TIMES. I. A Systematic Observation in Multiple Molecular Lines toward the Orion A and Ophiuchus Clouds

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Abstract

We have used the Taeduk Radio Astronomy Observatory to observe the Orion A and Ophiuchus clouds in the $J=1\rightarrow0$ lines of $^{13}$CO, $^{18}$O, HCN, HCO$^+$, and N$_2$H$^+$ and the $J=2\rightarrow1$ line of CS. The fully sampled maps with uniform noise levels are used to create moment maps. The variations of the line intensity and velocity dispersion with total column density, derived from dust emission maps, are presented and compared to previous work. The CS line traces density in the Orion A cloud is similar to that of starburst galaxies, while that in the Ophiuchus cloud is in between those of active galactic nuclei and starburst galaxies.

Unified Astronomy Thesaurus concepts: Molecular clouds (1072)

1. Introduction

Gas motion in molecular clouds (MCs) is generally turbulent (Larson 1981; Elmegreen & Scalo 2004; Heyer & Brunt 2004). Supersonic turbulence on a large scale acts as an internal pressure against the global gravitational collapse and also produces dense clumps in small scales via shocks (Evans 1999; Padoan et al. 1999, 2001; Mac Low & Klessen 2004). As turbulence dissipates, star formation becomes easier in the clumps (Padoan et al. 2001; Bergin & Tafalla 2007). Thus, turbulence plays a critical role in the evolution of clouds and star-forming regions, and understanding the properties of turbulence is key to understanding its role in star formation, especially for the earliest phase (Bergin & Tafalla 2007). However, the relation between the turbulence and star formation is still controversial.

To obtain the properties of turbulence in MCs, $J=1\rightarrow0$ transitions of $^{13}$CO and $^{18}$CO have been used (Heyer & Brunt 2004; Padoan et al. 2006, 2009; Brunt et al. 2009; Koch et al. 2017) because these transitions can easily trace molecular gas in the interstellar medium. However, these lines become optically thick toward the high column density regions and cannot trace the turbulent motions in a dense environment. The properties of turbulence derived from these optically thick lines might be ineffective for assessing the relation between turbulence and star formation since stars are generally formed in a dense environment. Recent surveys, such as the CARMA Large Area Star Formation Survey (CLASSy; Storm et al. 2014) and the Green Bank Ammonia Survey (GAS; Friesen et al. 2017; Monsch et al. 2018), used optically thin lines and found that the turbulence affects the formation of the kinematical and morphological structures of dense gas (Storm et al. 2014, 2016; Kirk et al. 2017; Chen et al. 2019). However, the CLASSy survey observed small areas limited to clump scale (about 1 pc $\times$ 1 pc). The small map size would limit the spatial size of turbulent motion that we can investigate, and the supersonic turbulent motion in large scales would not be probed. The GAS survey, using the NH$_3$ lines, is only focused on cold and dense gas.

To investigate the gas motions in various densities and spatial scales, it is necessary to map the entire MC in different molecular lines that can trace various density environments. Gaches et al. (2015) simulated a star-forming MC using a hydrodynamic simulation with post-processed three-dimensional photodissociation astrochemistry. They categorized molecular transitions into three groups (diffuse, intermediate, and dense tracers) that trace different density environments. Therefore, the spectral maps in different molecular transitions would represent the turbulent motions in different density environments if we chose the transitions from these three groups (Goodman et al. 1998). This systematic study of MCs can also provide detailed initial properties and constraints for the simulation of turbulent star-forming clouds.

To compare the properties of turbulence in different star-forming environments, we should observe MCs that have different
star-forming environments. The Orion A cloud can be divided into three regions: the integral-shaped filament (ISF), L1641, and L1647 from the north to the south (Lynds 1962; Meingast et al. 2016). Among these regions, the ISF encompasses active massive star-forming regions (Ikeda et al. 2007; Megeath et al. 2012; Furlan et al. 2016), and the other regions include low-mass star-forming regions (Allen & Davis 2008; Megeath et al. 2012; Nakamura et al. 2012; Furlan et al. 2016). In the Ophiuchus cloud, low-mass stars are actively forming in L1688 (Motte et al. 1998; Wilking et al. 2008; Zhang & Wang 2009; Dunham et al. 2015).

In this region, many dense cores (Oph-A through L) have been identified using DCO$^+$ (Loren et al. 1990), N$_2$H$^+$ (Pan et al. 2017), and millimeter continuum observations (Johnstone et al. 2004; Pattle et al. 2015). Some of these cores and their substructures were identified as “droplets,” which are the pressure-confined coherent cores (Chen et al. 2019, 2020). Also, a filamentary structure that stretches from L1688 to the northeast, L1709, contains one starless core and one protostellar core (Loren et al. 1990; Dunham et al. 2015; Pattle et al. 2015). The star formation in L1709 is less efficient than that in L1688 (Pattle et al. 2015). Because of their various star-forming environments and proximity (389–443 pc and 137 pc for the Orion A and Ophiuchus clouds, respectively; Ortiz-León et al. 2017; Kounkel et al. 2018), these clouds are ideal targets to compare the properties of the turbulence in the different star-forming environments.

The Orion A cloud has been mapped in various lines, including $J = 1$−0 of $^{13}$CO (Bally et al. 1987; Tatematsu et al. 1993; Nagahama et al. 1998; Ripple et al. 2013; Shimajiri et al. 2014; Kong et al. 2018), C$^{18}$O (Shimajiri et al. 2011; Tong et al. 2018), and N$_2$H$^+$ (Tatematsu et al. 2008; Nakamura et al. 2019). The Ophiuchus cloud has been mapped in the $J = 1$−0 line of $^{13}$CO (Loren 1989a; Ridge et al. 2006), HCN (Shimajiri et al. 2017), HCO$^+$ (Shimajiri et al. 2017), and N$_2$H$^+$ (Pan et al. 2017). However, most of the observations focused on the northern part of Orion A (the ISF and L1641-N; Tatematsu et al. 1993; Shimajiri et al. 2014; Kong et al. 2018) or L1688 in Ophiuchus (Pan et al. 2017; Shimajiri et al. 2017), which are the most active star-forming regions in each cloud. In addition, there are maps of the entire MCs, but these were done with larger beams and/or fewer transitions (Bally et al. 1987; Loren 1989a; Nagahama et al. 1998).

We performed a systematic observation toward the Orion A and Ophiuchus clouds in multiple molecular lines using the Taeduk Radio Astronomy Observatory (TRAO; Roh & Jung 1999; Jeong et al. 2019) 13.7 m telescope. All spectral maps were obtained by the TRAO Key Science Program (KSP) “mapping Turbulent properties In star-forming MolEcular clouds down to the Sonic scale” (TIMES; PI: Jeong-Eun Lee). Our program aims to obtain spectral maps of the entire Orion A and Ophiuchus clouds in multiple molecular lines in order to investigate the properties of turbulence in MCs that have different star-forming environments. This is the first observational study in multiple molecular lines that can trace various density environments (Gaches et al. 2015) toward the entire area of the target clouds with a consistent observational scheme, high velocity resolution, and high sensitivity. We especially designed our observations to achieve uniform noise levels throughout the maps in order to calculate turbulence statistics.

This first paper presents our observations and simple analyses. Further analysis of the turbulence in the clouds will be presented in the second paper. We describe the details of the observation program in Section 2. In Section 3, the method to produce moment 0, 1, and 2 maps with a high signal-to-noise ratio is described. We assess the uniformity of the data quality and morphological/kinematical features of the observed clouds in Section 4, where we also compare the integrated intensities of the observed lines with column densities derived from the dust continuum. Section 5 discusses the physical properties of the line-emitting gas in both clouds, and Section 6 presents a summary.

2. Observations

2.1. The TRAO 13.7 m Telescope

We obtained six molecular line maps toward each cloud using the 13.7 m radio telescope at TRAO in Daejeon, South Korea. The SEQUOIA-TRAO receiver, which has 16 pixels arranged in a 4 × 4 array, can obtain two molecular lines at 85−100 GHz or 100−115 GHz simultaneously. TRAO also provides the on-the-fly (OTF) observing mode, so that the combination of the simultaneous observation of two lines and the OTF mode with the multibeam receiver makes the TRAO telescope an excellent facility to map multiple molecular transitions toward a large area efficiently.

The back end is an FFT2G spectrometer that can accept the 32 IF outputs from SEQUOIA-TRAO. The FFT2G spectrometer has a bandwidth of 62.5 MHz with 4096 channels. Thus, its spectral resolution is about 15 kHz, corresponding to a velocity resolution of about 0.04 km s$^{-1}$ at 110 GHz. The main beam of the TRAO telescope has an almost circular pattern with a beam size of about 57″ and 49″ at 86 and 110 GHz, respectively (Jeong et al. 2019).

2.2. Mapping the Orion A and Ophiuchus Clouds

The Orion A and Ophiuchus clouds were divided into multiple 20′ × 20′ areas (submaps). The OTF mapping was performed toward each submap, along with the R.A. and decl. directions. Each OTF datum possibly contains a scanning noise (Emerson & Graeve 1988). The scanning noise is manifested by noise features along the scanning direction that originate from the variation of weather conditions during the scanning process. We minimize these noise features by combining the OTF maps in R.A. and decl. directions and achieve a uniform noise distribution on the covered area. The observed submaps were combined to build the spectral maps for the entire clouds. During the observation, the pointing uncertainty is less than 10″. The system noise temperature ranges from 250 to 400 K at 110 GHz and varies depending on the weather conditions and elevation of the clouds.

Both clouds were mapped in six molecular lines that can trace the diffuse to dense gas in MCs: $^{13}$CO $J = 1$−0, C$^{18}$O $J = 1$−0, HCN $J = 1$−0, HCO$^+$ $J = 1$−0, N$_2$H$^+$ $J = 1$−0, and CS $J = 2$−1. Two of these lines were observed together; each of the $^{13}$CO/C$^{18}$O, HCN/HCO$^+$, and N$_2$H$^+$/CS line pairs was simultaneously observed. Table 1 shows the line frequency, velocity resolution (ΔV), critical density ($n_{\text{crit}}$), and main-beam efficiency for each observed line. Note that the main-beam efficiencies are obtained by interpolation of the efficiencies measured by Jeong et al. (2019). All spectral maps were observed from 2016 January to 2019 April.

The observed areas toward the Orion A and Ophiuchus clouds are presented in Figure 1. The $^{13}$CO/C$^{18}$O and...
HCN/HCO$^+$ lines were mapped within the same area through the entire clouds. We obtained the visual extinction ($A_V$) maps provided by Dobashi (2011) and selected initially the submaps, which have $A_V$ higher than a certain value. We adopted $A_V$ of 2.0 and 4.0 for the Orion A and Ophiuchus clouds, respectively, which reasonably outline the structures of the clouds. The OTF observation was initially performed toward the selected submaps, and subsequently we extended the observation if the $^{13}$CO line had been significantly detected on the boundary of the observed area. Total mapped areas in the $^{13}$CO/C$^{18}$O and HCN/HCO$^+$ lines are $\sim$8.7 and $\sim$3.9 deg$^2$ of the Orion A and Ophiuchus clouds, respectively. For the N$_2$H$^+$/CS lines, observations were made toward the submaps where the observed C$^{18}$O map exhibits clump-like structures. The mapped areas are $\sim$4.0 and $\sim$1.6 deg$^2$ in the Orion A and Ophiuchus clouds, respectively. We observed the N$_2$H$^+$/CS lines deeper than the other lines because of their weak line intensities. Moreover, we chose representative star-forming regions for each cloud: the selected regions are the ISF and L1641-N cluster in the Orion A cloud and the L1688 region in the Ophiuchus cloud. For these regions, we observed the N$_2$H$^+$/CS lines even deeper to obtain high-sensitivity spectral maps. The boundaries of the mapped areas are marked in Figure 1. The total observed time to obtain all data was about 1672 hr: 1097 hr for the Orion A cloud and 575 hr for the Ophiuchus cloud.

The obtained maps were processed using the OTFTOOL and GILDAS/CLASS$^{13}$ programs with a cell size of 20″ and $\Delta V$ of about 0.1 km s$^{-1}$. Baselines were removed using a least $\chi^2$ fitting method with a first-order polynomial. The baseline fitting is performed for the line-free spectra in the velocity ranges that are outside of the velocity windows ($V_{\text{win}}$). To obtain good baseline, regions in velocity space ($V_{\text{space}}$) that are almost three times broader than $V_{\text{win}}$ are used. Some of the observed lines show broad wing structures toward OMC-1, where the energetic outflowing source Orion KL is located (see Section 4.2.1). For these line spectra, we applied velocity windows broader than $V_{\text{win}}$ of the other locations in the cloud. The $V_{\text{win}}$ and $V_{\text{space}}$ values for each spectral map are listed in Table 2.

3. Moment Maps with a Moment-masking Method

We produced the moment 0, 1, and 2 maps for the observed lines, which are equivalent to the maps of integrated intensity ($I_{\text{int}}$), intensity weighted mean velocity ($V_{\text{int}}$), and velocity dispersion ($\sigma_V$). In this process, the moment-masking method (Dame 2011) is applied. The moment-masking method is an efficient way to avoid the noise effect, which degrades the signal-to-noise ratio of the moment maps. This method

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Table 1

| Line                  | Rest Frequency (GHz) | Velocity Resolution (km s$^{-1}$) | Beam Size (arcsec) | $n_{\text{crit}}$ (cm$^{-3}$) | Beam Efficiency (%) |
|-----------------------|----------------------|----------------------------------|--------------------|-------------------------------|---------------------|
| $^{13}$CO $J = 1−0$  | 110.201              | 0.0838                           | 49.0               | $1 \times 10^3$              | 46 ± 2              |
| C$^{18}$O $J = 1−0$  | 109.782              | 0.0833                           | 49.1               | $1 \times 10^3$              | 46 ± 2              |
| HCN $J = 1−0$        | 88.631               | 0.1032                           | 56.0               | $2 \times 10^6$              | 45 ± 3              |
| HCO$^+$ $J = 1−0$    | 89.188               | 0.1026                           | 55.7               | $3 \times 10^5$              | 46 ± 3              |
| N$_2$H$^+$ $J = 1−0$ | 93.173               | 0.0982                           | 54.1               | $2 \times 10^5$              | 47 ± 2              |
| CS $J = 2−1$         | 97.980               | 0.0934                           | 52.0               | $3 \times 10^5$              | 48 ± 2              |

Notes.

$^a$ Critical densities for observed lines; from Ungerechts et al. (1997).

$^b$ Beam sizes and efficiencies for the observed lines are derived using a linear interpolation method based on those provided by Jeong et al. (2019).

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$^{13}$ http://www.iram.fr/IRAMFR/GILDAS
identifies emission-free pixels from the smoothed data and removes noise signals within the spectral cube data. The \( I_{\text{tot}} \) maps of the \(^{13}\text{CO} \) line in the Orion A and Ophiuchus clouds are presented in Figures 2 and 3, respectively. The \( V_{\text{lsr}} \) and \( \sigma_{V} \) values for the \(^{13}\text{CO} \) line of the Orion A cloud are presented in Figures 4 and 5, while those for the Ophiuchus cloud are presented in Figures 6 and 7, respectively. The other moment maps for the Orion A cloud are exhibited in Appendix A, and those for the Ophiuchus cloud are exhibited in Appendix B.

We also calculated the uncertainties of the \( I_{\text{tot}}, V_{\text{lsr}}, \) and \( \sigma_{V} \) values \((\epsilon_{\text{mom0}}, \epsilon_{\text{mom1}}, \) and \( \epsilon_{\text{mom2}}\), respectively) from the noise propagation. We measured \( T_{\text{rms}} \) from the line-free spectra of the regions outside \( V_{\text{win}} \) and adopted it as an uncertainty of the line intensity. The \( \epsilon_{\text{mom0}}, \epsilon_{\text{mom1}}, \) and \( \epsilon_{\text{mom2}} \) values are generally dominated by \( T_{\text{rms}} \) and the number of channels that are included in calculation. The contributions of the velocity uncertainty are minor compared to the other contributions.

For the HCN and \( \text{N}_2\text{H}^{+} \) lines that have multiple hyperfine transitions, we consider a single transition line to derive the \( V_{\text{lsr}} \) and \( \sigma_{V} \) correctly. For the HCN line, we adopted the strongest line at 88.631 GHz. We initially assumed that \( V_{\text{lsr}} \) of the 88.631 GHz line is the same as that of the CS line \( (V_{\text{lsr}}^{\text{CS}}) \). The moment values are derived from the velocity range between \( V_{\text{lsr}}^{\text{CS}} - 4 \) and \( V_{\text{lsr}}^{\text{CS}} + 3 \text{ km s}^{-1} \), which separate the hyperfine transitions of HCN. The hyperfine transitions of the HCN line are generally blended in the ISF; therefore, \( \sigma_{V} \) in the ISF region would be underestimated. For the \( \text{N}_2\text{H}^{+} \) line, we adopted an isolated transition at 93.176 GHz and derived the moment values from \( V_{\text{lsr}}^{\text{CS}} - 10.87 \) to \( V_{\text{lsr}}^{\text{CS}} + 4.87 \text{ km s}^{-1} \). Finally, we added 7.87 km s\(^{-1}\), which is the velocity difference between the rest frequency and the isolated hyperfine transition, to the derived \( V_{\text{lsr}} \).

### Table 2

| Line         | \( V_{\text{win}} \) \((\text{km s}^{-1})\) | \( V_{\text{space}} \) \((\text{km s}^{-1})\) |
|--------------|--------------------------------------------|---------------------------------------------|
| Orion A      |                                            |                                             |
| \(^{13}\text{CO}\) | (0, 20)                                   | (−20, 40)                                  |
| \(^{13}\text{C}^{18}\text{O}\) | (0, 20)                                   | (−20, 40)                                  |
| HCN          | (−10, 30)                                 | (−50, 70)                                  |
| HCO\(^{+}\)  | (−5, 25)                                 | (−35, 55)                                  |
| \(\text{N}_2\text{H}^{+}\) | (−5, 22)                                  | (−18, 35)                                  |
| CS           | (−5, 17)                                 | (−20, 40)                                  |
| Ophiuchus    |                                            |                                             |
| \(^{13}\text{CO}\) | (−1, 8)                                  | (−7, 14)                                   |
| \(^{13}\text{C}^{18}\text{O}\) | (−1, 8)                                  | (−10, 17)                                  |
| HCN          | (−8, 13)                                 | (−29, 34)                                  |
| HCO\(^{+}\)  | (−1, 8)                                 | (−10, 17)                                  |
| \(\text{N}_2\text{H}^{+}\) | (−10, 15)                                | (−35, 40)                                  |
| CS           | (−1, 8)                                 | (−10, 17)                                  |
| Near Orion KL\(^{a}\) | (−13, 30)                               | (−20, 40)                                  |
| \(^{13}\text{CO}\) | (−5, 25)                                 | (−15, 38)                                  |
| \(^{13}\text{C}^{18}\text{O}\) | (−30, 50)                                |                                             |
| HCN          | (−20, 40)                                |                                             |
| HCO\(^{+}\)  | (−20, 40)                                |                                             |
| CS           | (−15, 38)                                |                                             |

**Note.**

\(^{a}\) Velocity windows \((V_{\text{win}})\) for the line spectra with broad wing structures. Velocity spaces \((V_{\text{space}})\) for these lines are the same as that of the Orion A cloud.

### 4. Results

#### 4.1. Homogeneous Data Quality

One way to obtain the properties of turbulence from spectral cube data is by statistical analyses, such as the probability distribution functions \((\text{pdfs})\), two- or three-dimensional power spectra, and a wavelet transform of density or velocity fields \((\text{Gill} \& \text{Henriksen} 1990; \text{Klessen} 2000; \text{Ossenkopf} \& \text{Mac Low} 2002; \text{Kowal} \text{et al.} 2007; \text{Burkhart} \text{et al.} 2009; \text{Koch} \text{et al.} 2017)\). For some of these statistical analyses, it is quite important to have well-characterized uncertainties, so we focus here on the data uniformity.

Figure 8 displays the pdfs of \( T_{\text{rms}} \). The \( T_{\text{rms}} \) pdfs for each of the \(^{13}\text{CO}, \(^{13}\text{C}^{18}\text{O}, \text{HCN}, \) and \( \text{HCO}^{+} \) lines have a well-defined single Gaussian-like distribution. The mean and standard deviation of \( T_{\text{rms}} \) are given in Figure 8. For the \( \text{N}_2\text{H}^{+} \) and CS lines, the \( T_{\text{rms}} \) pdfs of the \( \text{N}_2\text{H}^{+} \) and CS lines have a pair of Gaussian-like components because of the high-sensitivity maps toward the selected star-forming regions. The filled histograms in the bottom panel are the pdfs for the high-sensitivity maps. The mean \( T_{\text{rms}} \) values for the \( \text{N}_2\text{H}^{+} \) and CS lines range from 0.10 to 0.11 K, and their standard deviations are less than 0.025 K. For the selected star-forming regions, the mean and standard deviation of \( T_{\text{rms}} \) are \( \sim0.09 \) and 0.006 K, respectively.

These small standard deviation values imply a homogeneous \( T_{\text{rms}} \) in the spectral maps. The \(^{13}\text{CO}, \(^{13}\text{C}^{18}\text{O}, \text{HCN}, \) and \( \text{HCO}^{+} \) data have similar mean \( T_{\text{rms}} \) values, and each of them has a uniform \( T_{\text{rms}} \) distribution across the observed area. Also, the pdfs of \( T_{\text{rms}} \) for the \( \text{N}_2\text{H}^{+} \) and CS data imply that \( T_{\text{rms}} \) does not significantly vary within each of the selected star-forming regions and the other areas.

#### 4.2. The Morphological and Kinematical Features of the Clouds

##### 4.2.1. The Orion A Cloud

In the Orion A cloud, spatial distributions of the observed lines are generally well correlated. All the lines follow a filamentary structure extending from the north to the south (from ISF to L1647-S). The \( I_{\text{tot}} \) in all lines are generally strong in the ISF (decl. \( > -6^\circ 2\)). Otherwise, all the lines in the southern filamentary structure are weaker than those in the ISF. Also the HCN, HCO\(^{+}, \) \( \text{N}_2\text{H}^{+}; \) and CS lines are not detected in the L1647 region (decl. \( < -9^\circ; \) see Figure 2, where these various regions are identified).

The observed lines reveal various structures within the Orion A cloud. The \(^{13}\text{C}^{18}\text{O}, \text{HCN}, \text{HCO}^{+}, \) \( \text{N}_2\text{H}^{+}; \) and CS lines are detected toward the regions where the \( I_{\text{tot}} \) of \(^{13}\text{CO} \) is strong. Among these lines, the \(^{13}\text{C}^{18}\text{O} \) and \( \text{N}_2\text{H}^{+} \) lines show clumpy structures, while the CS line shows relatively extended structures across the Orion A cloud. The HCN and HCO\(^{+} \) lines reveal extended filamentary structures in the ISF, while they reveal clumpy structures in the other regions.

The spatial distributions of the \(^{13}\text{C}^{18}\text{O}, \text{HCN}, \text{HCO}^{+}, \) \( \text{N}_2\text{H}^{+}; \) and CS lines are well correlated with those of young embedded protostars (Class 0/I young stellar objects (YSOs) and flat-spectrum sources) identified using Spitzer \((\text{Megeath} \text{et al.} 2012)\) and Herschel observations \((\text{Furlan} \text{et al.} 2016)\). Especially, the \(^{13}\text{C}^{18}\text{O} \) line presents a tight correlation between the spatial distribution of \( I_{\text{tot}} \) and the embedded protostars (Figure 9). Also, the HCN, HCO\(^{+}; \) and CS lines exhibit a similar spatial distribution (Figures A2, A3, and A5). These
Figure 2. The moment 0 (the equivalent of integrated intensity; $I_{\text{tot}}$) map of the $^{13}$CO line toward the Orion A cloud. The blue circle in the gray dashed circle in the upper left corner indicates the beam size of the TRAO telescope at 110 GHz. We annotated the $^{13}$CO maps with the names of the subregions (Lynds 1962; Meingast et al. 2016; Großschedl et al. 2018).

Figure 3. Same as Figure 2, but for the Ophiuchus cloud. The beam size is shown in the upper right corner of the map. The map is annotated with the names of the subregions (Lynds 1962; Loren 1989a).
lines are mainly found in the active star-forming regions (ISF and star-forming clusters) and Herbig-Haro (HH) objects (HH 1, HH 2, and HH 43).

Figures 4 and 5 present the $V_{\text{lsr}}$ and $\sigma_{V}$ maps of the $^{13}$CO line in the Orion A cloud. The $V_{\text{lsr}}$ map of the Orion A cloud exhibits a global velocity gradient from the north to the south (Heyer et al. 1992; Tatamatsu et al. 1993; Ikeda et al. 2007; Shimajiri et al. 2011; Kong et al. 2018). This global velocity gradient seems to be the motion of the overall Orion A cloud and could represent large-scale rotation (Bally et al. 1987), expansion (Kutner et al. 1977; Maddalena et al. 1986), or gravitational collapse (Hartmann & Burkert 2007). Statistical analyses without considering the overall motion of MC can cause misunderstanding of turbulence. Therefore, we should take the motion of the Orion A cloud into account when investigating the properties of turbulence in future studies. The $\sigma_{V}$ ranges from 0.2 to 2.0 km s$^{-1}$ throughout the Orion A cloud, except for some regions with high-$\sigma_{V}$ values. These regions are located in the eastern part of ISF and the L1647-N region. In these regions, there are multiple cloud components with different $V_{\text{lsr}}$. We will discuss these high-$\sigma_{V}$ regions in Appendix C.

Another notable feature is a broad wing structure in the observed lines toward OMC-1 (Kuiper et al. 1980; Rydbeck et al. 1981; Olofsson et al. 1982; Hasegawa et al. 1984). The $^{13}$CO, HCN, HCO$^{+}$, and CS lines present the blue- and redshifted broad wing structures (see Figure 10). For the HCN, HCO$^{+}$, and CS lines, the broad wing structures result in very high $I_{\text{tot}}$ values: the $I_{\text{tot}}$ toward OMC-1 are 241, 71, and 51 K km s$^{-1}$ in the HCN, HCO$^{+}$, and CS lines, respectively. The $\sigma_{V}$ values for the HCO$^{+}$ and CS lines are also high near OMC-1, while the $\sigma_{V}$ value for the HCN line is not significantly high because of the limited velocity range that we adopted.

The C$^{18}$O and N$_{2}$H$^{+}$ lines do not present clear wing structures in their spectra toward OMC-1. We compared the integrated intensities of the central peak ($I_{\text{center}}$) and the broad wing structures ($I_{\text{wing}}$) to check whether or not the weak broad structures exist in the C$^{18}$O and N$_{2}$H$^{+}$ lines. The velocity ranges that $I_{\text{center}}$ and $I_{\text{wing}}$ are derived over are summarized in Table 3. The observed lines generally peak at the velocity of 9 km s$^{-1}$. We
Figure 5. The moment 2 (the equivalent of velocity dispersion; $\sigma_v$) map for the $^{13}$CO line in the Orion A cloud.

Figure 6. Same as Figure 4, but for the Ophiuchus cloud.
Figure 7. Same as Figure 5, but for the Ophiuchus cloud.

Figure 8. The pdfs of the $T_{\text{rms}}$ for the observed maps in the Orion A (left panels) and Ophiuchus (right panels) clouds. The top panels show the pdfs for the $^{13}$CO, C$^{18}$O, HCN, and HCO$^+$ maps, and the bottom panels show those for the N$_2$H$^+$ and CS maps. The $T_{\text{rms}}$ pdfs for the N$_2$H$^+$ and CS lines toward the representative star-forming regions (orange dotted lines in Figure 1) are presented with the filled histograms. The mean and standard deviation for each pdf are summarized on the right side of each pdf.

Thus, derived $I_{\text{center}}$ over a velocity range from 5 to 13 km s$^{-1}$ assuming that the central peak extends up to ±4 km s$^{-1}$ from the line center. $I_{\text{wing}}$ was calculated over the velocity ranges from −11 to 5 km s$^{-1}$ and from 13 to 29 km s$^{-1}$ assuming that the wings extend up to ±20 km s$^{-1}$ from the line center. For the HCN and N$_2$H$^+$ lines, the velocity ranges for obtaining $I_{\text{center}}$ were set to...
cover all hyperfine components. Also, we set the velocity ranges of the wing structures to consider the broad emission features at the outermost parts of the observed lines.

Figure 11 presents the $I_{\text{center}}$ and $I_{\text{wing}}$ for each line. $I_{\text{wing}}$ values are generally proportional to $I_{\text{center}}$. The $^{13}\text{CO}$, HCN, HCO$^+$, and CS lines have relatively strong $I_{\text{wing}}$ values that are higher than 10 K km s$^{-1}$. $I_{\text{wing}}$ of C$^{18}$O is barely detected (1.1 ± 0.3 K km s$^{-1}$). Only the N$_2$H$^+$ line is not detected with a value of $-0.16 ± 0.17$ K km s$^{-1}$. Figure 12 presents the distributions of the broad wing emission in $^{13}\text{CO}$, C$^{18}$O, HCN, HCO$^+$, and CS. Note that the distribution of wing emission in C$^{18}$O is indistinguishable from the noise.

4.2.2. The Ophiuchus Cloud

In the Ophiuchus cloud, the observed lines exhibit spatial distribution trends that are similar to those in the Orion A cloud. The $^{13}\text{CO}$ line traces extended cloud structures from the L1688 to L1709 regions (the regions of the cloud are identified in Figure 3). The other lines mainly trace small and clumpy structures in the cloud. The line intensities are generally strong in L1688 (R.A. < 247.5), which is the most active star-forming region in this cloud. Also, the spatial distribution of the C$^{18}$O line emission is well correlated with that of the young embedded protostars identified using Spitzer (Dunham et al. 2015; see Figure 13).

In L1688, the observed lines are generally strong toward the star-forming cores (Oph-A through L; see Figure B4). But their relative strengths change depending on the lines. The star-forming cores have nonuniform conditions (Pattle et al. 2015; Punanova et al. 2016). Oph-A and Oph-C are affected by the external heating from the B2V star HD 147889 (Pattle et al. 2015; Punanova et al. 2016). Oph-B1 and Oph-B2 cores are the coldest among the cores (Pattle et al. 2015); Oph-B1 is one of the quiescent cores, while Oph-B2 is the most turbulent core (Punanova et al. 2016). Oph-E and Oph-F cores are the most evolved regions in L1688 (Pattle et al. 2015); Oph-E is strongly pressure confined, while Oph-F is marginally pressure confined. Also, Oph-F has a similar temperature to that of Oph-A without any external heating. These different environments result in the different relative strengths of the observed lines.
The moment maps of the $^{13}$CO line imply that the kinematic features of the Ophiuchus cloud are quite different from those of the Orion A cloud. The systematic variation of the $V_{\text{lsr}}$ in the Ophiuchus cloud is relatively small compared to that in the Orion A cloud. Also, the typical $\sigma_V$ value in the Ophiuchus cloud is smaller than that in the Orion A cloud. The small variation of $V_{\text{lsr}}$ and small $\sigma_V$ values imply that the Ophiuchus cloud is kinematically quiescent compared to the Orion A cloud (Loren 1989b).

The difference between the spatial distributions of the HCN and HCO$^+$ lines is striking (see Figures B2 and B3). The HCN line is mainly detected toward Oph-A, Oph-B1, Oph-B2, and Oph-B3 cores, while the HCO$^+$ line is predominantly detected toward Oph-A, Oph-C, Oph-E, and Oph-F cores. The peak $I_{\text{tot}}$ of the HCN and HCO$^+$ lines also appear in different cores. This result indicates that the HCN and HCO$^+$ lines trace different physical or chemical conditions in the Ophiuchus cloud.

4.3. Column Density Maps and $I_{\text{tot}}$ Variations with Column Density

Unbiased mapping toward two MCs in multiple molecular lines provides a good opportunity to assess how the line intensities respond to the physical parameters within clouds. Therefore, we investigated the variation of $I_{\text{tot}}$ as a function of column density ($N_{\text{H}}$).

We derived $N_{\text{H}}$ from the observations of dust continuum emission that can trace the amount of gas in a cloud (Goodman et al. 2009). The $N_{\text{H}}$ maps were derived by fitting a modified blackbody (MBB) into the spectral energy distribution (SED) of the continuum emission from cold dust. Archival Herschel PACS (100 μm) and SPIRE (250, 350, and 500 μm) continuum observations that were obtained as part of the Herschel Gould Belt Survey (André et al. 2010) are adopted. Note that the PACS 100 and 70 μm observations are not included in the SED fitting. The 100 μm continuum observation was not covered by the Herschel Gould Belt Survey (André et al. 2010). For the 70 μm band, the MBB fitting with a single temperature cannot fit the observed emission in some cases because of the contamination due to nonequilibrium emission from small dust grains (Roy et al. 2013). Even if the detailed dust model is applied to the SED fitting including the 70 μm data, the derived column density is not significantly different from that derived using the single-temperature MBB fitting without the 70 μm data (Bianchi 2013).

The continuum emission maps were calibrated using Planck observations of the same regions via the method in Chen et al. (2019). Using the calibrated data, the column density maps were derived in two steps (Friesen et al. 2017; Chen et al. 2019): (1) dust temperature ($T_d$) and optical depth ($\tau_{\text{d}}$) maps were found via the SED fitting, and (2) the $N_{\text{H}}$ maps were obtained from the $\tau_{\text{d}}$ map by multiplying by a conversion factor assuming a gas-to-dust mass ratio of 100,

$$\frac{N_{\text{H}}}{\tau_{\text{d}}} = \frac{1}{100 \kappa_{\text{H}_2} \mu_{\text{H}_2} m_{\text{H}}},$$

around 2.5 km s$^{-1}$. From this result, Loren (1989b) suggested that L1709 may be separate from L1688. Neither L1688 nor L1709 regions have any overall motions in the $^{13}$CO line. We also checked the optically thinner $^{18}$O line, but there is no overall motion in each region (see Appendix D). The $\sigma_V$ is about 0.5 km s$^{-1}$ across the Ophiuchus cloud.

The $I_{\text{tot}}$ variations with column density are shown in Figure 14. The $I_{\text{tot}}$ of the HCN and HCO$^+$ lines are plotted against the column density. The $I_{\text{tot}}$ values of L1688 are around 3.5 km s$^{-1}$, while that in L1709 is

![Figure 10](image_url)

**Figure 10.** Observed lines toward Orion KL. The red and blue dotted vertical lines indicate the velocity ranges where the red (from $-10$ to $+5$ km s$^{-1}$) and blue (from $+13$ to $+27$ km s$^{-1}$) wing structures are presented.

| Line   | Central Peak (km s$^{-1}$) | Blue/Red Wings (km s$^{-1}$) |
|--------|--------------------------|------------------------------|
| $^{13}$CO | (5.0, 13.0)               | (−11.0, 5.0)/(13.0, 29.0)   |
| $^{18}$O | (5.0, 13.0)               | (−11.0, 5.0)/(13.0, 29.0)   |
| HCN    | (0.2, 20.1)               | (−15.8, 0.2)/(20.1, 36.1)   |
| HCO$^+$| (5.0, 13.0)               | (−11.0, 5.0)/(13.0, 29.0)   |
| N$_2$H$^+$| (−1.7, 21.2)            | (−17.7, −1.7)/(21.2, 37.2) |
| CS     | (5.0, 13.0)               | (−11.0, 5.0)/(13.0, 29.0)   |

The $I_{\text{tot}}$ of the $^{13}$CO line in Oph-A is stronger than that in Oph-C, while that of $^{18}$O in Oph-A is similar to that in Oph-C. Lada & Wilking (1980) found that $^{13}$CO $J = 1 \rightarrow 0$ is optically thick with a self-absorption feature in some positions. We thus investigated the $^{13}$CO and $^{18}$O lines toward the dense cores, where the $^{13}$CO line can probably be optically thick. Figure 14 presents the $^{13}$CO and $^{18}$O line spectra toward the 13 cores in L1688 (Pan et al. 2017) and two DCO$^+$ cores in L1709 (Loren et al. 1990). Some of the dense cores present self-absorption features in their $^{13}$CO line spectra.

Figures 6 and 7 show the $V_{\text{lsr}}$ and $\sigma_V$ maps for the $^{13}$CO line in the Ophiuchus cloud. The $V_{\text{lsr}}$ value varies from $+1.5$ to $+4.0$ km s$^{-1}$ across the Ophiuchus cloud. The $V_{\text{lsr}}$ map shows that the L1688 and L1709 regions have different $V_{\text{lsr}}$. The $V_{\text{lsr}}$ values of L1688 are around 3.5 km s$^{-1}$, while that in L1709 is

The Velocity Ranges for the Central Peak and Broad Wings

Table 3

The Velocity Ranges for the Central Peak and Broad Wings

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Figure 11. Left: comparison between the integrated intensities for the central peak ($I_{\text{center}}$) and broad wing structures ($I_{\text{wing}}$) of the Orion KL line spectra presented in Figure 10. The 3σ error ranges are presented in the error bars; however, their sizes are similar to or smaller than the symbol size. The gray solid lines indicate the position of the origin, and each dashed line presents the straight line from the origin to each data point. Right: zoom-in on the origin of the diagram.

Figure 12. Spatial distributions of the broad wing emission. In each panel, the red and blue contours indicate the integrated intensities for the red- and blueshifted wings. The contour levels are 2, 6, and 9 K km s$^{-1}$. The background image exhibits the map of $I_{\text{center}}$.

Figure 13. Distribution of young embedded protostars in the Ophiuchus cloud. The background image is the $I_{\text{tot}}$ map of C$^{18}$O, and the YSO catalog provided by Dunham et al. (2015) is presented with red circles.
where \( \kappa_{\nu_0} \) is the opacity of 0.1 cm\(^2\) g\(^{-1}\) at \( \nu_0 \) of 1000 GHz (Hildebrand 1983), \( \mu_{\text{H}_2} \) is a mean molecular weight per H\(_2\) molecule of 2.8, and \( m_{\text{H}} \) is the mass of a hydrogen atom. The final map has a beam size of 36\(\arcsec\), which is the resolution of the SPIRE 500 \( \mu\)m data. We thus convolved the \( N_{\text{H}_2} \) map to have a resolution of 50\(\arcsec\), which is comparable to the beam sizes of the TRAO maps (see Table 1).

The \( I_{\text{tot}} \) of each observed line generally increases as \( N_{\text{H}_2} \) increases up to a certain \( N_{\text{H}_2} \) and remains relatively constant after that certain \( N_{\text{H}_2} \) (see Figures 15 and 16 for the Orion A and Ophiuchus clouds, respectively). We fit the \( I_{\text{tot}} \) variation with a power-law relation to characterize how \( I_{\text{tot}} \) of a molecular line changes as \( N_{\text{H}_2} \) increases. In this process, we divide the Orion A cloud into two subregions, the ISF region (decl. > \(-6^\circ\)) and the rest of the cloud (decl. < \(-6^\circ\)), because ISF is more likely to be affected by the photon-dominated region (PDR; Shimajiri et al. 2014). Hereafter, ISF, the other regions in the Orion A cloud, and the Ophiuchus cloud are referred to as the ISF, L1641, and Ophiuchus regions.

For each line in each of the ISF, L1641, and Ophiuchus regions, the mean values of the \( I_{\text{tot}} \), peak temperature (\( T_{\text{peak}} \)), \( T_b \), and \( \sigma_V \) for a given \( N_{\text{H}_2} \) are investigated. The line spectra were separated into regularly spaced \( \log(N_{\text{H}_2}) \) bins with a size of \( \Delta \log(N_{\text{H}_2}) = 0.1 \). We derived the mean values of \( I_{\text{tot}} \) and \( \sigma_V \) for each bin, weighting the values by the inverse of the square of the uncertainty. For the \( T_{\text{peak}} \) and \( T_b \), the arithmetic mean values are adopted. Note that the variation of \( T_b \) seems to be relatively constant because it generally varies from 12 to 20 K in most areas except near the heating sources (such as OMC-1 and NGC 1977 in the Orion A cloud and HD 147889 in the Ophiuchus cloud).

We investigated the power-law indices, which can explain the variation of the mean \( I_{\text{tot}} \) values (\( \bar{I}_{\text{tot}} \)). We fitted the data with a power law: \( \log I_{\text{fit}} = \log b + \alpha \log N_{\text{H}_2} \). The \( \chi^2 \) minimization technique was used to obtain the fit parameters. The \( \chi^2 \) value is defined as follows:

\[
\chi^2 = \sum \frac{(I_{\text{tot}} - I_{\text{fit}})^2}{\varepsilon_{\text{mom0}}} ,
\]

where the sum is over the bin numbers, \( I_{\text{fit}} \) is an expected \( I_{\text{tot}} \) value from the power-law fit, and \( \varepsilon_{\text{mom0}} \) is the uncertainty of \( I_{\text{tot}} \). For C\(^1\)\(^{18}\)O, HCN, HCO\(^+\), \( N_2\)H\(^+\), and CS, there are several data points with very weak and relatively constant \( I_{\text{tot}} \) at a low-\( N_{\text{H}_2} \) regime (\( N_{\text{H}_2} < 2 \times 10^{21} \) cm\(^{-2}\)). These data points are the weighted means of a few pixels. Their line spectra are generally dominated by the noise, although the moment-masking method identified them as emission lines. Therefore, we excluded these
data points from the power-law fitting. The $N_{\text{H}_2}$ ranges for power-law fits were visually defined. The $N_{\text{H}_2}$ ranges for the fitting and the best-fit power-law indices ($\alpha$) are listed in Table 4.

Figure 17 shows the $I_{\text{tot}}$ variation of the $^{13}$CO and C$^{18}$O lines. For these lines, we divided the $N_{\text{H}_2}$ range into three regimes: (1) the low-$N_{\text{H}_2}$ regime, where $I_{\text{tot}}$ steeply increase ($\alpha > 2.0$); (2) the intermediate-$N_{\text{H}_2}$ regime, where $I_{\text{tot}}$ is proportional to $N_{\text{H}_2}$ ($\alpha \sim 1.0$); and (3) the high-$N_{\text{H}_2}$ regime, where $I_{\text{tot}}$ becomes relatively constant ($\alpha < 1.0$). The detailed $N_{\text{H}_2}$ ranges are different depending on the lines and regions; however, their $I_{\text{tot}}$ variations are similar.

Figure 18 shows the $I_{\text{tot}}$ variations in HCN, HCO$^+$, and CS lines. The variations of $I_{\text{tot}}$ are quite different depending on the lines and regions and cannot be explained with a single trend. Their $I_{\text{tot}}$ variations should be interpreted individually. The $I_{\text{tot}}$ variation of the N$_2$H$^+$ line is presented in Figure 19. The N$_2$H$^+$ line is only detected at the high-$N_{\text{H}_2}$ regions, where $N_{\text{H}_2}$ is higher than $10^{22}$ cm$^{-2}$. We will discuss these results in Sections 5.2 and 5.3.

5. Discussion

5.1. Broad Wing Structures in the Orion KL Spectra

As noted above, the Orion KL region shows wide line wings in $^{13}$CO, HCN, HCO$^+$, and CS; marginally in C$^{18}$O; and not in N$_2$H$^+$. Wannier & Phillips (1977) suggested that $^{12}$CO $J = 1$–0 is optically thin in the wings. The $^{13}$CO and C$^{18}$O lines thus would be optically thinner at the line wings. In this case, the intensity ratio between the $^{13}$CO and C$^{18}$O lines is probably close to their abundance ratio (Wannier & Phillips 1977). The ratio between $I_{\text{wing}}$ of the $^{13}$CO and C$^{18}$O lines is $10.5 \pm 2.8$. 

![Figure 15](https://example.com/fig15.png)

**Figure 15.** Comparison of $I_{\text{tot}}$ and column density ($N_{\text{H}_2}$) in the Orion A cloud. From the top to bottom panels, the diagrams show the $^{13}$CO, C$^{18}$O, HCN, HCO$^+$, N$_2$H$^+$, and CS lines.

![Figure 16](https://example.com/fig16.png)

![Figure 17](https://example.com/fig17.png)

![Figure 18](https://example.com/fig18.png)

![Figure 19](https://example.com/fig19.png)
This value is close to the abundance ratio determined by Shimajiri et al. (2014) \((X^{\text{CO}})/X^{\text{C\ O}} = 12.14\) within a 1\(\sigma\) range.

The ratios between \(I_{\text{wing}}\) and \(I_{\text{center}}\) for the HCN, HCO\(^+\), and CS lines are slightly different. The origins of the broad wing structures were discussed in previous works (Kuiper et al. 1980; Rydbeck et al. 1981; Olofsson et al. 1982; Hasegawa et al. 1984). The bipolar outflows aligned with the line of sight are suggested as the origin of the high-velocity wings (Olofsson et al. 1982). In this case, the high-velocity emission is spatially confined close to Orion KL. For the HCO\(^+\) line, the contribution of the shocked gas is also suggested (Rydbeck et al. 1981; Olofsson et al. 1982; Johansson et al. 1984). In addition, the abundance enhancement of HCN and HCO\(^+\) in the high-velocity components is also reported (Rydbeck et al. 1981; Johansson et al. 1984). Hasegawa et al. (1984) analyzed the CS line and suggested the existence of a large gas disk around the Orion KL nebula. They also mentioned that the high-velocity emission corresponding to the bipolar outflows was not observed in CS. These results may be related to the differences in ratios between \(I_{\text{wing}}\) and \(I_{\text{center}}\).

5.2. Variation of \(I_{\text{tot}}\) as a Function of \(N_{\text{H}_2}\)

If all the following assumptions are true (the lines are optically thin, stimulated radiative processes can be ignored, excitation temperatures are much lower than the kinetic temperature \(T_K\), and the abundance of the species is constant), the line intensity is proportional to \(n^2\) because every collision leads to a photon. If the line-of-sight depth is constant, the line intensity is also proportional to \(N_{\text{H}_2}\), as is generally true for optical or infrared emission lines. All these conditions are rarely met for millimeter-wave molecular emission lines. The fact that the excitation temperature is limited below by the radiation temperature and above by the kinetic temperature constrains the regime of densities over which every collision

![Figure 16. Same as Figure 15, but for the Ophiuchus cloud.](image)
The dependence of optical depth near unity and excitation temperatures near the peak indeed levels off near $T_d$ as predicted for optically thick, thermalized lines. None of the other transitions reach this point, so the fits to their slopes indicate that they lie primarily in the intermediate zone between growing like $N_{\text{H}_2}$ and the plateau. $N_2H^+$ is the exception, with slope near the predicted value of 2 over a substantial range of $N_{\text{H}_2}$ in the ISF, where $T_K$ is relatively high.

Kauffmann et al. (2017) analyzed the $^{13}$CO, C$^{18}$O, HCN, and $N_2H^+$ lines in the northern part of ISF and presented the normalized line-to-mass ratio as a function of the visual extinction ($A_v$) derived from Herschel column density. Figure 2 in Kauffmann et al. (2017) showed that there is a certain $A_v$ regime where the line-to-mass ratios remain relatively constant, which means that the $I_{\text{tot}}$ is proportional to $N_{\text{H}_2}$. Table 5 shows the $A_v$ regimes where the line-to-mass ratio remains constant and corresponding $N_{\text{H}_2}$ values for each line for the lines studied by Kauffmann et al. (2017) and the corresponding values for our study.

For the $^{13}$CO, C$^{18}$O, and $N_2H^+$ lines, the $N_{\text{H}_2}$ regime with $\alpha$ of about 1.0 is generally consistent with that from Kauffmann et al. (2017). The $N_{\text{H}_2}$ regimes for $\alpha \approx 1.0$ that are derived in this study are larger than those of Kauffmann et al. (2017). For the HCN line, the $N_{\text{H}_2}$ regime is quite different from what Kauffmann et al. (2017) presented. Kauffmann et al. (2017) only adopted a small region north of $-5:10:00$ decl. (J2000) to avoid the effect of radiation that is emitted from the Orion Nebula. However, the whole region north of $-6:00:00$ decl. (J2000), including OMC-1, is included in this study. The different results for column density regimes might be caused by the difference in the areas that are included in each analysis.

### 5.2.1. $^{13}$CO J = 1–0

The $^{13}$CO line has $\alpha > 2$ where $N_{\text{H}_2} < 10^{22}$ cm$^{-2}$. The uncertainty of $\alpha$ in these regimes is larger than that in the other regimes. Thus, detailed interpretation of $I_{\text{tot}}$ variation using $\alpha$ could be uncertain. The $\alpha$ values in intermediate-$N_{\text{H}_2}$ regimes are close to 1.0 and become shallower in the high-$N_{\text{H}_2}$ regime ($\alpha \approx 0.3$). This result indicates that the $^{13}$CO lines in both clouds are optically thick toward high-$N_{\text{H}_2}$ regions and cannot trace all the gas along the line of sight. In the Ophiuchus cloud, self-absorption features appear in the $^{13}$CO line spectra toward the star-forming cores. These results are consistent with previous studies showing that the $^{13}$CO line can be optically thick in the Orion A (Shimajiri et al. 2014) and Ophiuchus (Lada & Wilking 1980) clouds.

In this analysis, we neglected the effect of abundance variation within MCs. In fact, the $I_{\text{tot}}$ variation of the $^{13}$CO line also can be affected by the chemical difference between the subregions. The ISF region is also affected by the PDRs heated by the Trapezium stars (Shimajiri et al. 2014). In cold dense regions, $^{13}$CO can freeze onto dust grains.

### 5.2.2. C$^{18}$O J = 1–0

The observed C$^{18}$O lines preferentially trace regions of higher column density than are traced by the $^{13}$CO line. This is understood as the effect of lower abundance (Wilson & Rood 1994), which translates into lower optical depth and less radiative trapping. When $N_{\text{H}_2}$ is smaller than $3 \times 10^{22}$ cm$^{-2}$, only a few weak emission lines were detected. If we observe both clouds more deeply, the $I_{\text{tot}}$ variation in very low $N_{\text{H}_2}$ regimes would be accessible.
In the intermediate-\(N_{\text{H}_2}\) regime, where \(N_{\text{H}_2}\) is between \(1.6 \times 10^{22}\) cm\(^{-2}\) and \(5.0 \times 10^{23}\) cm\(^{-2}\), the \(\alpha\) values are \(-1\). If \(N_{\text{H}_2}\) exceeds \(5.0 \times 10^{22}\) cm\(^{-2}\), the slopes become shallower. In the ISF and Ophiuchus regions, \(\alpha\) becomes comparable to zero. For the ISF region, Shimajiri et al. (2014) found that \(\text{C}^{18}\text{O}\) \(J = 1-0\) is optically thin, and the abundance of \(\text{C}^{18}\text{O}\) would be affected by the selective photodissociation in PDR chemistry. Abundance variations caused by photodissociation or freezeout (Caselli et al. 1999) can also affect the line emission. In the Ophiuchus region, \(I_{\text{tot}}\) sharply increases beyond \(N_{\text{H}_2}\) of \(10^{23}\) cm\(^{-2}\). This increase results from a selection bias; the highest \(N_{\text{H}_2}\) bin originates only from the Oph-A core that has the highest \(N_{\text{H}_2}\) and \(T_d\) within the Ophiuchus region.

5.2.3. HCN \(J = 1-0\) and HCO\(^+\) \(J = 1-0\)

The \(I_{\text{tot}}\) for the HCN and HCO\(^+\) lines shows different variation depending on the lines and regions. Also, the \(\alpha\) for a given line and region changes in different ways depending on the \(N_{\text{H}_2}\) regimes. Only the \(I_{\text{tot}}\) variation for the HCO\(^+\) line in the ISF region is similar to what the \(^{13}\text{CO}\) and \(\text{C}^{18}\text{O}\) lines exhibited. This difference seen in the HCO\(^+\) and HCN lines may be due to different star formation activities in different regions. HCO\(^+\) and HCN have been known as good tracers of star formation activities because they become abundant in the gas affected by shocks and high-energy UV photons.

5.2.4. CS \(J = 1-0\)

The \(I_{\text{tot}}\) variation of the CS line shows that \(\alpha\) decreases as \(N_{\text{H}_2}\) increases, similar to what was seen for \(^{13}\text{CO}\) and \(\text{C}^{18}\text{O}\) lines. However, the \(\alpha\) values are generally greater than or similar to 1. Only the Ophiuchus cloud has \(\alpha\) significantly smaller than 1 (\(\alpha = 0.63\)) when \(\log(N_{\text{H}_2})\) exceeds 22.6.

Table 4 shows that the \(I_{\text{tot}}\) variation of CS can be explained with \(\alpha\) of about 1.0 across the large \(N_{\text{H}_2}\) regime. In the ISF and L1641 regions, the \(N_{\text{H}_2}\) regimes with \(\alpha \sim 1.0\) are extended over one order of magnitude. This result indicates that the \(I_{\text{tot}}\) of CS is proportional to \(N_{\text{H}_2}\) over the broad range of \(N_{\text{H}_2}\) in the Orion A cloud. Pety et al. (2017) also mentioned that CS \(J = 2-1\) is one of the more useful column density tracers in the Orion B cloud.

5.2.5. \(N_2\text{H}^+\) \(J = 1-0\)

The \(N_2\text{H}^+\) line increases superlinearly at low column densities before approaching a more linear growth at higher column densities. This behavior reflects the low abundance of this species in gas of low column density and high CO abundance. It makes it a good probe of gas column density for regions of relatively high column density.

The dominant formation mechanism of the \(N_2\text{H}^+\) molecule is

\[
\text{H}_3^+ + \text{N}_2 \rightarrow \text{N}_2\text{H}^+ + \text{H}_2. \tag{3}
\]

When the CO abundance is close to \(10^4\), which is a typical value in MCs (Wilson & Rood 1994; van Dishoeck et al. 1995), \(\text{H}_3^+\) mainly combines with CO to form HCO\(^+\). Also, \(N_2\text{H}^+\) is destroyed by combining with CO,

\[
\text{N}_2\text{H}^+ + \text{CO} \rightarrow \text{N}_2 + \text{HCO}^+. \tag{4}
\]

Therefore, the \(N_2\text{H}^+\) line can be abundant in dense gas where CO is depleted from the gas phase (Bergin & Langer 1997;
Aikawa et al. 2001; Lee et al. 2003, 2004; Tatematsu et al. 2008). Therefore, \( I_{\text{tot}} \) of the N\(_2\)H\(^+\) line represents the column density of the dense gas if we assume that the N\(_2\)H\(^+\) line is optically thin.

The mean \( I_{\text{tot}} \) value at a given \( N_{\text{H}_2} \) in the ISF region is slightly higher than that of the L1641 and Ophiuchus regions. This result implies that the amount of dense gas along the line of sight in the ISF region is slightly larger than that in the L1641 and Ophiuchus regions.

Table 5

| Line          | \( \log(A_{\nu}) \) (mag) | \( \log(N_{\text{H}_2})^a \) (cm\(^{-2}\)) | \( \log(N_{\text{H}_2})^b \) (cm\(^{-2}\)) |
|---------------|---------------------------|------------------------------------------|------------------------------------------|
| \(^13\)CO     | 0.7–1.0                   | 21.7–22.0                                | 21.7–22.3                                |
| C\(^18\)O     | 1.0–1.3                   | 22.0–22.3                                | 22.2–22.8                                |
| HCN           | 0.7–1.4                   | 21.7–22.4                                | 22.9–23.3                                |
| N\(_2\)H\(^+\) | 1.8–2.0                   | 22.8–23.0                                | 22.8–23.3                                |

Notes.

\(^a\) The column density is derived via an equation, \( A_{\nu}/\text{mag} = N_{\text{H}_2}/9.4 \times 10^{20} \text{ cm}^{-2} \) (Kauffmann et al. 2017).

\(^b\) The \( N_{\text{H}_2} \) regimes in Table 4 are repeated for comparison.

The \( I_{\text{tot}} \) of the N\(_2\)H\(^+\) line is proportional to the amount of cold and dense gas along the line of sight if the N\(_2\)H\(^+\) line is optically thin. The mean \( I_{\text{tot}} \) value at a given \( N_{\text{H}_2} \) in the ISF region is slightly higher than that of the L1641 and Ophiuchus regions. This result implies that the amount of dense gas along the line of sight in the ISF region is slightly larger than that in the L1641 and Ophiuchus regions.

Figure 18. Same as Figure 17, but for the HCN (top), HCO\(^+\) (middle), and CS (bottom) lines.

Figure 19. Same as the left panel of Figure 17, but for the N\(_2\)H\(^+\) line.
the L1641 and Ophiuchus regions. Tatematsu et al. (2008) also mentioned that the abundance of N$_2$H$^+$ decreases toward the south in the ISF. Therefore, the difference in I$_{tot}$ of N$_2$H$^+$ also can be explained with an abundance difference between the regions.

5.3. Variation of Velocity Dispersion with Column Density

The right panels of Figures 17 and 18 display the rms velocity dispersion (moment 2; $\sigma_V$) versus N$_{H_2}$. The dispersion depends strongly on N$_{H_2}$, increasing by factors of 3–5, depending on the lines and regions. Weak lines can produce unrealistically small values of $\sigma_V$, but we have tried to avoid that by using the moment-masking method to make the $\sigma_V$ map and by adopting the average values weighted by the inverse of the square of the uncertainty. Consequently, we believe that the strong trends in $\sigma_V$ versus N$_{H_2}$ are real.

Two simple cloud models can be adopted to describe the increasing N$_{H_2}$ toward the center from the outer region: (1) a structure with a varying depth, like a cylinder with a uniform density located along the sky plane, and (2) a structure with a uniform depth, such as a slab with varying density, as illustrated in Figure 20. The observed line width is determined by sampling a turbulent velocity field along the line of sight (y-direction). If the line width correlates with path length, as expected from the turbulent velocity field (Larson 1981; Solomon et al. 1987; Heyer & Schloerb 1997; Klessen 2000), the $\sigma_V$ increases with N$_{H_2}$ in the cylindrical model, while that remains constant in the slab-like model. This result suggests that the cylinder cloud model can explain the low-N$_{H_2}$ edges of the cloud with low $\sigma_V$, unlike the slab-like cloud model.

5.4. Line Luminosities and Luminosity Ratios

The line luminosity of each line in the Orion A and Ophiuchus clouds is calculated by

$$L_{\text{line}} = D^2 \theta_{\text{pix}}^2 \sum_{i} N_{\text{pix}}^i,$$  \hspace{1em} (5)

where $D$, $\theta_{\text{pix}}$, $N_{\text{pix}}$, and $I_{\text{tot,pix}}$ are the distance, angular size of a pixel (20'), number of pixels, and line-integrated intensity per pixel, respectively. The $I_{\text{tot,pix}}$ is defined as

$$I_{\text{tot,pix}} = \frac{\theta_{\text{pix}}^2}{2\pi} \frac{1}{\sqrt{2\ln(2)}} I_{\text{tot}},$$  \hspace{1em} (6)

where $\theta_{\text{beam}}$ is the beam size. The distance to the Orion A cloud is assumed to be 416.3 pc, which is the average of the distances to the Orion nebular cluster, L1641, and L1647 (389, 417, and 443 pc, respectively; Kounkel et al. 2018). For the Ophiuchus cloud, we adopted 137 pc (Ortiz-León et al. 2017).

The value of $N_{\text{pix}}$ requires discussion. We have done the summation in two ways. In the first, only the pixels that in the moment-masked map of each line were included. Very weak emission extended over large areas can, however, contribute substantially to the line luminosity (Evans et al. 2020). For a
comparison to other galaxies where all the emission is included in a beam, we need to include that emission. We did that by including all pixels in the original spectral maps. The resulting values are denoted by “unbiased” in Table 6. The comparison of the two values confirms that regions where individual lines are not clearly detected nonetheless add substantial luminosity to some lines, especially HCN and HCO$^+$ in Ophiuchus. The drawback of including all pixels is that baseline subtraction must be very good to avoid systematic offsets; an example is the negative luminosity of N$_2$H$^+$ from the unbiased method. That line is clearly very concentrated with no contribution from very extended regions.

Table 6 presents the ratios of the total line luminosities to that of the $^{13}$CO line, which has the highest line luminosity in both clouds; the total line luminosities of the $^{13}$CO line in the Orion A and Ophiuchus clouds are 290.3 and 10.9 K km s$^{-1}$ pc$^2$, respectively. The total line luminosities of the C$^{18}$O, HCN, HCO$^+$, and CS lines are all lower than 10% of the $^{13}$CO luminosity. The line ratios follow similar patterns in the two clouds. However, as mentioned above, the luminosities derived from the moment-mapped maps of HCO$^+$ and HCN are much smaller than those from unbiased maps, indicative of the extended weak HCO$^+$ and HCN emission.

The $^{12}$CO-to-C$^{18}$O and HCO$^+$-to-HCN luminosity ratios are also given in Table 6. The $^{13}$CO-to-C$^{18}$O and HCO$^+$-to-HCN luminosity ratios have been used to study the properties of galaxies (Krips et al. 2008; Jiménez-Donaire et al. 2017; Méndez-Hernández et al. 2020). The $^{13}$CO-to-C$^{18}$O ratios are much larger than those for starburst (3.4 ± 0.9) and normal spiral galaxies (6.0 ± 0.9; Jiménez-Donaire et al. 2017). Méndez-Hernández et al. (2020) found a $^{13}$CO-to-C$^{18}$O ratio of 2.5 ± 0.6 with the stacked spectra of 24 galaxies. The weak detection of the C$^{18}$O line could cause a large uncertainty in the ratio. The observation of the C$^{18}$O line in galaxies with better sensitivities is needed to confirm this difference.

The HCO$^+$-to-HCN ratio for galaxies has been used to distinguish the phenomena in galaxies, such as an active galactic nucleus (AGN) and starburst. The HCO$^+$-to-HCN ratios for the AGN-dominated galaxies that were studied by Krips et al. (2008) are about 0.66, increasing to about 1.5 as the contribution of the starburst increases. The ratio in Orion A (1.2–1.5) is similar to that for starbursts, while that in Ophiuchus (1.0) is intermediate between those of AGNs and those of starbursts.

6. Summary

We obtained large and homogeneous line maps of the Orion A and Ophiuchus clouds in six different molecular transitions as one of the TRAO-KSPs, TIMES. Both clouds were mapped in $^{13}$CO $J = 1–0/C^{18}$O $J = 1–0$, HCN $J = 1–0/HCO^+ J = 1–0$, and N$_2$H$^+ J = 1–0/CS J = 2–1$ using the TRAO 13.7 m telescope. The areas of mapped regions were 8.7 and 3.9 deg$^2$ toward the Orion A and Ophiuchus clouds, respectively, with ~50″ beam size. We discussed the physical and chemical environments traced by the observed lines in both clouds. The main results are summarized as follows:

1. The observed $^{13}$CO line traces relatively diffuse gas in the MCs. For the Orion A cloud, there are a large-scale north–south velocity gradient and complex velocity structures. For the Ophiuchus cloud, the L1688 and L1709 regions have different velocities and generally show random motions. The Ophiuchus cloud is kinematically quiescent compared to the Orion A cloud.

2. The C$^{18}$O line traces high column density regions, which are potentially the birthplace of the stars. The emission-line maps show clumpy structures, and their spatial distribution is well correlated with that of the young embedded protostars.

3. The N$_2$H$^+$ line traces cold and dense clumps/cores in the observed clouds. These clumps/cores seem to be embedded in the clumps that are revealed by the C$^{18}$O line.

4. The CS $J = 2–1$ line traces the broadest range of the column density (over one order of magnitude), making it a good probe of column density in MCs.

5. The HCN and HCO$^+$ lines trace the gas affected by the active star-forming activities. In the Orion A cloud, both emission lines coexist in the ISF, the active star-forming clusters (L1641-N, L1641-C, L1641-S cluster), and nearby the HH objects. In the Ophiuchus cloud, however, the HCN line is mainly detected toward Oph-A and Oph-B, while the HCO$^+$ line is emitted from Oph-C, Oph-E, and Oph-F.

6. The high-velocity wing structures are marginally detected in the C$^{18}$O line spectrum obtained toward the OMC-1. The N$_2$H$^+$ lines do not have high-velocity wings.

7. The velocity dispersions all increase strongly with column density, suggesting that the edges of the cloud are largely defined by small path length, not just low volume density.

8. The $^{13}$CO-to-C$^{18}$O line luminosity ratios for the Orion A and Ophiuchus clouds are much larger than that of starburst galaxies, while the HCO$^+$-to-HCN ratios are comparable to that of the starburst galaxies.

In a companion paper (Yun et al. 2021), we use the TIMES data to explore the relationship between turbulence and star formation activity in MCs. We apply principal component analysis (PCA; Heyer & Schloerb 1997; Brunt & Heyer 2013), which is one of the statistical methods used to derive the low-order velocity structure function, to the spectral maps presented in this paper. The uniform coverage, sensitivity, and range of

Table 6

| Cloud            | $L_{^{13}$CO} | $L_{C^{18}$O} | $L_{HCN}$ | $L_{^{13}$CO} | $L_{C^{18}$O} | $L_{CS}$ | $L_{^{13}$CO}/$L_{C^{18}$O} | $L_{HCN}/L_{C^{18}$O} |
|-----------------|---------------|---------------|-----------|---------------|---------------|----------|----------------------------|-----------------------|
| Orion A        | 1.000         | 0.039         | 0.025     | 0.036         | 0.005         | 0.030    | 25.673                     | 1.458                  |
| Orion A (unbiased) | 1.000         | 0.049         | 0.030     | 0.036         | 0.005         | 0.040    | 20.475                     | 1.179                  |
| Ophiuchus       | 1.000         | 0.076         | 0.009     | 0.009         | 0.004         | 0.029    | 13.180                     | 0.987                  |
| Ophiuchus (unbiased) | 1.000         | 0.089         | 0.055     | 0.056         | −0.001        | 0.035    | 11.236                     | 1.007                  |
gas tracers included in the TIMES program are ideal for studying MC kinematics and turbulence.

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Appendix A

Moment 0, 1, and 2 Maps for the Orion A Cloud

We generated the moment maps for each of the C$^{18}$O, HCN, HCO$^+$, N$_2$H$^+$, and CS lines in the Orion A cloud through the method described in Section 3. Figures A1–A5 present the $I_{\text{tot}}$ maps, and Figures A6–A15 present the $V_{\text{lsr}}$ and $\sigma_V$ maps of each line.

Figure A1. Same as Figure 2, but for the C$^{18}$O line. We annotated the C$^{18}$O map with the names of the associated sources (Davis et al. 2009; Mairs et al. 2016; Meingast et al. 2016).
Figure A2. Same as Figure 2, but for the HCN line. We annotated the map with the names of the associated sources (Davis et al. 2009; Mairs et al. 2016; Meingast et al. 2016).
Figure A3. Same as Figure 2, but for the HCO$^+$ line. We annotated the map with the names of the associated sources (Davis et al. 2009; Mairs et al. 2016; Meingast et al. 2016).
Figure A4. Same as Figure 2, but for the N$_2$H$^+$ line. We annotated the map with the names of the associated sources (Davis et al. 2009; Mairs et al. 2016; Meingast et al. 2016).
Figure A5. Same as Figure 2, but for the CS line. We annotated the map with the names of the associated sources (Davis et al. 2009; Mairs et al. 2016; Meingast et al. 2016).

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Figure A6. Same as Figure 4, but for the C$^{18}$O line. The color scale of the $V_{lsr}$ map is the same as that of the $^{13}$CO line (Figure A6).
Figure A7. Same as Figure 5, but for the C$^{18}$O line.
Figure A8. Same as Figure 4, but for the HCN line.
Figure A9. Same as Figure 5, but for the HCN line. Note that the $\sigma_V$ of the HCN line near the ISF would be underestimated (see Section 3 for more details).
Figure A10. Same as Figure 4, but for the HCO$^+$ line.
Figure A11. Same as Figure 5, but for the HCO$^+$ line.
Figure A12. Same as Figure 4, but for the N$_2$H$^+$ line.
Figure A13. Same as Figure 5, but for the N$_2$H$^+$ line.
Figure A14. Same as Figure 4, but for the CS line.
Appendix B

Moment 0, 1, and 2 Maps for the Ophiuchus Cloud

The moment maps of the $^{18}$O, HCN, HCO$^+$, N$_2$H$^+$, and CS lines in the Ophiuchus cloud were generated through the same method that was applied to the Orion A data. Figures B1–B5 present the $I_{\text{tot}}$ maps, and Figures B6–B15 present the $V_{\text{lsr}}$ and $\sigma_V$ maps of each line.

Figure A15. Same as Figure 5, but for the CS line.
Figure B1. Same as Figure 3, but for the C$^{18}$O line. The sources associated with the observed line are marked (Lynds 1962; Loren 1989a; Loren et al. 1990; Pan et al. 2017).

Figure B2. Same as Figure 3, but for the HCN line. The sources associated with the observed line are marked (Lynds 1962; Loren 1989a; Loren et al. 1990; Pan et al. 2017).

Figure B3. Same as Figure 3, but for the HCO$^+$ line. The sources associated with the observed line are marked (Lynds 1962; Loren 1989a; Loren et al. 1990; Pan et al. 2017).
Figure B4. Same as Figure 3, but for the N$_2$H$^+$ line. The names of the associated cores are marked (Lynds 1962; Loren 1989a; Loren et al. 1990; Pan et al. 2017).

Figure B5. Same as Figure 3, but for the CS line. The sources associated with the observed line are marked (Lynds 1962; Loren 1989a; Loren et al. 1990; Pan et al. 2017).

Figure B6. Same as Figure 6, but for the C$^{18}$O line. The color scale of the map is the same as that of the $^{13}$CO line (Figure 6).
Figure B7. Same as Figure 7, but for the $^{13}$CO line.

Figure B8. Same as Figure 6, but for the HCN line.

Figure B9. Same as Figure 7, but for the HCN line.
Figure B10. Same as Figure 6, but for the HCO$^+$ line.

Figure B11. Same as Figure 7, but for the HCO$^+$ line.

Figure B12. Same as Figure 6, but for the N$_2$H$^+$ line.
Figure B13. Same as Figure 7, but for the N$_2$H$^+$ line.

Figure B14. Same as Figure 6, but for the CS line.

Figure B15. Same as Figure 7, but for the CS line.
Appendix C
Multiple Cloud Components along the Line of Sight in the Orion A Cloud

Figures 5 and 7 exhibit several small high-$\sigma_V$ regions. There are high-$\sigma_V$ regions in the ISF and L1647 of the Orion A cloud. In the Ophiuchus cloud, there is a small high-$\sigma_V$ region in the northern part of L1688. In each cloud, these regions have $\sigma_V$ that are higher than the typical value of $\sigma_V$ in the other part of the cloud.

Figures C1 and C2 show the position–velocity (PV) diagrams for these high-$\sigma_V$ regions in the Orion A cloud, and Figure C3 presents the PV diagram for the high-$\sigma_V$ region in the Ophiuchus cloud. The PV diagrams demonstrate that there are two cloud components along the lines of sight at the high-$\sigma_V$ regions. Thus, the high-$\sigma_V$ values are caused by multiple gas components with different line-of-sight velocities. In the ISF region, the interactions between the MC and nearby sources, such as a foreground expending nebula and protostellar outflows, seem to produce these multiple cloud components (Shimajiri et al. 2014; Kong et al. 2018). In the L1647 and L1688 regions, there might be foreground or background cloud components with different line-of-sight velocities.

Figure C1. PV diagrams for the high-$\sigma_V$ regions in the ISF. The positions where the PV diagrams are extracted are presented with the solid lines on the $\sigma_V$ map of $^{13}$CO (the first panel). The PV diagrams along the solid lines (A, B, and C) are presented in the second, third, and fourth panels. The dotted horizontal lines in each PV diagram represent the position of the high-$\sigma_V$ regions on each line. The offset on the y-axis of the PV diagrams indicates a displacement from east to west on the line.

Figure C2. Same as Figure C1, but for the high-$\sigma_V$ regions in L1709.
Appendix D
Random Motion of the L1688 Cloud

Because the observed $^{13}$CO line can be optically thick toward the dense part of L1688, the $V_{lsr}$ map for $^{13}$CO (Figure 6) cannot exactly present the global motion of the cloud. Therefore, the optically thinner lines, such as the C$^{18}$O and CS lines, should be used to trace the global motion. However, the $V_{lsr}$ maps of the C$^{18}$O and CS lines do not present any large-scale motions of the L1688 cloud (Figures B6 and B10). Loren (1989b) also suggested that the gas motion in the L1688 cloud is more complex than simple rotation. They measured $V_{lsr}$ of the Ophiuchus cores using the $^{13}$CO and DCO$^+$ lines and found that the velocity variation for the DCO$^+$ lines is larger than that for the $^{13}$CO lines. Therefore, we assume that there is no global motion in L1688.

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Figure C3. Same as Figure C1, but for the high-$\sigma_V$ region in L1688.
Erratum: “TIMES. I. A Systematic Observation in Multiple Molecular Lines toward the Orion A and Ophiuchus Clouds” (2021, ApJS, 256, 16)

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1. Explanation of Need for Erratum

In a recent paper, Tafalla et al. (2023) compared line luminosities for Orion using a sampling method to our results in the published article. The comparison revealed large discrepancies, necessitating the current erratum to correct errors and to make the results more useful for future comparisons. The next section should replace Section 5.4 of the published article. The changes are the following: we now give results in units of $T_{mb}$; we give values using both the original, moment-masking technique and a method that uses all the pixels (unbiased); for both methods, we performed a very careful baseline fit to the final summed spectrum. These changes produced much better agreement between our unbiased luminosities and those of the sampling method.

5.4 Line Luminosities and Luminosity Ratios

The line luminosity of each line in the Orion A and Ophiuchus clouds is calculated by

$$L_{line} = \frac{D^2 \Omega_{pix} N_{pix}}{\eta_{B}} \sum l_{tot}$$

where $\eta_{B}$, $D$, $\Omega_{pix}$, $N_{pix}$, and $l_{tot}$ are the main-beam efficiency, distance, solid angle of a pixel, number of pixels, and integrated intensity of the observed lines on the $T_{A}^{*}$ scale, respectively. The resulting luminosity is then on the $T_{mb}$ scale for easier comparison to other results. The distance to the Orion A cloud is assumed to be 416.3 pc, which is the average of the distances to the Orion nebular cluster, L1641, and L1647 (389, 417, and 443 pc, respectively; Kouwenk et al. 2018). For the Ophiuchus cloud, we adopted 137 pc (Ortiz-León et al. 2017). The derived line luminosities are listed in Table 6.

The value of $N_{pix}$ requires discussion. We have done the summation in two ways. In the first, only the pixels that were in the moment-masked map of each line were included. However, the moment-masking method will exclude weak emission lines that are not detected in individual pixels. Very weak emission extended over large areas can contribute substantially to the line luminosity (Evans et al. 2020). For a comparison to other galaxies where all the emission is included in a beam, we need to include that emission. We did that by including all pixels in the original spectral maps. The resulting values are denoted by “unbiased” in Table 6. The comparison of the two values confirms that regions where individual lines are not clearly detected nonetheless add substantial luminosity to some lines, especially HCN and HCO$^+$ in Ophiuchus, where the unbiased values are about 6 times higher than the values using moment masking. This discrepancy reflects the importance of including very weak, but widespread, emission in computing the total luminosity.

The unbiased luminosities for the Orion A cloud can now be compared to those in Tafalla et al. (2023). Correcting for the slightly different distance assumptions, the ratios of line luminosities derived by Tafalla et al. (2023) and this work are 1.18 for $^{13}$CO, 0.95 for C$^{18}$O, 1.22 for HCN, 1.28 for HCO$^+$, and 1.46 for CS. The first four agree within reasonable uncertainties associated with exact sky coverage and the statistical limitations of the sampling method. The higher ratio for CS probably reflects the fact that our map coverage of CS was less extensive than the coverage of the other species.
The $^{13}$CO-to-C$^{18}$O and HCO$^+$-to-HCN luminosity ratios are also given in Table 6. The $^{13}$CO-to-C$^{18}$O and HCO$^+$-to-HCN luminosity ratios have been used to study the properties of galaxies (Krips et al. 2008; Jiménez-Donaire et al. 2017; Méndez-Hernández et al. 2020). The $^{13}$CO-to-C$^{18}$O ratios are much larger than those for starburst (3.4 ± 0.9) and normal spiral galaxies (6.0 ± 0.9; Jiménez-Donaire et al. 2017). Méndez-Hernández et al. (2020) found a $^{13}$CO-to-C$^{18}$O ratio of 2.5 ± 0.6 with the stacked spectra of 24 galaxies. The weak detection of the C$^{18}$O line could cause a large uncertainty in the ratio. The observation of the C$^{18}$O line in galaxies with better sensitivities is needed to confirm this difference.

The HCO$^+$-to-HCN ratio for galaxies has been used to distinguish phenomena in galaxies, such as an active galactic nucleus (AGN) and starbursts. The HCO$^+$-to-HCN ratios for the AGN-dominated galaxies that were studied by Krips et al. (2008) are about 0.66, increasing to about 1.5 as the contribution of the starbursts increases. The ratios in the Orion A (0.99) and Ophiuchus clouds (0.91) are intermediate between those of AGN and those of starbursts.

### Table 6

| Cloud               | $L_{^{13}CO}$ | $L_{^{18}CO}$ | $L_{HCN}$ | $L_{HCN}$ | $L_{HCO^+}$ | $L_{CS}$ | $L_{^{13}CO}/L_{^{18}CO}$ | $L_{HCO^+}/L_{HCN}$ |
|---------------------|---------------|---------------|-----------|-----------|-------------|---------|--------------------------|---------------------|
| Orion A             | 3036.81       | 237.91        | 113.81    | 123.46    | 111.23      | 24.39   | 1.386                    | 0.986               |
| Orion A (unbiased)  | 3346.81       | 124.47        | 124.53    | 20.89     | 112.63      | 24.39   | 1.386                    | 0.986               |
| Ophiuchus           | 113.81        | 8.78          | 11.92     | 10.84     | 0.89        | 5.29    | 0.909                    |                     |
| Ophiuchus (unbiased)| 123.46        | 10.99         | 11.92     | 10.84     | 0.89        | 5.29    | 0.909                    |                     |

### References

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