Chemical Compositions in the Vicinity of Protostars in Ophiuchus

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Received 2021 June 10; revised 2021 August 24; accepted 2021 August 24; published 2021 November 26

Abstract

We have analyzed Atacama Large Millimeter/submillimeter Array Cycle 4 Band 6 data toward two young stellar objects (YSOs), Oph-emb5 and Oph-emb9, in the Ophiuchus star-forming region. The YSO Oph-emb5 is located in a relatively quiescent region, whereas Oph-emb9 is irradiated by a nearby bright Herbig Be star. Molecular lines from cyclic-C2H2 (C2H2H), H2CO, CH3OH, 13C0, C18O, and DCO+ have been detected from both sources, while DCN is detected only in Oph-emb9. Around Oph-emb5, C2H2H is enhanced at the west side, relative to the IR source, whereas H2CO and CH3OH are abundant at the east side. In the field of Oph-emb9, moment 0 maps of the C2H2H lines show a peak at the eastern edge of the field of view, which is irradiated by the Herbig Be star. Moment 0 maps of CH3OH and H2CO show peaks farther from the bright star. We derive the N(C2H2H)/N(CH3OH) column density ratios at the peak positions of C2H2H and CH3OH near each YSO, which are identified based on their moment 0 maps. The N(C2H2H)/N(CH3OH) ratio at the C2H2H peak is significantly higher than at the CH3OH peak by a factor of ~19 in Oph-emb9, while the difference in this column density ratio between these two positions is a factor of ~2.6 in Oph-emb5. These differences are attributed to the efficiency of the photon-dominated region chemistry in Oph-emb9. The higher DCO+ column density and the detection of DCN in Oph-emb9 are also discussed in the context of UV irradiation flux.

Unified Astronomy Thesaurus concepts: Astrochemistry (75); Interstellar molecules (849)

1. Introduction

Chemical composition is a powerful tool with which to investigate the physical conditions and their evolution (Caselli & Ceccarelli 2012) from core scale (<0.1 pc) to clump scale in molecular clouds (~1 pc; Taniguchi et al. 2020). These studies around low-mass protostars are essential for understanding the formation processes of our solar system and complex organic molecules (COMs) detected in solar system bodies (Ceccarelli et al. 2017). Chemical differentiation around low-mass young stellar objects (YSOs) has been proposed since the late 2000s. One such chemical process is called hot-corino chemistry, which leads to abundant COMs consisting of more than six atoms (Herbst & van Dishoeck 2009). The other important one is called warm carbon-chain chemistry (WCCC; Sakai et al. 2008). Recent observations have shown chemical differentiation not only around low-mass YSOs, but also around high-mass YSOs as well (Taniguchi et al. 2018, 2019b, 2021a). Although the origin of the chemical differentiation around YSOs is still controversial, three possible factors have been proposed: the different timescale of the prestellar collapse (Sakai et al. 2008), the different ultraviolet (UV) radiation field (Spezzano et al. 2016), and the different timescale of the warm-up stage (Taniguchi et al. 2019a). In order to reveal the effects of the above factors, we need to investigate molecular spatial distributions on large scales (e.g., the clump scale).

Our Sun is considered to have been born as a member of a cluster (Adams 2010; Jensen et al. 2019). In such a region, nearby sources may play important roles in chemical processes. One of the processes affecting chemical composition is UV radiation, as was suggested by Spezzano et al. (2016) based on observations toward starless cores. They found that CH3OH is abundant in a region well shielded against the interstellar radiation field, while cyclic-C2H2 (hereafter c-C2H2) is enhanced in the irradiated environment. Such a chemical differentiation implies a different chemical composition in ice mantles, as shown by the CH4/CH3OH ice-mantle abundance ratio (Spezzano et al. 2016, 2020), because the gas-phase c-C2H2 can be considered to form from CH3 by the WCCC mechanism (Hassel et al. 2008). The UV radiation destroys CO molecules forming carbon atoms (C), which lead to the CH2-rich ice, and finally the carbon-chain-rich gas.

Chemical differentiation around low-mass YSOs has been studied using single-dish telescopes. Lindberg et al. (2016) carried out survey observations of C2H and CH3OH toward 16 low-mass YSOs in the Ophiuchus and Corona Australis molecular clouds using the Kitt Peak 12 m radio telescope and APEX. They proposed a spatial separation between these two types of molecules. Another study by Lindberg et al. (2017) presented APEX observations of H2CO and c-C2H2 toward protostars in the Ophiuchus star-forming region. They suggested that the c-C2H2 emission traces the more shielded parts of the envelope, whereas the H2CO emission mainly
traces the outer irradiated envelopes. Their suggestion seems to be opposite to the finding in starless cores (Spezzano et al. 2016, 2020). Our target YSOs, identified as Oph-emb5 and Oph-emb9 in this paper, were also reported by Lindberg et al. (2016, 2017), and carbon-chain species (C2H and c-C3H2) and COMs (CH3OH and H2CO) have been detected from both YSOs. These studies (Lindberg et al. 2016, 2017), however, were single-dish single-pointing observations, and spatial variation among these molecular lines were not resolved. High-angular-resolution and high-sensitivity observations are needed to study the effects of UV radiation on chemical composition around YSOs in order to distinguish between nearby sources and target YSOs.

In this paper, we report Atacama Large Millimeter/submillimeter Array (ALMA) Band 6 data toward two YSOs in the Ophiuchus region. The Ophiuchus region is a nearby star-forming region (~140 pc; Ortiz-León et al. 2018) with Class II YSOs relatively more abundant than YSOs of other classes, similar to the Lupus I region and the Chamaeleon region (Dunham et al. 2015). A bright Herbig Be star (S1) irradiates the ρ Oph A cloud (Lindberg et al. 2017). The YSO Oph-emb9, one of our target sources, is located in this cloud and is irradiated by the Herbig Be star from the east. The YSO Oph-emb5 is located in the ρ Oph B cloud with no nearby irradiation sources. The distance between the ρ Oph A cloud and the ρ Oph B cloud is ~0.55 pc, and we can assume that the other initial conditions are comparable. Thus, these are good target regions to study effects of nearby bright sources on the chemical differentiation around YSOs.

The structure of the present paper is as follows. In Section 2, we explain the data sets and reduction procedure. The resultant continuum maps are presented in Section 3.1, moment 0 maps of the detected molecular lines are shown in Section 3.2, spectra and spectral analyses are presented in Section 3.3, and finally moment 2 maps of 13CO and 15N2 are shown in Section 3.4. Our main conclusions are summarized in Section 4.

## 2. Observations and Data Reduction

We have analyzed ALMA Band 6 archival data toward two YSOs in the Ophiuchus region taken as part of a Cycle 4 project. Table 1 summarizes the coordinates and properties of our two target YSOs. Based on the infrared spectral indices, Oph-emb5 and Oph-emb9 are classified as Flat SED and Class I, respectively.

| Source     | R.A. (J2000)\(^{a}\) | Decl. (J2000)\(^{a}\) | L\(_{bol}\) (L\(_{⊙}\))\(^{b}\) | T\(_{bol}\) (K)\(^{b}\) | M\(_{bol}\) (M\(_{⊙}\))\(^{b}\) | α\(_{陨\, \text{IR}}\) \(^{c}\) | Class \(^{d}\) |
|------------|----------------------|----------------------|---------------------|-----------------|-----------------|---------------|--------|
| Oph-emb5   | 16°27′41.96          | −24°27′27.77         | 0.1 (0.1)           | 87 (28)         | 0.15 (0.01)     | −0.05 (0.05) | Flat   |
| Oph-emb9   | 16°26′25.44          | −24°23′01.73         | 0.12 (0.37)         | 135 (49)        | 0.65 (0.05)     | 0.87 (0.05)  | I      |

Notes. Numbers in parentheses indicate uncertainties corrected by the distances.

\(^{a}\) Coordinates of infrared sources determined by the Spitzer observations (Enoch et al. 2009).

\(^{b}\) Bolometric luminosities at a distance of 125 pc taken from Enoch et al. (2009) and scaled to the newly measured distances (140.2 pc and 138.6 pc for Oph-emb5 and Oph-emb9, respectively; Ortiz-León et al. 2018).

\(^{c}\) Bolometric temperature taken from Enoch et al. (2009).

\(^{d}\) Envelope masses at a distance of 125 pc taken from Enoch et al. (2009) and scaled to the newly measured distances (140.2 pc and 138.6 pc for Oph-emb5 and Oph-emb9, respectively; Ortiz-León et al. 2018).

\(^{e}\) IR spectral indexes (α\(_{陨\, \text{IR}}\)) taken from Enoch et al. (2009).

\(^{f}\) Classification taken from White et al. (2015).

Figure 1 shows the Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010) images toward the two target YSOs. Oph-emb9 is irradiated by a luminous Herbig Be star S1 (also known as GSS35), located 2′ (~16,800 au) east of the ρ Oph A cloud (Lindberg et al. 2017). This Herbig Be star has spectral class of B4 (Bouvier & Appenzeller 1992) and luminosity of ~1000–1600 L\(_{⊙}\) (Bontemps et al. 2001; Wilking et al. 2005). On the other hand, Oph-emb5 is located in a relatively isolated region and is not affected by any other sources.

The data sets contain the 12 m array, 7 m array, and total power (TP) data. The 12 m array and 7 m array data were obtained in 2017 March. The TP observations were carried out in 2016 October toward Oph-emb9, and 2016 November and December and 2017 March and April toward Oph-emb5. Coordinates of the phase reference centers are (α\(_{J2000}\), δ\(_{J2000}\)) = (16°27′21.83, −24°27′27.56) and (16°26′25′49, −24°23′01.66) toward Oph-emb5 and Oph-emb9, respectively.

Table 2 summarizes the details of each spectral window. The correlator setup with a frequency resolution of 61 kHz was used for molecular line observations. This frequency resolution corresponds to a velocity resolution of ~0.084 km s\(^{-1}\). The velocity resolutions for each resultant cube are also summarized in Table 2. We employed a velocity resolution of 0.2 km s\(^{-1}\), when lines can be resolved sufficiently by this velocity resolution. The fields of view (FoVs) of the 12 m array and 7 m array are ~27′′ and ~46′′, respectively.

We carried out data reduction and imaging using the Common Astronomy Software Application (CASA; McMullin et al. 2007) on the pipeline-calibrated visibilities. We ran the calibration scripts using CASA version 4.7.0 for all of the data except for the TP data toward Oph-emb5, which was run with version 4.7.2.

The interferometric data cubes were created using the CASA “tclean” task after concatenating, combining the 12 m array and 7 m array data by task “concat.” Briggs weighting with a robust parameter of 0.5 was applied. The TP images were made using the “sdimaging” task. We combined the interferometer data with the TP data by using the feather task in CASA. A definition and characteristics are summarized in Evans et al. (2009).
Continuum images \((\lambda = 1.38 \text{ mm})\) with the 12 m array data were made by tclean task with the specmode of “mfs” in CASA. The center frequency and bandwidth for these continuum data are 217.0 GHz and 2 GHz, respectively. The resulting angular resolutions are \(2\arcsecond \times 1\arcsecond 5\) and \(1\arcsecond 8 \times 1\arcsecond 3\) for Oph-emb5 and Oph-emb9, respectively. The noise levels of the continuum images are \(6.0 \times 10^{-2} \text{ mJy beam}^{-1}\) and 1.0 mJy beam\(^{-1}\) for Oph-emb5 and Oph-emb9, respectively.

### 3. Results and Analyses

#### 3.1. Continuum Images

The continuum images toward the two YSOs are shown in Figure 2. The yellow crosses indicate the positions of infrared (IR) sources identified by the Spitzer Core to Disk (c2d) Legacy program (Enoch et al. 2009). Continuum emission is detected toward the YSO Oph-emb9. On the other hand, no continuum emission was detected toward the YSO Oph-emb5. Kamazaki et al. (2019) also did not detect the continuum emission toward this source (J162721 in their paper) at the 1.3 mm wavelength using ALMA. The nondetection of dust continuum emission has also been reported toward other Class I YSOs (e.g., Taniguchi et al. 2021b).

### Table 2

| Frequency Range (GHz) | Molecule | Transition | \(\Delta v^a\) (km s\(^{-1}\)) |
|-----------------------|----------|------------|-------------------------------|
| 217.92–217.96         | \(c\)-C\(_2\)H\(_2\) | \(5_{1,4} - 4_{2,3}\) | 0.084                         |
| 217.80–217.84         | \(c\)-C\(_2\)H\(_2\) | \(6_{0,6} - 5_{1,5}\) | 0.084                         |
| 218.20–218.24         | H\(_2\)CO | \(3_{0,3} - 2_{0,2}\) | 0.2                           |
| 218.45–218.49         | H\(_2\)CO | \(3_{2,2} - 2_{1,1}\) | 0.084/0.2\(^b\)              |
| 218.74–218.78         | H\(_2\)CO | \(3_{1,1} - 2_{0,0}\) | 0.084/0.2\(^b\)              |
| 218.42–218.46         | CH\(_3\)OH | \(4_{-2,3} - 3_{-1,2}\) | 0.084/0.2\(^b\)              |
| 219.54–219.58         | C\(_{18}\)O | 2 – 1 | 0.2                           |
| 220.38–220.41         | \(^{13}\)CO | 2 – 1 | 0.2                           |
| 216.09–216.13         | DCO\(^+\) | 3 – 2 | 0.084                         |
| 217.22–217.26         | DCN | 3 – 2 | 0.084                         |
| 216.0–218.0           | Continuum | ... | ...                           |

**Notes.**

\(^a\) Velocity resolution of the resultant cubes.

\(^b\) The velocity resolution of 0.084 km s\(^{-1}\) and 0.2 km s\(^{-1}\) were applied for Oph-emb5 and Oph-emb9 data, respectively.

Continuum images \((\lambda = 1.38 \text{ mm})\) with the 12 m array data were made by tclean task with the specmode of “mfs” in CASA. The center frequency and bandwidth for these continuum data are 217.0 GHz and 2 GHz, respectively. The resulting angular resolutions are \(2\arcsecond \times 1\arcsecond 5\) and \(1\arcsecond 8 \times 1\arcsecond 3\) for Oph-emb5 and Oph-emb9, respectively. The noise levels of the continuum images are \(6.0 \times 10^{-2} \text{ mJy beam}^{-1}\) and 1.0 mJy beam\(^{-1}\) for Oph-emb5 and Oph-emb9, respectively.

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3.2. Moment 0 Maps of the Observed Molecular Lines

Figures 3 and 4 show moment 0 maps of the observed molecular lines toward Oph-emb5 and Oph-emb9, respectively. Table 3 summarizes information on the noise levels for each panel.

Around Oph-emb5, there are differences in spatial distributions between carbon-chain species (c-C₃H₂) and COMs (H₂CO and CH₃OH). The hydrocarbon c-C₃H₂ is enhanced in the region west of the IR source (shown in panels (a) and (b) in Figure 3). On the other hand, H₂CO and CH₃OH tend to be enhanced to the east of the IR source. The H₂CO (3_{0,3} − 2_{0,2}) line (panel (c)) is more extended than its other lines (panels (d) and (e)). This seems to be caused by the different upper-state energies (Table 3). The peaks of CH₃OH are consistent with those of H₂CO. Peaks of C¹⁸O and ¹³CO (panels (g) and (h)) are located at the northeast edge and their spatial distributions resemble that of H₂CO (3_{0,3} − 2_{0,2}) line. The DCO⁺ moment 0 map shows an extended structure (panel (i)). We did not detect the DCN line toward Oph-emb5 (panel (j)).

In Oph-emb9, the observed molecular emission for all detected lines is enhanced in the eastern part of the FoV. This side is irradiated by the nearby Herbig Be star (Figure 1). More details are discussed in Section 3.2.1. H₂CO shows an elongated feature from the northeast to the southwest. The CH₃OH emission shows a similar tendency as H₂CO, and their peaks are consistent with each other. In addition, a weak CH₃OH peak is associated with the IR source. The emission from C¹⁸O and ¹³CO is generally strong in the eastern edge of the FoV, and ¹³CO shows an additional, less strong and more concentrated, emission peak to the west. The orientation of the ¹³CO emission peaks is consistent with the molecular outflow (Artur de la Villarmois et al. 2019). We have detected the DCN line toward Oph-emb9. Its spatial distribution is the most compact and is different from the other deuterated species, DCO⁺. The upper-state energy of the observed DCN line (E_up/k = 20.9 K) is similar to that of DCO⁺ (20.7 K), and it follows that the different spatial distributions are not caused by different excitation conditions. The details are discussed in Section 3.2.2.

3.2.1. Comparison of Spatial Distributions of c-C₃H₂ with H₂CO and CH₃OH

In this subsection, we investigate effects of the UV radiation from the Herbig Be star on the chemistry around the observed YSOs by comparing the spatial distributions of c-C₃H₂ with H₂CO and CH₃OH. In astrochemical models, c-C₃H₂ can be formed by the destruction of large hydrocarbons through UV irradiation (top-down chemistry) or through the accumulation of C and H atoms to form small hydrocarbons (bottom-up chemistry) (Murillo et al. 2018). Large hydrocarbons could also be formed by destruction of dust grains (e.g., Zhen et al. 2014). In a more specific bottom-up chemistry, small hydrocarbons can be efficiently formed in the gas phase via ion–molecule reactions including C⁺ (e.g., Maluendes et al. 1993; Le Gal et al. 2017).

In the case of Oph-emb5, c-C₃H₂ is enhanced at the west side, whereas H₂CO and CH₃OH are enhanced at the eastern parts relative to the YSO. Since Oph-emb5 is unlikely affected by any sources (Lindberg et al. 2017), these features are not induced by the UV radiation, but may indicate effects of stellar feedback, such as the molecular outflows. We discuss this point further in Section 3.4.1.

In Oph-emb9, the spatial distributions of c-C₃H₂ show peaks at the eastern edge of the field, which is irradiated by the Herbig Be star. On the other hand, the spatial distributions of H₂CO and CH₃OH show maxima that are located farther from the Herbig Be star, and closer to the center of the field. The differences of the spatial distributions between small hydrocarbons and COMs in Oph-emb9 imply that top-down chemistry may efficiently contribute to the c-C₃H₂ formation under conditions of UV irradiation.
Figure 3. Moment 0 maps (combination of 12 m array, 7 m array, and TP) of \( c\text{-C}_2\text{H}_2 \) in panels (a) and (b), \( \text{H}_2\text{CO} \) in panels (c)–(e), \( \text{CH}_3\text{OH} \) in panel (f), \( \text{C}^{18}\text{O} \) in panel (g), \( ^{13}\text{CO} \) in panel (h), DCO\(^+\) in panel (i), and DCN in panel (j) toward Oph-emb5. The yellow crosses indicate positions of the infrared sources (Enoch et al. 2009). The contour levels are indicated in each panel at the bottom. The use of "\( \sigma \)" means that contours are based on the rms noise level, and using "\( \% \)" means contours are relative to the peak intensity. The rms noise levels for each panel are summarized in Table 3. The filled black ellipses indicate the beam sizes of \( 2'' \times 1''/5 \). In panels (b) and (f), \( c\text{-C}_2\text{H}_2 \) Peak and \( \text{CH}_3\text{OH} \) Peak are indicated as white dashed circles (see Section 3.3).
Figure 4. Moment 0 maps (combination of 12 m array, 7 m array, and TP) of c-C$_3$H$_2$ in panels (a) and (b), H$_2$CO in panels (c)–(e), CH$_3$OH in panel (f), C$^{18}$O in panel (g), $^{13}$CO in panel (h), DCO$^+$ in panel (i), and DCN in panel (j) toward Oph-emb9. The yellow crosses indicate positions of the infrared sources (Enoch et al. 2009). The contour levels are indicated in each panel at the bottom. The use of \( \sigma \) means that contours are based on the rms noise level, and using \( \% \) means contours relative to the peak intensity. The rms noise levels for each panel are summarized in Table 3. The filled black ellipses indicate the beam sizes of 1$''$8 $\times$ 1$''$3. In panels (b) and (f), c-C$_3$H$_2$ Peak and CH$_3$OH Peak are indicated as white dashed circles (see Section 3.3). The black dashed arrows in panel (h) indicate the direction of the molecular outflow (Artur de la Villarmois et al. 2019).
3.2.2. Comparison of Spatial Distributions of DCO\(^+\) and DCN

In this subsection, we discuss the higher DCO\(^+\) column density in Oph-emb9 compared with Oph-emb5 and the sole DCN detection in Oph-emb9 as seen in their moment 0 maps.

The DCO\(^+\) ion is considered to be formed in the gas phase mainly by the following reaction in cold environments (<30 K; Ceccarelli et al. 2014):

\[
\text{H}_2\text{D}^+ + \text{CO} \rightarrow \text{DCO}^+ + \text{H}_2. \tag{1}
\]

Another reaction that could produce DCO\(^+\) in warm regions (>30 K; Adams & Smith 1985) is

\[
\text{HCO}^+ + \text{D} \rightarrow \text{DCO}^+ + \text{H}. \tag{2}
\]

In the case of DCN, the main formation pathways (Millar et al. 1989; Turner 2001) are

\[
\text{CH}_2\text{D}^+ + \text{H}_2 \rightarrow \text{CH}_4\text{D}^+ + \nu, \tag{3}
\]

\[
\text{CH}_4\text{D}^+ + \text{e}^- \rightarrow \text{CHD} + \text{H}_2 + \text{H}, \tag{4}
\]

followed by

\[
\text{CHD} + \text{N} \rightarrow \text{DCN} + \text{H}, \tag{5}
\]

or

\[
\text{CH}_2\text{D}^+ + \text{e}^- \rightarrow \text{CHD} + \text{H}, \tag{6}
\]

followed by Reaction (5). Hence, DCN is mainly formed by CH\(_3\)D\(^+\). The CH\(_3\)D\(^+\) ion is formed by reaction between CH\(_3\) and HD, and the endothermicity of the backward reaction is 654 K, which is higher than the reaction between H\(_2\) and HD (232 K), which forms H\(_2\)D\(^+\) (Oberg & Bergin 2021). As a result, CH\(_3\)D\(^+\) survives more easily in warmer gas (30 < T < 100 K) compared to H\(_2\)D\(^+\) (<30 K; Ceccarelli et al. 2014).

This means that DCN can efficiently form in warmer regions, whereas DCO\(^+\) can exist both in cold and warm regions due to Reactions (1) and (2).

In Oph-emb9, the UV radiation from the Herbig Be star can heat the gas and produce both the precursor ions HCO\(^+\) and CH\(_2\)D\(^-\) (Lindberg et al. 2017), leading to DCO\(^+\) (via Reaction (2), >30 K) and DCN (via Reactions (3) to (6), >30 K). In fact, the DCN spatial distribution follows that of the irradiated material, where the gas temperature is expected to be higher (Figure 4). On the other hand, in the case of Oph-emb5, the nondetection of DCN results from lower-temperature conditions, which implies formation of DCO\(^-\) via Reaction (1) (<30 K). The lower column density of DCO\(^+\) in Oph-emb5 compared to Oph-emb9 corresponds to lower H\(_2\)D\(^+\) abundance due to weaker UV irradiation.

3.3. Spectral Analysis

The spectral analysis of the detected lines of H\(_2\)CO, CH\(_3\)OH, c-C\(_3\)H\(_2\), DCO\(^+\), and DCN was carried out using the CASSIS software (Vastel et al. 2015) together with the CDMS\(^{12}\) and JPL\(^{13}\) spectroscopic databases. For the spectral analysis, we constructed 6\(^\prime\) (840 au) beam average spectra to balance the angular resolution and sensitivity. We pick two positions around each YSO, which are the strong c-C\(_3\)H\(_2\) emission positions, and the strong CH\(_3\)OH emission positions. They are chosen because each position seems to represent different chemical features. We indicate these locations as “c-C\(_3\)H\(_2\) Peak” and “CH\(_3\)OH Peak,” respectively. Panels (b) and (f) in Figures 3 and 4 indicate the positions and the beam (6\(^\prime\)) used for spectral analysis.

We applied the Markov Chain Monte Carlo method assuming the local thermodynamic equilibrium model in CASSIS. In this method, the column density (N), excitation temperature (T\(_\text{ex}\)), line width (FWHM), and radial velocity (V\(_\text{LSR}\)) were treated as semi-free parameters within certain ranges, and solutions were obtained by a \(\chi^2\) minimization. The excitation temperatures of c-C\(_3\)H\(_2\) and H\(_2\)CO were derived to be 8.7 ± 1.0 K and 15.5 ± 0.7 K in Oph-emb5 and 9.9 ± 0.3 K and 36.2 ± 0.4 K in Oph-emb9, respectively, based on APEX

\(^{12}\) https://cdms.astro.uni-koeln.de

\(^{13}\) https://spec.jpl.nasa.gov
| Species       | c-C_3H_2 Peak | CH_3OH Peak | Oph-emb5 | Oph-emb9 |
|--------------|--------------|-------------|----------|----------|
|              | N (cm^{-2})  | T_ex (K)    | FWHM (km s^{-1}) | V_{LSR} (km s^{-1}) | N (cm^{-2})  | T_ex (K)    | FWHM (km s^{-1}) | V_{LSR} (km s^{-1}) |
| c-C_3H_2     | (7.7 \pm 1.2) \times 10^{11} | 15.3 \pm 2.2 | 0.57 \pm 0.09 | 3.94 \pm 0.04 | (6.3 \pm 1.0) \times 10^{11} | 12.0 \pm 1.4 | 0.83 \pm 0.11 | 3.93 \pm 0.11 |
| H_2CO        | (2.9 \pm 2.1) \times 10^{13} | 11.6 \pm 0.9 | 1.36 \pm 0.09 | 3.78 \pm 0.09 | (1.7 \pm 0.5) \times 10^{13} | 16.7 \pm 1.9 | 1.28 \pm 0.07 | 3.763 \pm 0.005 |
| H_2CO\textsuperscript{b} | (5.6 \pm 4.3) \times 10^{14} | 14.0 \pm 3.6 | 0.78 \pm 0.08 | 3.52 \pm 0.08 | (1.52 \pm 0.08) \times 10^{14} | 17.8 \pm 0.9 | 0.63 \pm 0.07 | 3.765 \pm 0.004 |
| CH_3OH       | (5.3 \pm 0.9) \times 10^{13} | 29.9 \pm 4.7 | 0.84 \pm 0.07 | 3.53 \pm 0.08 | (1.1 \pm 0.5) \times 10^{14} | 21.0 \pm 7.0 | 0.82 \pm 0.07 | 3.87 \pm 0.02 |
| DCO\textsuperscript{c} | (2.5 \pm 0.2) \times 10^{12} | 11.7 \pm 0.5 | 0.83 \pm 0.02 | 3.98 \pm 0.03 | (4.4 \pm 1.1) \times 10^{12} | 11.3 \pm 0.6 | 0.73 \pm 0.07 | 3.70 \pm 0.18 |

N(c-C_3H_2)/N(CH_3OH)\textsuperscript{c} \quad 0.015 \pm 0.003

N(c-C_3H_2)/N(CH_3OH)\textsuperscript{c} \quad 0.006 \pm 0.003

Notes. The errors are the standard deviation.
\textsuperscript{a} The values are derived from fitting of the 3_{0,3} - 2_{0,3} line.
\textsuperscript{b} The values are derived from fitting of the 3_{2,2} - 2_{2,1} and 3_{3,1} - 2_{2,0} lines.
\textsuperscript{c} The errors are calculated from the standard deviation of the column densities.
observations (Lindberg et al. 2017). We then set the excitation temperature range from 10 K to 40 K.

Table 4 summarizes fitting results. Since the H$_2$CO ($3_{0,3} - 2_{0,2}$) line has different spatial distributions (Figures 3 and 4) and different upper-state energies (Table 3) from the other two lines, these lines probably do not trace the same regions. We then derived parameters for H$_2$CO with the following two cases: (a) using the $3_{0,3} - 2_{0,2}$ line, and (b) using the $2_{2,2} - 2_{2,1}$ and $3_{2,1} - 2_{2,0}$ lines.

Figures 5 and 6 show spectra at the c-C$_3$H$_2$ Peak and CH$_3$OH Peak in Oph-emb5, and Figures 7 and 8 show spectra at each position in Oph-emb9. Purple curves indicate the fitted results (Table 4). The second velocity components may have been detected in the H$_2$CO and CH$_3$OH spectra, especially at the c-C$_3$H$_2$ Peak of Oph-emb5. However, we cannot fit these second components well with the current velocity resolution, and we therefore did not consider the second velocity component in our analyses. The radial velocities are almost consistent with previous APEX observations (Lindberg et al. 2017).

3.3.1. Comparison of the N(c-C$_3$H$_2$)/N(CH$_3$OH) Ratio Derived from CASSIS

UV radiation, if sufficiently intense, produces photon-dominated regions (PDRs). In PDR chemistry, small hydrocarbons
such as c-C₃H₂ can be abundant in less shielded regions (e.g., \( A_v \sim 1.43 \) mag; Tiwari et al. 2019), while CH₃OH formation is efficient in more shielded regions (\( A_v > 2 \) mag; Esplugues et al. 2019). In order to investigate the effects of UV irradiation from the nearby Herbig Be star on Oph-emb9, we derive the \( N(c-C_3H_2)/N(CH_3OH) \) ratio at each position as summarized in Table 4. The ratios at the c-C₃H₂ Peak and the CH₃OH Peak in Oph-emb5 are derived to be 0.015 ± 0.003 (1σ) and 0.006 ± 0.003, and those in Oph-emb9 are calculated as 0.37 ± 0.06 and 0.020 ± 0.011, respectively.

As a general trend, the \( N(c-C_3H_2)/N(CH_3OH) \) ratios around Oph-emb9 are higher than those around Oph-emb5. This means that c-C₃H₂ is relatively more abundant compared to CH₃OH in Oph-emb9. Hence, this region may be affected by the UV radiation from the Herbig Be star.

We compare these ratios at the c-C₃H₂ peak and the CH₃OH peak around each YSO. In the case of Oph-emb5, the \( N(c-C_3H_2)/N(CH_3OH) \) ratio at the c-C₃H₂ Peak is higher than that at the CH₃OH Peak by a factor of \( \sim 2.6 \). In Oph-emb9, the difference between the c-C₃H₂ Peak and the CH₃OH Peak is a factor of \( \sim 18.5 \). Hence, c-C₃H₂ is significantly enhanced at the c-C₃H₂ Peak in Oph-emb9 compared to Oph-emb5. All of these results also support the PDR chemistry around Oph-emb9, which is likely driven by the nearby Herbig Be star. The PDR chemistry in this source was also suggested by the layered structures of CO and its isotopologues (Yamagishi et al. 2019). Our conclusion that the chemistry in the field of view of Oph-emb9 is strongly affected by the Herbig Be star is consistent with their results.

### 3.4. Moment 2 Maps of the \( ^{13}\text{CO} \) and \( ^{18}\text{O} \) Lines

Figure 9 shows moment 2 maps (velocity dispersion maps) of the \( ^{13}\text{CO} \) \((J = 2 \rightarrow 1)\) and \( ^{18}\text{O} \) \((J = 2 \rightarrow 1)\) lines toward Oph-emb5 and Oph-emb9, respectively. Channel maps of these lines are presented in Figures 11–14 in the Appendix. Around Oph-emb5, there are two velocity dispersion peaks in the \( ^{13}\text{CO} \) moment 2 maps. The moment 2 maps of \( ^{13}\text{CO} \) and \( ^{18}\text{O} \) are similar to each other around Oph-emb9; two dispersion maxima are located at the eastern and western positions, respectively.

#### 3.4.1. Comparisons of Molecular Distributions and Velocity Dispersion

In this subsection, we investigate the relationship between the chemical differentiation and velocity dispersion, which is
an indicator of gas turbulent motions. Figure 10 shows comparisons of the $^{13}$CO moment 2 map (color scales) and the spatial distributions of H$_2$CO and c-C$_3$H$_2$ (black contours). The black contours in the upper and bottom panels indicate moment 0 maps of the H$_2$CO ($3_{0,3} - 2_{0,2}$) line and the c-C$_3$H$_2$ ($6_{0,6} - 5_{1,5}$) line, respectively.

There is no spatial relationship between the $^{13}$CO moment 2 map and the H$_2$CO moment 0 map around Oph-emb5, while the c-C$_3$H$_2$ moment 0 map peaks at the location of the largest velocity dispersion position. The H$_2$CO emission may be associated with another source, which is located out of the field of view of these observations. However, we cannot determine this from the current data set.

The peak of the H$_2$CO moment 0 map corresponds to the largest velocity dispersion position in the $^{13}$CO moment 2 map around Oph-emb9. These results may suggest that COMs (H$_2$CO and CH$_3$OH) are enhanced by the shock chemistry induced by the nearby Herbig Be star or the molecular outflow originated from the Oph-emb9 YSO (White et al. 2015). Large-scale enhancement of CH$_3$OH by shock has been reported in other cluster-forming regions (e.g., Taniguchi et al. 2020). The H$_2$CO emission is strongly enhanced in the

Figure 7. Spectra of H$_2$CO and CH$_3$OH toward Oph-emb9. Purple curves indicate the fitted results obtained using the CASSIS software.
eastern direction from the IR source, while the enhancement is not efficient on the opposite side. If the molecular outflow is the sole source of the enhancement of these COMs, this spatial difference cannot be explained. An alternative explanation is that a strong shock region at the eastern position is produced by a combination of the molecular outflow from Oph-emb9 and the effect of gas compression from the Herbig Be star.

The peak in the c-C$_3$H$_2$ moment 0 map does not coincide with the peak in the $^{13}$CO moment 2 map. As mentioned in Section 3.3.1, the PDR chemistry seems to enhance c-C$_3$H$_2$ around Oph-emb9, and the shock chemistry is unlikely related to the formation of c-C$_3$H$_2$. In fact, the line widths of H$_2$CO and CH$_3$OH are larger than that of c-C$_3$H$_2$ (see Table 4). In summary, the chemical processes around Oph-emb9 are strongly affected by the nearby Herbig Be star, the UV radiation, and probably gas compression.

4. Conclusions

We present Band 6 ALMA Cycle 4 archival data toward two YSOs in the Ophiuchus region. Oph-emb9 is irradiated by a nearby Herbig Be star, while Oph-emb5 is located in a relatively quiescent region. Using the data, we investigate effects from a nearby bright star on the chemistry around the target YSOs. The high-angular-resolution data with ALMA...
enable us to investigate the chemical processes in more detail compared to previous single-dish data (Lindberg et al. 2017).

We have detected \( c\)-C\(_3\)H\(_2\), H\(_2\)CO, CH\(_3\)OH, 13CO, C\(_{18}\)O, DCO\(^+\), and DCN in Oph-emb9, and all of them except for DCN in Oph-emb5. The small hydrocarbon \( c\)-C\(_3\)H\(_2\) and COMs (H\(_2\)CO and CH\(_3\)OH) show different spatial distributions around both YSOs, which indicate the chemical differentiation.

The \( N(\text{\textit{c}}\text{-C}_3\text{H}_2)/N(\text{CH}_3\text{OH}) \) column density ratios around Oph-emb9 are higher than those around Oph-emb5. Furthermore, \( c\)-C\(_3\)H\(_2\) is greatly enhanced at its peak position, which is irradiated by the Herbig Be star. These results indicate the PDR chemistry around the Oph-emb9 YSO driven by the Herbig Be star.

We compare the moment 0 maps of \( c\)-C\(_3\)H\(_2\) and H\(_2\)CO with the \( ^{13}\)CO moment 2 maps. In the case of Oph-emb5, the peak position of the \( c\)-C\(_3\)H\(_2\) moment 0 map corresponds to the position with the largest velocity dispersion in the \( ^{13}\)CO moment 2 map. Moreover, the peak of the H\(_2\)CO moment 0 map is consistent with the position with the largest velocity dispersion in Oph-emb9. Such results imply that shock chemistry enhances the gas-phase COMs around Oph-emb9. The strong shock seems to be induced by a combination of the nearby Herbig Be star and the molecular outflow from Oph-emb9 itself.

We have investigated the higher DCO\(^+\) column density and the detection of DCN in Oph-emb9. The main formation pathway of DCO\(^+\) around Oph-emb9 seems to be the reaction HCO\(^+\) + D \( \rightarrow \) DCO\(^+\) + H in relatively warm region (30 < \( T < 100 \) K). This is supported by the detection of DCN, which is expected to be formed in warm regions. In addition, the UV radiation from the Herbig Be star can enhance the gas-phase HCO\(^+\) abundance with ion–molecule chemistry. On the other hand, the dominant formation pathway of DCO\(^+\) around Oph-emb5 is the reaction of H\(_2\)D\(^+\) + CO \( \rightarrow \) DCO\(^+\) + H\(_2\), which can proceed only in cold regions (<30 K).
This paper makes use of the following ALMA data: ADS/JAO.ALMA#2016.1.00319.S. ALMA is a partnership of ESO (representing its member states), NSF (USA) and NINS (Japan), together with NRC (Canada), MOST and ASIAA (Taiwan), and KASI (Republic of Korea), in cooperation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI/NRAO and NAOJ. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. This work included analyses carried out with the CASSIS software and the CDMS and JPL spectroscopic databases. CASSIS has been developed by IRAP-UPS/CNRS. This work was supported by JSPS KAKENHI grant No. JP20K14523. K.T. acknowledges support from Japan Foundation for Promotion of Astronomy. S.T. is supported by JSPS KAKENHI Grant Nos. JP21H00048 and JP21H04495. This research was carried out in part at the Jet Propulsion Laboratory, which is operated for NASA by the California Institute of Technology. E.H. thanks the National Science Foundation for support through grant AST-1906489. We thank the anonymous referee whose valuable comments helped improve the quality of the paper.

Facility: Atacama Large Millimeter/submillimeter Array (ALMA)

Software: Common Astronomy Software Applications package (CASA; McMullin et al. 2007), CASSIS (Caux et al. 2011).

Appendix

Channel Maps of $^{13}$CO and C$^{18}$O Lines

Figures 11–14 show channel maps of the $^{13}$CO and C$^{18}$O lines toward Oph-emb5 and Oph-emb9, respectively.
Figure 11. Channel maps of $^{13}$CO ($J = 2 - 1$) toward Oph-emb5. Contour levels are in steps of 50σ from 50σ to 350σ (1σ = 4.5 mJy beam$^{-1}$). The yellow crosses indicate positions of the infrared sources (Enoch et al. 2009). The filled black ellipses indicate the beam sizes of 2''2 × 1''5.
Figure 12. Channel maps of C$^{18}$O ($J = 2 - 1$) toward Oph-emb5. Contour levels are in steps of 50σ from 50σ to 350σ (1σ = 3.0 mJy beam$^{-1}$). The yellow crosses indicate positions of the infrared sources (Enoch et al. 2009). The filled black ellipses indicate the beam sizes of $2''2 \times 1''5$. 
Figure 13. Channel maps of $^{13}$CO ($J = 2 - 1$) toward Oph-emb9. Contour levels are in steps $50\sigma$ from $50\sigma$ to $350\sigma$ ($1\sigma = 10$ mJy beam$^{-1}$). The yellow crosses indicate positions of the infrared sources (Enoch et al. 2009). The filled black ellipses indicate the beam sizes of 1$''$8 $\times$ 1$''$3.
Figure 14. Channel maps of C$^{18}$O ($J = 2 - 1$) toward Oph-emb9. Contour levels are in steps $50\sigma$ from $50\sigma$ to $450\sigma$ ($1\sigma = 6.7$ mJy beam$^{-1}$). The yellow crosses indicate positions of the infrared sources (Enoch et al. 2009). The filled black ellipses indicate the beam sizes of $1\" \times 1\"$.3.
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