$A_J$ relationship to the $\tau_{353}$-based $N_H$ model reproduces the scatter correlation, which indicates a large amount of optically thick HI around the molecular clouds. The average $\tau_{HI}$ and $T_s$ in the Chamaeleon region are derived to be $\sim 1.3$ and $\sim 63 K$, respectively.

3. A distribution of an $X_{CO}$ factor in the Chamaeleon complex was derived. We found variations of $X_{CO} \sim (0.5–3) \times 10^{20} cm^{-2} K^{-1} km^{-1} s$, which is consistent with the typical value in the Galaxy. This is possibly due to different physical conditions related to the surrounding ISRF.

4. Gas properties in the Chamaeleon region are compared with the MBM 53–55 and Perseus molecular cloud regions. The Chamaeleon region has moderate $\tau_{HI}$, $T_s$, and $X_{CO}$ among the three regions. The moderate ISRF in the diffuse medium and low-mass star formation activities in the cores of clouds may relate to these gas properties.

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Software: HEALPix (Górski et al. 2005).

**Appendix A**

**H I Gas Distribution Separated in Velocity**

Figure 16 indicates an H I velocity channel map from $-40$ to $+20$ km s$^{-1}$ separated into 5 km s$^{-1}$ intervals whose integrated intensities are averaged by the velocity range, which gives the H I brightness temperature ($T_{HI}$). These gas distributions exhibit roughly three structures.

1. Local clouds extensively distributed at $-5$ km s$^{-1} \lesssim V_{LSR} \lesssim +10$ km s$^{-1}$.
2. Elongated gas structure crossing the whole region around $b \sim -25^\circ$ at $-20$ km s$^{-1} \lesssim V_{LSR} \lesssim -5$ km s$^{-1}$ (IVA; see Planck Collaboration XXVIII 2015).
3. High-velocity component located at $302^\circ \lesssim l \lesssim 314^\circ$ and $-30^\circ \lesssim b \lesssim -12^\circ$ seen at $V_{LSR} \lesssim -20$ km s$^{-1}$.

In Figure 17, we give examples of the spectra showing these line profiles. The red and blue spectra have strong emission from the IVA and high-velocity components. To avoid contamination from other than the local clouds, the IVA-dominated region at $l < 290^\circ$ and $b < -22^\circ$ and regions with high-velocity components are masked in the present study. Strong emission from the LMC outskirts detected at $+200$ km s$^{-1} \lesssim V_{LSR} \lesssim +300$ km s$^{-1}$ is also dropped by mask (c) (see Figure 2).
Appendix B

Correlations of $W_{\text{HI}}$ and $W_{\text{CO}}$ with $\tau_{353}$

We present correlations of $W_{\text{HI}}$ and $W_{\text{CO}}$ with $\tau_{353}$ sorted by $T_d$ in Figures 18 and 19, respectively.

Figure 16. The H I velocity channel distribution from $-40$ to $+20$ km s$^{-1}$, whose intensities are averaged within the velocity intervals of 5 km s$^{-1}$, giving the brightness intensity ($T_{\text{HI}}$) in units of K.

Figure 17. Examples of the H I line profiles for the three regions with sizes of $1^\circ.0 \times 1^\circ.0$ having the characteristic line profiles of the local (black), IVA (red), and high-velocity (blue) components. The brightness temperature ($T_b$) on the y-axis is a sum of the $T_b$ of each pixel. The regions with the red and blue spectra are included in the masked area.
Figure 18. Correlation plots (in density) between $\tau_{353}$ and $W_{HI}$ sorted by several $T_d$ intervals. The dashed curves show the theoretical functions of Equation (7) for $\alpha = 1.2$, with $\tau_{HI} \ll 1$ and $\tau_{HI} = 0.34$, 1.0, and 2.0 from left to right.
Appendix C

Derivation of Reference Points in the $N_H$ Model

The reference points in the $N_H$ model, $\tau_{353,\text{ref}}$ and $N_{H,\text{ref}}$, are determined in the same manner as in Okamoto et al. (2017) for a study of the Perseus cloud. Figure 20(a) shows a scatter plot between $T_d$ and $\langle S \rangle$ (dispersion of each $T_d$ interval in the $\tau_{353}$–$W_{\text{HI}}$ plot). The $\langle S \rangle$ is defined as the mean of the variance, which is derived from the areas of the right-angled triangles formed by the data points and the regression line for each $T_d$ interval (Okamoto et al. 2017). Figure 20(b) template relationship between $\langle T_{\text{HI}} \rangle$ and $\langle S \rangle$ for the MBM 53–55 region. The solid line indicates the result of a linear regression. The $\langle T_{\text{HI}} \rangle$ for the highest-$T_d$ points in the Chamaeleon region can be estimated from $\langle S \rangle$ by using this template. The result gives $\langle T_{\text{HI}} \rangle = 0.34$.

Figure 20. (a) Correlations between $T_d$ and $\langle S \rangle$ (dispersion in the $\tau_{353}$–$W_{\text{HI}}$ relationship) for the MBM 53–55 and Chamaeleon regions. For the Chamaeleon region, the data with different dust temperatures are shown with the different colors adopted in Figure 15(c). Here $\langle S \rangle$ is defined as the mean area of the right-angled triangles formed by the data points and the regression line for each $T_d$ interval (Okamoto et al. 2017). (b) Template relationship between $\langle T_{\text{HI}} \rangle$ and $\langle S \rangle$ for the MBM 53–55 region. The solid line indicates the result of a linear regression. The $\langle T_{\text{HI}} \rangle$ for the highest-$T_d$ points in the Chamaeleon region can be estimated from $\langle S \rangle$ by using this template. The result gives $\langle T_{\text{HI}} \rangle = 0.34$. 

Figure 19. Correlation plots (in density) between $\tau_{353}$ and $W_{\text{CO}}$ sorted by several $T_d$ intervals. The horizontal dashed lines indicate the 3σ confidence level in $W_{\text{CO}}$.
The Astrophysical Journal, 878:131 (19pp), 2019 June 20

Kento Tachihara, Katsuhiro Hayashi

Figure 21. The $X_{\text{CO}}$ distribution derived from the correlation between $W_{\text{CO}}$ and $N_{\text{H}}$ (see Section 5.3). (a) $1.5' \times 1.5'$-based map smoothed with a two-dimensional Gaussian function with a kernel size of 3 pixels and $\sigma = 1'$. (b) $2' \times 2'$-based map with a Gaussian function of $\sigma = 1'$. (c) $2.5' \times 2.5'$-based map with a Gaussian function of $\sigma = 1.7'$. The grid sizes are (a) $0.75' \times 0.75'$, (b) $1.0' \times 1.0'$, and (c) $1.25' \times 1.25'$.

Table 2
Dispersion of Several $T_d$ Intervals in the $\tau_{353}-W_{\text{HI}}$ Relationship for the Chamaeleon and MBM 53–55 Regions

| $T_d$ (K) | Chamaeleon | MBM 53–55 |
|-----------|-------------|------------|
|           | $\langle S/\rangle$ (10$^{-1}$ K km s$^{-1}$) | $\langle S/\rangle$ (10$^{-3}$ K km s$^{-1}$) |
| 21.5$<$   | 0.34        | 0.34       |
| 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       |

Notes. (a) $T_d$ range. (b) Dispersions of each $T_d$ for the Chamaeleon region. (c) Same as column (b) but for the MBM 53–55 region. (d) H I optical depth ($\langle \tau_{\text{HI}} \rangle$) for the MBM 53–55 region in each $T_d$ (Table 3 in Okamoto et al. 2017).

formed by each data point and regression line obtained by the fit to the data points in each $T_d$ interval (see Figure 18 in Okamoto et al. 2017). As seen in panel (a), the dispersion in $T_d$ tends to become small with increasing $T_d$. Panel (b) represents a correlation between the averaged $\tau_{\text{HI}}$ ($\langle \tau_{\text{HI}} \rangle$) and $\langle S/\rangle$ in each $T_d$ for the MBM 53–55 region. We found a good positive correlation. By using this correlation as a template, the $\tau_{\text{HI}}$ for the highest $T_d$ in the Chamaeleon region is derived to be 0.34. Given a correlation, $N_{\text{H,ref}} = (1.15 \times 10^5) \times X_{\text{HI}} \times \tau_{353, \text{ref}}$, which is derived from the data points in the highest $T_d$ for $|b| > 15^\circ$ in the all-sky data (F15), the model curve in Equation (7) with $\tau_{\text{HI}} = 0.34$ gives $\tau_{353, \text{ref}} = 7.8 \times 10^{-7}$ and $N_{\text{H,ref}} = 1.6 \times 10^{20}$ cm$^{-2}$ through the fit to the data points only for the highest $T_d$ in the $\tau_{353}-W_{\text{HI}}$ relationship. Table 2 summarizes the calculated dispersions in the $\tau_{353}-W_{\text{HI}}$ relationship for the Chamaeleon and MBM 53–55 regions.

Appendix D
$X_{\text{CO}}$ Distribution

We present the obtained $X_{\text{CO}}$ maps with the different grid sizes in Figure 21.

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18
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The Astrophysical Journal, 878:131 (19pp), 2019 June 20 Hayashi et al.