

# The Detection of a Hot Molecular Core in the Extreme Outer Galaxy

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# Abstract

Interstellar chemistry in low-metallicity environments is crucial to understand chemical processes in the past metalpoor universe. Recent studies of interstellar molecules in nearby low-metallicity galaxies have suggested that metallicity has a significant effect on the chemistry of star-forming cores. Here we report the first detection of a hot molecular core in the extreme outer Galaxy, which is an excellent laboratory to study star formation and the interstellar medium in a Galactic low-metallicity environment. The target star-forming region, WB 89-789, is located at a galactocentric distance of 19 kpc. Our Atacama Large Millimeter/submillimeter Array observations in 241-246, 256-261, 337-341, and 349-353 GHz have detected a variety of carbon-, oxygen-, nitrogen-, sulfur-, and silicon-bearing species, including complex organic molecules (COMs) containing up to nine atoms, toward a warm (>100 K) and compact (<0.03 pc) region associated with a protostar ( $\sim 8 \times 10^3 L_{\odot}$ ). Deuterated species such as HDO, HDCO, D<sub>2</sub>CO, and CH<sub>2</sub>DOH are also detected. A comparison of fractional abundances of COMs relative to CH<sub>3</sub>OH between the outer Galactic hot core and an inner Galactic counterpart shows a remarkable similarity. On the other hand, the molecular abundances in the present source do not resemble those of lowmetallicity hot cores in the Large Magellanic Cloud. The results suggest that great molecular complexity exists even in the primordial environment of the extreme outer Galaxy. The detection of another embedded protostar associated with high-velocity SiO outflows is also reported.

Unified Astronomy Thesaurus concepts: Astrochemistry (75); Interstellar molecules (849); Protostars (1302); Stellar jets (1607); Submillimeter astronomy (1647)

### 1. Introduction

Understanding the star formation and interstellar medium (ISM) at low metallicity is crucial to unveil physical and chemical processes in the past Galactic environment or those in high-redshift galaxies, where the metallicity was significantly lower compared to the present-day solar neighborhood.

Hot molecular cores are one of the early stages of star formation, and they play a key role in the formation of the chemical complexity of the ISM. Physically, hot cores are defined as having a small source size ( $\leq 0.1$  pc), high density  $(\gtrsim 10^6 \text{ cm}^{-3})$ , and warm gas/dust temperature  $(\gtrsim 100 \text{ K})$  (e.g., van Dishoeck & Blake 1998; Kurtz et al. 2000). The chemistry of hot cores is characterized by the sublimation of ice mantles, which accumulated over the course of star formation. In cold molecular clouds and prestellar cores, gaseous molecules and atoms are frozen onto dust grains. With dust temperatures increasing owing to star formation activities, chemical reactions among heavy species become active on grain surfaces, forming larger complex molecules (e.g., Garrod & Herbst 2006). In addition, sublimated molecules, such as CH<sub>3</sub>OH and NH<sub>3</sub>, are subject to further gas-phase reactions (e.g., Nomura & Millar 2004; Taquet et al. 2016). As a result, warm and dense gas around protostars become chemically rich, and embedded protostars are observed as one of the most powerful molecular line emitters, called a hot core. They are important targets for astrochemical studies of star-forming regions, because a variety of molecular species, including complex organic molecules (COMs), are often detected in hot cores (Herbst & van Dishoeck 2009 and references therein). Thus, detailed studies of the chemical properties of hot cores are important for

understanding complex chemical processes triggered by star formation.

Recent ALMA (Atacama Large Millimeter/submillimeter Array) observations of hot molecular cores in a nearby lowmetallicity galaxy, the Large Magellanic Cloud (LMC), have suggested that the metallicity has a significant effect on their molecular compositions (Shimonishi et al. 2016b, 2020; Sewiło et al. 2018); e.g., the metallicity of the LMC is  $\sim 1/2-1/3$  of the solar neighborhood. A comparison of molecular abundances between LMC and Galactic hot cores suggests that organic molecules (e.g., CH<sub>3</sub>OH, a classical hot-core tracer) show a large abundance variation in low-metallicity hot cores (Shimonishi et al. 2020). There are organic-poor hot cores that are unique to the LMC (Shimonishi et al. 2016b), while there are relatively organic-rich hot cores, where the abundances of organic molecules roughly scale with the metallicity (Sewiło et al. 2018). Astrochemical simulations for low-metallicity hot cores suggest that dust temperature during the initial iceforming stage would play a key role in giving rise to the chemical diversity of organic molecules (Acharyya & Herbst 2018; Shimonishi et al. 2020). On the other hand, sulfur-bearing molecules such as SO<sub>2</sub> and SO are commonly detected in known LMC hot cores, and their molecular abundances roughly scale with the metallicity of the LMC. Although the reason is still under debate, the results suggest that SO<sub>2</sub> can be an alternative molecular species to trace hotcore chemistry in metal-poor environments.

The above results suggest that molecular abundances in hot cores do not always simply scale with the elemental abundances of their parent environments. However, it is still

unclear if the observed chemical characteristics of LMC hot cores are common in other low-metallicity environments or they are uniquely seen only in the LMC. Currently, known low-metallicity hot-core samples are limited to those in the LMC. It is thus vital to understand the universal characteristics of interstellar chemistry by studying the chemical compositions of star-forming cores in diverse metallicity environments.

Recent surveys (e.g., Anderson et al. 2015, 2018; Izumi et al. 2017; Wenger et al. 2021) have found a number of  $(\sim 10-20)$ star-forming region candidates in the extreme outer Galaxy, which is defined as having a galactocentric distance  $(D_{GC})$ larger than 18 kpc (Yasui et al. 2006; Kobayashi et al. 2008). The extreme outer Galaxy has a very different environment from those in the solar neighborhood, with lower metallicity (less than -0.5 dex, Fernández-Martín et al. 2017; Wenger et al. 2019), lower gas density (e.g., Nakanishi & Sofue 2016), and small or no perturbation from spiral arms. Such an environment is of great interest for studies of the star formation and ISM in the early phase of the Milky Way formation and those in dwarf galaxies (Ferguson et al. 1998; Kobayashi et al. 2008). The low-metallicity environment is in common with the Magellanic Clouds, and thus the extreme outer Galaxy is an ideal laboratory to test the universality of the low-metallicity molecular chemistry observed in the LMC and SMC.

Among star-forming regions in the extreme outer Galaxy, WB 89–789 (IRAS 06145+1455; 06<sup>h</sup>17<sup>m</sup>24<sup>s</sup>2, 14°54′42″, J2000) has a particularly young and active nature (Brand & Wouterloot 1994). It is located at the galactocentric distance of 19.0 kpc, and its distance from Earth is 10.7 kpc (based on optical spectroscopy of a K3 III star; Brand & Wouterloot 2007). The metallicity of WB 89-789 is estimated to be a factor of 4 lower than the solar value according to the Galactic oxygen abundance gradient reported in the literature (Fernández-Martín et al. 2017; Bragança et al. 2019; Wenger et al. 2019; Arellano-Córdova et al. 2020, 2021). The region is associated with dense clouds traced by CS and CO (Brand & Wouterloot 2007). The total mass of the cloud is estimated to be  $6 \times 10^3 M_{\odot}$  for a ~10 pc diameter area (Brand & Wouterloot 1994). An H<sub>2</sub>O maser is detected toward the region (Wouterloot et al. 1993), but no centimeter radio continuum is found (Brand & Wouterloot 2007). Several Class I protostar candidates were identified by previous infrared observations (Brand & Wouterloot 2007).

We here report the first detection of a hot molecular core in the extreme outer Galaxy based on submillimeter observations toward WB 89–789 with ALMA. Section 2 describes the details of the target source, observations, and data reduction. The observed molecular line spectra and images, as well as analyses of physical and chemical properties of the source, are presented in Section 3. A discussion about the properties of the hot core and comparisons of molecular abundances with known Galactic and LMC hot cores is given in Section 4. This section also presents the detection of another embedded protostar with high-velocity outflows in the WB 89–789 region. The conclusions are given in Section 5.

### 2. Target, Observations, and Data Reduction

### 2.1. Target

The target star-forming region is WB 89–789 (Brand & Wouterloot 1994). The region contains three Class I protostar candidates identified by near-infrared observations



**Figure 1.** Near-infrared two-color image of the WB 89–789 star-forming region based on 2MASS data (Skrutskie et al. 2006). Blue is the *J* band (1.25  $\mu$ m), and red is the  $K_s$  band (2.16  $\mu$ m). The image size is 100" × 100". The green square indicates the field of view of the ALMA submillimeter images shown in Figures 4–5.

(Brand & Wouterloot 2007), and one of them is a main target of the present ALMA observations. The region observed with ALMA is indicated on a near-infrared two-color image shown in Figure 1. The observed position is notably reddened compared with other parts of WB 89–789.

### 2.2. Observations

Observations were conducted with ALMA in 2018 and 2019 as part of the Cycle 5 (2017.1.01002.S) and Cycle 6 (2018.1.00627.S) programs (PI: T. Shimonishi). A summary of the present observations is shown in Table 1. The pointing center of the antennas is R.A. =  $06^{h}17^{m}23^{s}$  and decl. =  $14^{\circ}54'$ 41'' (ICRS). The total on-source integration time is 115.5 minutes for Band 6 data and 64.1 minutes for Band 7. Flux and bandpass calibrators are J0510+1800, J0854+2006, and J0725-0054 for Band 6, and J0854+2006 and J0510+1800 for Band 7. Phase calibrators are J0631+2020 and J0613 +1708 for Band 6 and J0643+0857 and J0359+1433 for Band 7. Four spectral windows are used to cover the sky frequencies of 241.40-243.31, 243.76-245.66, 256.90-258.81, and 258.76-260.66 GHz for Band 6, ad 337.22-339.15, 339.03-340.96, 349.12-351.05, and 350.92-352.85 GHz for Band 7. The channel spacing is 0.98 MHz, which corresponds to  $1.2 \text{ km s}^{-1}$  for Band 6 and 0.85 km s<sup>-1</sup> for Band 7. The total number of antennas is 45-49 for Band 6 and 43-44 for Band 7. The minimum-maximum baseline lengths are 15.1-783.5 m for Band 6 and 15.1-500.2 m for Band 7. The FWHM of the primary beam is about 25" for Band 6 and 18" for Band 7.

### 2.3. Data Reduction

Raw data are processed with the Common Astronomy Software Applications (CASA) package. We use CASA 5.4.0 (Band 6) and

Observation Summary										
	Observation	Observation On-source		Number	Bas	seline			Channel	
	Date	Time (min)	PWV <sup>a</sup> (mm)	of Antennas	Min (m)	Max (m)	Beam size <sup>b</sup> (" × ")	MRS <sup>c</sup> (")	Spacing	
Band 6 (250 GHz)	2018 Dec 6— 2019 Apr 16	115.5	0.5–1.5	45–49	15.1	783.5	0.41  imes 0.50	5.6	0.98 MHz (1.2 km s <sup>-1</sup> )	
Band 7 (350 GHz)	2018 Apr 30— 2018 Aug 22	64.1	0.6–1.0	43–44	15.1	500.2	0.46  imes 0.52	5.4	0.98 MHz $(0.85 \text{ km s}^{-1})$	

Table 1

Notes.

<sup>1</sup> Precipitable water vapor.

<sup>b</sup> The average beam size of the continuum achieved by TCLEAN with Briggs weighting and the robustness parameter of 0.5. Note that we use a common circular restoring beam size of 0.1750 for Band 6 and 7 data to construct the final images.

<sup>c</sup> Maximum recoverable scale.

5.1.1 (Band 7) for the calibration and CASA 5.5.0 for the imaging. position angle of  $-36^{\circ}$  for Band 6 and  $0.45^{\circ}-0.46^{\circ}\times0.51^{\circ}-0.52^{\circ}$ with a position angle of  $-54^{\circ}$  for Band 7 are achieved with Briggs weighting and a robustness parameter of 0.5. In this paper, we use a common circular restoring beam size of 0"50, which corresponds to 0.026 pc (5350 au) at the distance of WB 89-789. The synthesized images are corrected for the primary beam pattern using the impbcor task in CASA. The continuum image is constructed by selecting line-free channels. Before the spectral extraction, the continuum emission is subtracted from the spectral data using the CASA's uvcontsub task.

The spectra and continuum flux are extracted from the  $0^{\prime\prime}_{...50}$ diameter circular region centered at R.A.  $= 06^{h}17^{m}24^{s}073$  and decl. =  $14^{\circ}54'42''_{27}$  (ICRS), which corresponds to the submillimeter continuum center of the target and is equivalent to the hot-core position. Hereafter, the source is referred to as WB 89-789 SMM1.

### 3. Results and Analysis

### 3.1. Spectra

Figures 2–3 show submillimeter spectra extracted from the continuum center of WB 89-789 SMM1. Spectral lines are identified with the aid of the Cologne Database for Molecular Spectroscopy<sup>6</sup> (CDMS; Müller et al. 2001, 2005) and the molecular database of the Jet Propulsion Laboratory<sup>7</sup> (JPL; Pickett et al. 1998). The detection criterion adopted here is the  $3\sigma$  significance level and the velocity coincidence with the systemic velocity ( $V_{svs}$ ) of WB 89–789 SMM1 (34.5 km s<sup>-1</sup>). The lines with a significance level higher than  $2.5\sigma$  but lower than  $3\sigma$  are indicated as tentative detection in the tables in Appendix A. More than 85% of lines are detected above the  $5\sigma$ level.

Line parameters are measured by fitting a Gaussian profile to detected lines. We estimate the peak brightness temperature, the FWHM, the LSR velocity, and the integrated intensity for each line based on the fitting. For spectral lines for which a Gaussian profile does not fit well, their integrated intensities are calculated by directly integrating the spectrum over the frequency region of emission. Full details of the line fitting can be found in Appendix A (tables of measured line parameters) and Appendix B (figures of fitted spectra). The table also contains the estimated upper limits on important nondetection lines.

A variety of carbon-, oxygen-, nitrogen-, sulfur-, and siliconbearing species, including COMs containing up to nine atoms, are detected from WB 89-789 SMM1 (see Table 2). Multiple high-excitation lines (upper state energy >100 K) are detected for many species. Measured line widths are typically 3-6 km  $s^{-1}$ . Most of the lines consist of a single velocity component, but SiO has Doppler-shifted components at  $V_{\rm sys} \pm 5 \text{ km s}^{-1}$  as indicated in Figure B1 in Appendix B.

#### 3.2. Images

Figures 4-5 show synthesized images of continuum and molecular emission lines observed toward the target region. The images are constructed by integrating spectral data in the velocity range where the emission is detected. Most molecular lines, except for those of the molecular radicals CN, CCH, and NO, have their intensity peak at the continuum center, which corresponds to the position of a hot core. Simple molecules such as H<sup>13</sup>CO<sup>+</sup>, H<sup>13</sup>CN, CS, and SO are extended compared to the beam size. Secondary intensity peaks are also seen in those species. Complex molecules and HDO are concentrated at the hot-core position. A characteristic symmetric distribution is seen in SiO. Further discussion about the distribution of the observed emission is presented in Section 4.2.

### 3.3. Derivation of Column Densities, Gas Temperatures, and Molecular Abundances

#### 3.3.1. Rotation Diagram Analysis

Column densities and rotation temperatures are estimated based on the rotation diagram analysis for the molecular species where multiple transitions with different excitation energies are detected (Figure 6). We here assume an optically thin condition and the local thermodynamic equilibrium (LTE). We use the following formulae based on the standard treatment of the rotation diagram analysis (e.g., Sutton et al. 1995; Goldsmith & Langer 1999):

$$\log\left(\frac{N_u}{g_u}\right) = -\left(\frac{\log e}{T_{\text{rot}}}\right)\left(\frac{E_u}{k}\right) + \log\left(\frac{N}{Q(T_{\text{rot}})}\right),\tag{1}$$

where

$$\frac{N_u}{g_u} = \frac{3k \int T_b dV}{8\pi^3 \nu S \mu^2},\tag{2}$$

https://www.astro.uni-koeln.de/cdms

http://spec.jpl.nasa.gov



Figure 2. ALMA band 6 spectra extracted from the 0.750 (0.026 pc) diameter region centered at the present hot molecular core in the extreme outer Galaxy, WB 89–789 SMM1. Detected emission lines are labeled. Unidentified lines are indicated by "?". The source velocity of 34.5 km s<sup>-1</sup> is assumed.

and  $N_u$  is a column density of molecules in the upper energy level,  $g_u$  is the degeneracy of the upper level, k is the Boltzmann constant,  $\int T_b dV$  is the integrated intensity estimated from the observations,  $\nu$  is the transition frequency, S is the line strength,  $\mu$  is the dipole moment,  $T_{\text{rot}}$  is the rotational temperature,  $E_u$  is the upper state energy, N is the total column density, and  $Q(T_{rot})$  is the partition function at  $T_{rot}$ . All of the spectroscopic parameters required in the analysis are extracted from the CDMS or JPL database. Derived column densities and rotation temperatures are summarized in Table 3.

Most molecular species are well fitted by a single temperature component. Data points in diagrams of  $CH_3CN$  and  $C_2H_5CN$  are



Figure 3. Same as in Figure 2, but for ALMA Band 7.

relatively scattered. For CH<sub>3</sub>OH, CH<sub>3</sub>CN, HNCO, SO<sub>2</sub>, and HCOOCH<sub>3</sub>, transitions with relatively large  $S\mu^2$  values at low  $E_u$  (<300 K) are excluded from the fit in order to avoid the possible effect of optical thickness (see gray points in Figure 6). Adapted threshold values are log  $S\mu^2 > 1.1$  for CH<sub>3</sub>OH, log  $S\mu^2 > 2.4$  for CH<sub>3</sub>CN, log  $S\mu^2 > 1.6$  for HNCO, log  $S\mu^2 > 1.2$  for SO<sub>2</sub>, and log  $S\mu^2 > 1.8$  for HCOOCH<sub>3</sub>.

Complex organic molecules, HDO, and SO<sub>2</sub> show high rotation temperatures (>130 K). This suggests that they originate from a warm region associated with a protostar. On the other hand,  $C^{33}S$  and D<sub>2</sub>CO, and H<sub>2</sub>CS show lower temperatures, suggesting that they arise from a colder region in the outer part of the protostellar envelope. SO also shows a low rotation temperature. Its  $T_{rot}$  is close to that of  $C^{33}S$ . However,

 Table 2

 Summary of Detected Molecular Species

2 atoms	3 atoms	4 atoms	5 atoms	6 atoms	7 atoms	8 atoms	9 atoms
CN	HDO	H <sub>2</sub> CO	c-C <sub>3</sub> H <sub>2</sub>	CH <sub>3</sub> OH	CH <sub>3</sub> CHO	HCOOCH <sub>3</sub>	CH <sub>3</sub> OCH <sub>3</sub>
NO	$H^{13}CO^+$	HDCO	HC <sub>3</sub> N	<sup>13</sup> CH <sub>3</sub> OH	c-C <sub>2</sub> H <sub>4</sub> O		C <sub>2</sub> H <sub>5</sub> OH
CS	$\mathrm{HC}^{18}\mathrm{O}^+$	$D_2CO$	H <sub>2</sub> CCO	CH <sub>2</sub> DOH			C <sub>2</sub> H <sub>5</sub> CN
C <sup>34</sup> S	H <sup>13</sup> CN	HNCO	HCOOH	CH <sub>3</sub> CN			
C <sup>33</sup> S	HC <sup>15</sup> N	$H_2CS$		NH <sub>2</sub> CHO			
SO	CCH						
<sup>34</sup> SO	$SO_2$						
<sup>33</sup> SO	<sup>34</sup> SO <sub>2</sub>						
SiO	OCS						
	<sup>13</sup> OCS						

SO lines are often optically thick in dense cores, particularly for low- $E_u$  lines, thus the derived rotation temperature would be an upper limit.

#### 3.3.2. Column Densities of Other Molecules

Column densities of molecular species for which rotation diagram analysis is not applicable are estimated from Equation (1) after solving it for N. Their rotation temperatures are estimated as follows, by taking into account that the sight line of WB 89–789 SMM1 contains both cold and warm gas components as described in Section 3.3.1.

The rotation temperature of  $C^{33}S$  is applied to those of CS and  $C^{34}S$ , considering a similar distribution of isotopologues. Similarly, the rotation temperature of D<sub>2</sub>CO is applied to H<sub>2</sub>CO and HDCO, and to that of SO<sub>2</sub> to <sup>34</sup>SO<sub>2</sub>. For other species, we assume that molecules with an extended spatial distribution trace a relatively low-temperature region rather than a high-temperature gas associated with a hot core. CN, CCH, H<sup>13</sup>CO<sup>+</sup>, HC<sup>18</sup>O<sup>+</sup>, H<sup>13</sup>CN, HC<sup>15</sup>N, NO, SiO, <sup>34</sup>SO, <sup>33</sup>SO, and c-C<sub>3</sub>H<sub>2</sub> correspond to this case. We assume a rotation temperature of 35 K for those species, which is roughly equivalent to that of C<sup>33</sup>S.

High gas temperatures are observed for COMs, SO<sub>2</sub>, and HDO, which are associated with a compact hot-core region. The average temperature of those species is ~200 K. We assume this temperature for column density estimates (including upper limit) of c-C<sub>2</sub>H<sub>4</sub>O, HC<sub>3</sub>N, <sup>13</sup>CH<sub>3</sub>CN, <sup>13</sup>OCS, and CH<sub>3</sub>SH. Estimated column densities are summarized in Table 3.

We have also estimated column densities of selected species based on non-LTE calculations with RADEX (van der Tak et al. 2007). For input parameters, we use the H<sub>2</sub> gas density of  $2.1 \times 10^7$  cm<sup>-3</sup> according to our estimate in Section 3.3.3 and the background temperature of 2.73 K. Kinetic temperatures are assumed to be the same as temperatures tabulated in Table 3. The line intensities and widths are taken from the tables in Appendix A.<sup>8</sup> We assume an empirical 10% uncertainty for input line intensities. The resultant column densities are summarized in Table 3. The calculated non-LTE column densities are reasonably consistent with the LTE estimates.

### 3.3.3. Column Density of H<sub>2</sub>, Dust Extinction, and Gas Mass

A column density of molecular hydrogen  $(N_{\rm H_2})$  is estimated from the dust continuum data. We use the following equation to calculate  $N_{\rm H_2}$  based on the standard treatment of optically thin dust emission:

$$N_{\rm H_2} = \frac{F_\nu / \Omega}{2\kappa_\nu B_\nu (T_d) Z \mu m_{\rm H}},\tag{3}$$

where  $F_{\nu}/\Omega$  is the continuum flux density per beam solid angle as estimated from the observations,  $\kappa_{\nu}$  is the mass absorption coefficient of dust grains coated by thin ice mantles at 1200/ 870  $\mu$ m as taken from Ossenkopf & Henning (1994), and we here use 1.07 cm<sup>2</sup> g<sup>-1</sup> for 1200  $\mu$ m and 1.90 cm<sup>2</sup> g<sup>-1</sup> for 870  $\mu$ m,  $T_d$  is the dust temperature and  $B_{\nu}(T_d)$  is the Planck function, Z is the dust-to-gas mass ratio,  $\mu$  is the mean atomic mass per hydrogen (1.41, according to Cox 2000), and  $m_{\rm H}$  is the hydrogen mass. We use the dust-to-gas mass ratio of 0.002, which is obtained by scaling the Galactic value of 0.008 by the metallicity of the WB 89–789 region.

A line of sight toward a hot core contains dust grains with different temperatures because of the temperature gradient in a protostellar envelope. Representative dust temperatures (i.e., mass-weighted average temperature) would fall somewhere in between that of a warm inner region and a cold outer region. Shimonishi et al. (2020) presented a detailed analysis of effective dust temperature in the sight line of a low-metallicity hot core in the LMC, based on a comparison of  $N_{\rm H_2}$  derived by submillimeter dust continuum with the above method, model fitting of spectral energy distributions (SEDs), and the 9.7  $\mu$ m silicate dust absorption depth. The paper concluded that  $T_d = 60$  K for the dust continuum analysis yields an  $N_{\rm H_2}$  value that is consistent with those obtained by other different methods. This temperature corresponds to an intermediate value between a cold gas component ( $\sim$ 50 K) represented by SO and a warm component ( $\sim$ 150 K) represented by CH<sub>3</sub>OH and SO<sub>2</sub> in this LMC hot core. The present hot core, WB 89-789 SMM1, harbors similar temperature components as discussed in Sections 3.3.1 and 3.3.2. We thus applied  $T_d = 60$ K for the present source. The continuum brightness of SMM1 is measured to be  $11.33 \pm 0.05$  mJy beam<sup>-1</sup> for 1200  $\mu$ m and Is measured to be 11.55  $\pm$  0.05 mJy beam <sup>-1</sup> for 1200  $\mu$ m and 28.0  $\pm$  0.2 mJy beam<sup>-1</sup> for 870  $\mu$ m (3 $\sigma$  uncertainty). Based on the above assumption, we obtain  $N_{\rm H_2} = 1.6 \times 10^{24}$  cm<sup>-2</sup> for 1200  $\mu$ m and  $N_{\rm H_2} = 1.2 \times 10^{24}$  cm<sup>-2</sup> for the 870  $\mu$ m. The  $N_{\rm H_2}$ value changes by a factor of up to 1.6 when the assumed  $T_d$  is varied between 40 and 90 K.

 $<sup>\</sup>begin{array}{c} \hline & \text{The following lines are used for non-LTE calculation with RADEX;} \\ & \mathrm{H^{13}CO^{+}(3-2), \, \mathrm{HC^{18}O^{+}(4-3), \, \mathrm{H_2CO}(5_{1,5}-4_{1,4}), \, \mathrm{c-C_3H_2}(3_{2,1}-2_{1,2}), \, \mathrm{CN}(N=3-2, J=5-3), \, \mathrm{H_{2}^{-3}, \, F=\frac{5}{2}-\frac{5}{2}, \, \mathrm{H^{13}CN}(3-2), \, \mathrm{HC^{15}N}(3-2), \, \mathrm{HC_{3N}}(27-26), \, \mathrm{NO}(J=\frac{7-5}{2-2}, \Omega=\frac{1}{2}, \, F=\frac{9+7-7}{2}, \, \mathrm{CH_{3}CN}(14_{0}-13_{0}), \, \mathrm{SiO}(6-5), \, \mathrm{CS}(5-4), \, \mathrm{OCS}(20-19), \, \mathrm{H_{2}CS}(7_{1,6}-6_{1,5}), \, \mathrm{SO}(N_{J}\!=\!6_{6}\!-\!5_{5}), \, \mathrm{and} \, \mathrm{CH_{3}OH}(7_{5} \, \mathrm{E-6_{5} \, \mathrm{E}}). \end{array}$ 



**Figure 4.** Integrated intensity distributions of molecular emission lines. Gray contours represent the 1.2 mm continuum distribution and the contour levels are  $5\sigma$ ,  $10\sigma$ ,  $20\sigma$ ,  $40\sigma$ , and  $100\sigma$  of the rms noise (0.044 mJy beam<sup>-1</sup>). Low signal-to-noise ratio regions (S/N < 2) are masked. The spectra discussed in the text are extracted from the region indicated by the black open circle. The blue cross represents the 1.2 mm continuum center. The synthesized beam size is shown by the gray filled circle in each panel. North is up, and east is to the left.

Alternatively, a column density of molecular hydrogen can be determined by the model fitting of the observed SED. The best-fit SED discussed in Section 4.1 yields  $A_V = 184$  mag. We here use a standard value of  $N_{\rm H}/E(B-V) = 5.8 \times 10^{21}$  cm<sup>-2</sup> mag<sup>-1</sup> (Draine 2003) and a slightly high  $A_V/E(B-V)$  ratio of 4 for dense clouds (Whittet et al. 2001). Taking into account a factor of 4 lower metallicity, we obtain  $N_{\rm H_2}/A_V = 2.9 \times 10^{21}$  cm<sup>-2</sup> mag<sup>-1</sup>, where we assume that all the hydrogen atoms are in the form of H<sub>2</sub>. Using this conversion factor, we obtain  $N_{\rm H_2} = 5.3 \times 10^{23}$  cm<sup>-2</sup>. This  $N_{\rm H_2}$  is similar to the  $N_{\rm H_2}$  derived from the aforementioned method assuming  $T_d = 150$  K. Such  $T_d$  may be somewhat high as a typical dust temperature in the line of sight, but it is not a very unrealistic value given the observed temperature range of molecular gas toward WB 89–789 SMM1.

In this paper, we use  $N_{\rm H_2} = 1.1 \times 10^{24} \rm cm^{-2}$  as a representative value, which corresponds to the average of  $N_{\rm H_2}$  derived by the dust continuum data and the SED fitting. This  $N_{\rm H_2}$  corresponds to  $A_V = 380$  mag using the above conversion factor. Assuming the source diameter of 0.026 pc and a





uniform spherical distribution of gas around a protostar, we estimate the gas number density to be  $n_{\rm H_2} = 2.1 \times 10^7 \text{ cm}^{-3}$ , where the total gas mass of 13  $M_{\odot}$  is enclosed. Similarly, the mass for a 0.1 pc diameter region (i.e., a canonical size of dense cores) is estimated to be 75  $M_{\odot}$  with  $T_d = 60$  K, where Band 6 and Band 7 estimates are averaged. For the whole field shown in Figures 4–5, which roughly corresponds to a 0.5 pc diameter region, the total mass is estimated to be 800–2500  $M_{\odot}$ , where we assume  $T_d = 20$ –10 K for extended dust emission. Note that this is a lower limit because the maximum recoverable scale of the present observations is 5.".4 (0.28 pc).

#### 3.3.4. Fractional Abundances and Isotope Abundance Ratios

Fractional abundances with respect to H<sub>2</sub> are shown in Table 4, which are calculated based on column densities estimated in Sections 3.3.1–3.3.3. The fractional abundances normalized by the CH<sub>3</sub>OH column density are also discussed in Sections 4.3–4.4 because of the nonnegligible uncertainty associated with  $N_{\rm H_2}$  (see Section 3.3.3).

Abundances of HCO<sup>+</sup>, HCN, SO, CS, OCS, and CH<sub>3</sub>OH are estimated from their isotopologues, H<sup>13</sup>CO<sup>+</sup>, H<sup>13</sup>CN, <sup>34</sup>SO, C<sup>34</sup>S, O<sup>13</sup>CS, and <sup>13</sup>CH<sub>3</sub>OH. Detections of isotopologue species for SO, CS, OCS, and CH<sub>3</sub>OH imply that the main



**Figure 6.** Results of rotation diagram analyses. Upper-limit points are shown by the downward arrows. The solid lines represent the fitted straight line. Derived column densities and rotation temperatures are shown in each panel. The open squares are excluded in the fit because they significantly deviate from other data points. The gray squares are also excluded in the fit because of their large  $S\mu^2$  values. CH<sub>3</sub>OH is fitted using only E-type transitions, which are shown in blue. For HCOOH, trans- (square) and cis- (circle) species are plotted together. See Section 3.3.1 for details.

species would be optically thick. Isotope abundance ratios of  ${}^{12}\text{C}/{}^{13}\text{C} = 150$  and  ${}^{32}\text{S}/{}^{33}\text{S} = 35$  are assumed, which are obtained by extrapolating the relationship between isotope ratios and galactocentric distances reported in Wilson & Rood (1994) and Humire et al. (2020) to  $D_{\text{GC}} = 19$  kpc.

Abundance ratios are derived for several rare isotopologues; we obtain  $CH_2DOH/CH_3OH = 0.011 \pm 0.002$ ,  $D_2CO/HDCO = 0.45 \pm 0.10$ ,  ${}^{34}SO/{}^{33}SO = 5 \pm 1$ ,  $C^{34}S/C^{33}S = 2 \pm 1$ , and  ${}^{32}SO_2/{}^{34}SO_2 = 20 \pm 4$ . The  ${}^{32}SO_2/{}^{34}SO_2$  ratio in WB 89–789 SMM1 is similar to the solar

 Table 3

 Estimated Rotation Temperatures, Column Densities, and Source Sizes

Molecule	$T_{\rm rot}$	<i>N</i> (X)	N(X) Non-LTE	Size
	(K)	$(cm^{-2})$	$(cm^{-2})$	(")
H <sub>2</sub>		$1.1  imes 10^{24}$		0.85 <sup>c</sup>
H <sup>13</sup> CO <sup>+</sup>	35	$(7.0 \pm 0.1)  imes 10^{12}$	$(7.6 \pm 0.9) \times 10^{12}$	>1.5 <sup>d</sup>
$\mathrm{HC}^{18}\mathrm{O}^+$	35	$(5.8 \pm 0.9)  imes 10^{11}$	$(5.7 \pm 0.6) \times 10^{11}$	1.18 <sup>d</sup>
ССН	35	$(2.7\pm0.1) imes10^{14}$		$>2^{d}$
c-C <sub>3</sub> H <sub>2</sub>	35	$(9.5 \pm 2.2)  imes 10^{13}$	$(8.2\pm0.9) imes10^{13a}$	>1 <sup>d</sup>
H <sub>2</sub> CO	39	$(1.1 \pm 0.1)  imes 10^{14}$	$(1.3 \pm 0.1)  imes 10^{14a}$	>1.5 <sup>d</sup>
HDCO	39	$(5.1 \pm 0.3)  imes 10^{13}$		>1 <sup>d</sup>
D <sub>2</sub> CO	$39^{+6}_{-5}$	$(2.3 \pm 0.5) \times 10^{13}$		>1 <sup>d</sup>
CN	35	$(3.3\pm 0.2) imes 10^{14}$	$(2.5\pm 0.3) imes 10^{14}$	>2 <sup>d</sup>
H <sup>13</sup> CN	35	$(1.2\pm 0.1) imes 10^{13}$	$(1.1 \pm 0.1)  imes 10^{13}$	0.92 <sup>d</sup>
HC <sup>15</sup> N	35	$(6.3 \pm 0.2) \times 10^{12}$	$(5.8 \pm 0.6)  imes 10^{12}$	0.75 <sup>d</sup>
HC <sub>3</sub> N	200	$(2.7 \pm 0.3) \times 10^{13}$	$(2.1 \pm 0.2) \times 10^{13}$	0.65
NO	35	$(9.0 \pm 2.5)  imes 10^{14}$	$(8.9 \pm 0.9)  imes 10^{14}$	>1.5 <sup>d</sup>
HNCO	$237^{+17}_{-15}$	$(3.0 \pm 0.2)  imes 10^{14}$		0.54
CH <sub>3</sub> CN	$279^{+12}_{-11}$	$(1.8 \pm 0.1) \times 10^{14}$	$(8.6 \pm 0.8)  imes 10^{13}$	0.51
<sup>13</sup> CH <sub>3</sub> CN	200	$<5 \times 10^{12}$		
C <sub>2</sub> H <sub>5</sub> CN	$130^{+20}_{-15}$	$(6.3 \pm 1.7) \times 10^{13}$		0.52
NH <sub>2</sub> CHO	$140^{+8}_{-7}$	$(4.2 \pm 0.7) \times 10^{13}$		0.56
SiO	35	$(2.5 \pm 0.2) \times 10^{12}$	$(2.5 \pm 0.3)  imes 10^{12}$	0.65
CS	36	$(1.5 \pm 0.2) \times 10^{14}$	$(2.0 \pm 0.3) \times 10^{14}$	>1.5
C <sup>34</sup> S	36	$(3.1 \pm 0.1) \times 10^{13}$		0.70
C <sup>33</sup> S	$36^{+4}_{-3}$	$(1.5 \pm 0.2) \times 10^{13}$		0.61
OCS	$106^{+6}_{-5}$	$(6.5 \pm 0.5) \times 10^{14}$	$(6.4 \pm 0.7)  imes 10^{14}$	0.55
<sup>13</sup> OCS	200	$(8.7 \pm 2.4) \times 10^{13}$		0.45
H <sub>2</sub> CS	$43^{+3}_{-2}$	$(1.5 \pm 0.1) \times 10^{14}$	$(1.4 \pm 0.2) \times 10^{14a}$	0.62
so	$35^{+1}_{-1}$	$(4.0 \pm 0.3) \times 10^{14}$	$(4.5 \pm 0.5) \times 10^{14}$	0.70 <sup>d</sup>
<sup>34</sup> SO	35	$(5.9 \pm 0.1) \times 10^{13}$		0.66
<sup>33</sup> SO	35	$(1.1 \pm 0.1) \times 10^{13}$		0.53
SO <sub>2</sub>	$166^{+5}_{-5}$	$(1.2 \pm 0.1) \times 10^{15}$		0.53
<sup>34</sup> SO <sub>2</sub>	166	$(5.9 \pm 0.9) \times 10^{13}$		0.51
CH <sub>2</sub> SH	200	$<3 \times 10^{14}$		
HDO	$217^{+14}_{-12}$	$(2.2 \pm 0.2) \times 10^{15}$		0.52
CH <sub>2</sub> OH	$245^{+4}_{-4}$	$(1.9\pm0.1)\times10^{16}$	$(2.6 \pm 0.1) \times 10^{16b}$	0.51
<sup>13</sup> CH <sub>2</sub> OH	$181^{+10}$	$(2.8 \pm 0.2) \times 10^{15}$		0.46
CH_DOH	$155^{+18}$	$(4.6 \pm 0.3) \times 10^{15}$		0.52
НСООСН.	$181^{+6}$	$(1.6 \pm 0.6) \times 10^{15}$ $(8.6 \pm 0.4) \times 10^{15}$		0.51
	$137_{-5}$	$(0.0 \pm 0.1) \times 10^{15}$		0.51
	$137_{-4}$ 126 + 14	$(2.0 \pm 0.1) \times 10^{14}$		0.52
$C_2 n_5 0 n$	$150_{-12}$	$(9.0 \pm 1.3) \times 10^{14}$		0.30
	$192_{-34}^{-34}$	$(0.4 \pm 0.8) \times 10$		0.49
trans-HCOOH	/1-9	$(2.7 \pm 0.6) \times 10^{-7}$		0.58
cis-HCOOH	$69^{+50}_{-21}$	$(2.4 \pm 1.2) \times 10^{13}$		0.49
H <sub>2</sub> CCO	$92^{+14}_{-11}$	$(1.0 \pm 0.2) \times 10^{14}$		0.55
c-C <sub>2</sub> H <sub>4</sub> O	200	$(8.9 \pm 2.0) \times 10^{13}$		0.47

Notes. For  $T_{rot}$  and N(X), those derived from rotation diagrams are shown in italics. Uncertainties and upper limits are of the  $2\sigma$  level and do not include systematic errors due to adopted spectroscopic constants. See Sections 3.3.1–3.3.3 and 4.2 for details.

<sup>a</sup> Assuming ortho/para ratio of 3.

<sup>b</sup> Assuming E-CH<sub>3</sub>OH/A-CH<sub>3</sub>OH ratio of unity (Wirström et al. 2011).

<sup>c</sup> Size of continuum emission.

<sup>d</sup> Associated with the extended component.

 ${}^{32}\text{S}/{}^{34}\text{S}$  ratio (22, Wilson & Rood 1994), although we expect a slightly higher value in the outer Galaxy due to the  ${}^{32}\text{S}/{}^{34}\text{S}$  gradient in the Galaxy (Chin et al. 1996; Humire et al. 2020). Astrophysical implications for the deuterated species are discussed in Section 4.4.

The rotation diagram of  $CH_3CN$  is rather scattered. Although its isotopologue line is not detected, optical thickness might affect the column density estimate, as  $CH_3CN$  is often optically thick in hot cores (e.g., Fuente et al. 2014). To obtain a possible range of its column density, we use the rotation diagram of <sup>12</sup>CH<sub>3</sub>CN data to estimate a lower limit and the nondetection of the <sup>13</sup>CH<sub>3</sub>CN(19<sub>0</sub>–18<sub>0</sub>) line at 339.36630 GHz ( $E_u = 163$  K) for an upper limit.

We have also repeated the analysis for the spectra extracted from a 0.1 pc (1.93) diameter region at the hot-core position, for the sake of comparison with LMC hot cores (see Section 4.4). Those abundances are also summarized in Table 4. The abundances for a 0.1 pc area do not drastically

 Table 4

 Estimated Fractional Abundances

Molecule	N(X)	/N <sub>H2</sub>
	0.026 pc area	0.1 pc area
HCO <sup>+a</sup>	$(9.5 \pm 3.2)  imes 10^{-10}$	$(1.5 \pm 0.3) \times 10^{-9}$
H <sub>2</sub> CO	$(1.0 \pm 0.3)  imes 10^{-10}$	$(1.2 \pm 0.1)  imes 10^{-10}$
HDCO	$(4.7 \pm 1.3) \times 10^{-11}$	$(3.9 \pm 0.2) \times 10^{-11}$
D <sub>2</sub> CO	$(2.1\pm0.7) imes10^{-11}$	$(2.0 \pm 0.3)  imes 10^{-11}$
C <sub>2</sub> H	$(2.5\pm0.7) imes10^{-10}$	$(5.8 \pm 1.2)  imes 10^{-10}$
c-C <sub>3</sub> H <sub>2</sub>	$(8.6 \pm 3.1) \times 10^{-11}$	$(5.9 \pm 1.2)  imes 10^{-11}$
CN	$(3.0\pm0.8) imes10^{-10}$	$(6.6 \pm 1.3)  imes 10^{-10}$
HCN <sup>a</sup>	$(1.7 \pm 0.6)  imes 10^{-9}$	$(1.2 \pm 0.3)  imes 10^{-9}$
HC <sub>3</sub> N	$(2.5\pm0.7) imes10^{-11}$	$(1.4 \pm 0.1)  imes 10^{-11}$
NO	$(8.1 \pm 3.2) \times 10^{-10}$	$(1.6 \pm 0.1)  imes 10^{-9}$
HNCO	$(2.7\pm0.8) imes10^{-10}$	$(7.1 \pm 0.6)  imes 10^{-11}$
CH <sub>3</sub> CN <sup>b</sup>	$(4.2 \pm 2.7)  imes 10^{-10}$	$(3.7 \pm 2.8)  imes 10^{-10}$
C <sub>2</sub> H <sub>5</sub> CN	$(5.8 \pm 2.2)  imes 10^{-11}$	$(2.4 \pm 0.9)  imes 10^{-11}$
NH <sub>2</sub> CHO	$(3.8 \pm 1.2)  imes 10^{-11}$	$(1.8\pm 0.1)\times 10^{-11}$
SiO	$(2.2 \pm 0.6)  imes 10^{-12}$	$(1.2 \pm 0.1) \times 10^{-12}$
CS <sup>c</sup>	$(9.7 \pm 3.3) \times 10^{-10}$	$(6.4 \pm 1.3) \times 10^{-10}$
SO <sup>c</sup>	$(1.9 \pm 0.5)  imes 10^{-9}$	$(1.3\pm 0.3)  imes 10^{-9}$
OCS <sup>a</sup>	$(1.2 \pm 0.5)  imes 10^{-8}$	$(4.1 \pm 1.4)  imes 10^{-9}$
H <sub>2</sub> CS	$(1.4 \pm 0.4) \times 10^{-10}$	$(9.0 \pm 1.0)  imes 10^{-11}$
SO <sub>2</sub>	$(1.1 \pm 0.3)  imes 10^{-9}$	$(2.9\pm0.1) imes10^{-10}$
CH <sub>3</sub> SH	$< 3 \times 10^{-10}$	$<\!\!2 imes 10^{-10}$
HDO	$(2.0 \pm 0.6)  imes 10^{-9}$	$(7.7 \pm 0.9)  imes 10^{-10}$
CH <sub>3</sub> OH <sup>a</sup>	$(3.8 \pm 1.3) \times 10^{-7}$	$(1.7 \pm 0.3)  imes 10^{-7}$
CH <sub>2</sub> DOH	$(4.2 \pm 1.2) \times 10^{-9}$	$(1.5 \pm 0.2)  imes 10^{-9}$
HCOOCH <sub>3</sub>	$(7.8 \pm 2.2)  imes 10^{-9}$	$(3.0 \pm 0.2) \times 10^{-9}$
CH <sub>3</sub> OCH <sub>3</sub>	$(2.3 \pm 0.6)  imes 10^{-9}$	$(1.0\pm 0.1) imes 10^{-9}$
C <sub>2</sub> H <sub>5</sub> OH	$(8.7 \pm 2.7) \times 10^{-10}$	$(3.3 \pm 0.8) \times 10^{-10}$
CH <sub>3</sub> CHO	$(5.8 \pm 1.8)  imes 10^{-10}$	$(2.1 \pm 0.4) \times 10^{-10}$
HCOOH <sup>d</sup>	$(2.7 \pm 1.0)  imes 10^{-10}$	$(1.2\pm0.4) imes10^{-10}$
H <sub>2</sub> CCO	$(9.2 \pm 3.0) \times 10^{-11}$	$(3.7\pm0.9) imes10^{-11}$
c-C <sub>2</sub> H <sub>4</sub> O	$(8.1 \pm 2.8)  imes 10^{-11}$	$(5.9 \pm 1.2)  imes 10^{-11}$

**Notes.** Uncertainties and upper limits are of the  $2\sigma$  level. Column densities of molecules for a 0.026 pc area are summarized in Table 3. An empirical uncertainty of 30% is assumed for  $N_{\text{H}_2}$ .

<sup>a</sup> Estimated from the <sup>13</sup>C isotopologue with  ${}^{12}C/{}^{13}C = 150$ .

<sup>b</sup> Rotation diagram analysis of CH<sub>3</sub>CN is used to derive a lower limit and the nondetection of <sup>13</sup>CH<sub>3</sub>CN for an upper limit.

<sup>c</sup> Estimated from the <sup>34</sup>S isotopologue with  ${}^{32}S/{}^{34}S = 35$ .

<sup>d</sup> Sum of trans- and cis- species.

vary from those for a 0.026 pc area. Molecules with a compact spatial distribution (e.g., COMs) tend to decrease their abundances by a factor of  $\sim 2-3$  in the 0.1 pc data due to the beam dilution effect. In contrast, those with extended spatial distributions and intensity peaks outside the hot-core region (H<sup>13</sup>CO<sup>+</sup>, CCH, CN, and NO) increase by a factor of  $\sim 2$  in the 0.1 pc data.

### 4. Discussion

# 4.1. Hot Molecular Core and Protostar Associated with WB 89–789 SMM1

The nature of WB 89–789 SMM1 is characterized by (i) the compact distribution of warm gas (~0.03 pc, see Section 4.2), (ii) the high gas temperature that can trigger the ice sublimation ( $\geq 100$  K, Section 3.3.1), (iii) the high density (2 × 10<sup>7</sup> cm<sup>-3</sup>, Section 3.3.3), (iv) the association with a luminous protostar (see below), and (v) the presence of chemically rich molecular gas. Those properties suggest that the source is associated with a hot molecular core.



**Figure 7.** The SED of WB 89–789 SMM1. The plotted data are obtained by the ESO 2.2 m telescope (pluses, black; Brand & Wouterloot 2007), the WISE allsky survey (open diamonds, light green; Wright et al. 2010), AKARI FIS allsky survey (open diamonds, blue; Yamamura et al. 2010), and ALMA (filled star, red, this work). The angular resolution of each data is indicated in brackets. The gray dashed line indicates the best-fitted SED with the model of Robitaille et al. (2007).

Figure 7 shows an SED of SMM1, where the data are collected from available databases and literature (Brand & Wouterloot 2007; Wright et al. 2010; Yamamura et al. 2010). The bolometric luminosity of the source is estimated to be  $8.4 \times 10^3 L_{\odot}$  based on the SED fitting with the model of Robitaille et al. (2007). This luminosity is equivalent to a stellar mass of about 10  $M_{\odot}$  according to the mass–luminosity relationship of zero-age main-sequence (ZAMS) stars (Zinnecker & Yorke 2007).

Note that far-infrared data, which is important for the luminosity determination of embedded sources, is insufficient for SMM1. Only upper limits are provided due to the low angular resolution of available AKARI FIS all-sky survey data. Thus, the derived luminosity (and therefore mass) may be lower than the current estimate. Future high-spatial-resolution infrared observations in those missing wavelengths are highly required.

Alternatively, we can estimate the luminosity of SMM1 by scaling the luminosity of a low-metallicity LMC hot core, ST16, whose SED is well determined based on a comprehensive infrared data set from 1 to  $1200 \,\mu$ m (Shimonishi et al. 2020). This LMC hot core has a total luminosity of  $3.1 \times 10^5 L_{\odot}$  and a  $K_s$ -band magnitude ( $[K_s]$ ) of 13.4 mag at 50 kpc, while SMM1 has  $[K_s] = 14.7$  mag at 10.7 kpc. Scaling the luminosity of ST16 with the distance and  $K_s$ -band magnitude, we obtain  $4.3 \times 10^3 L_{\odot}$  for SMM1, which is a factor of 2 lower than the estimate by the SED fitting. In either case, present estimates suggest that the luminosity of SMM1 would correspond to the lower end of high-mass ZAMS or upper end of intermediate-mass ZAMS.

### 4.2. Distribution of Molecular Line Emission and Dust Continuum

The observed emission lines and continuum show different spatial distributions depending on species. Those distributions



Figure 8. Schematic illustration of the molecular gas distribution and the temperature structure in WB 89–789 SMM1.

have important clues to understand their origins. A schematic illustration of the temperature structure and molecular gas distribution in WB 89–789 SMM1 is shown in Figure 8 based on the discussion in this section.

We have estimated the spatial extent of the observed emission by fitting a two-dimensional Gaussian to the continuum center (Table 3). Compact distributions (FWHM =0."5–0."6, 0.026–0.031 pc), comparable with the beam size, are seen in HDO, COMs, CH<sub>3</sub>CN, HNCO, OCS, and high-excitation SO<sub>2</sub> lines. HC<sub>3</sub>N is slightly extended (FWHM = 0."65). They are concentrated at the hot-core position, suggesting that they originate from a warm region where ice mantles are sublimated.

SO, <sup>34</sup>SO, <sup>33</sup>SO, and low-excitation SO<sub>2</sub> show relatively compact distributions (FWHM = 0."5–0."7, 0.026–0.036 pc) at the hot-core position, but also show a secondary peak at the south side of the hot core. This secondary peak coincides with the peak of the NO emission. Other sulfur-bearing species such as C<sup>34</sup>S, C<sup>33</sup>S, and H<sub>2</sub>CS show compact distributions (FWHM = 0."6–0."0.7, 0.031–0.052 pc) centered at the hot core.

A characteristic distribution that is symmetric to the hot-core position is seen in SiO. It shows a compact emission (FWHM =  $0.^{\prime\prime}65$ ) at the hot-core center, but also shows other peaks at the northeast and southwest sides of the hot core. Those secondary peaks are slightly elongated. SiO is a well-known shock tracer. The observed structure would have originated from the shocked gas produced by bipolar protostellar outflows. A driving source of the outflows would be a protostar embedded in a hot core as the distribution of SiO is symmetric with the hot-core position.

Even extended distributions (FWHM > 1."0) are seen in CN, CCH, H<sup>13</sup>CO<sup>+</sup>, HC<sup>18</sup>O<sup>+</sup>, H<sup>13</sup>CN, HC<sup>15</sup>N, NO, CS, H<sub>2</sub>CO, and HDCO, D<sub>2</sub>CO, and low-excitation CH<sub>3</sub>OH. Gas-phase reactions and nonthermal desorption of icy species would have a nonnegligible contribution to the formation of those species because they are widely distributed beyond the hot core. We note that dust continuum, H<sup>13</sup>CN, HC<sup>15</sup>N have a moderately sharp peak (FWHM < 1."0) at the hot-core position in addition to the extended component. c-C<sub>3</sub>H<sub>2</sub> shows a patchy distribution, whose secondary peak at the southwest of the hot core does not coincide with those of other species.

Molecular radicals (CN, CCH, and NO) do not have their emission peak at the hot-core position. This would suggest that the chemistry outside the hot-core region largely contributes to



**Figure 9.** Velocity maps (moment 1) of CN and CCH lines. The color scale indicates the offset velocity relative to the systemic velocity of  $34.5 \text{ km s}^{-1}$ . A possible direction of outflows expected from the distributions of SiO is shown by the red arrows. Contours represent the integrated intensity distribution, and the contour levels are 8%, 20%, 40%, and 60% of the peak value. Low signal-to-noise regions (S/N < 5) are masked. The blue cross represents the 1.2 mm continuum center.

their production. CN and CCH are known to be abundant in photodissociation regions (PDRs) because atomic carbon is efficiently provided by the photodissociation of CO under moderate UV fields (e.g., Fuente et al. 1993; Jansen et al. 1995; Sternberg & Dalgarno 1995; Rodriguez-Franco et al. 1998; Pety et al. 2017). In the present source, their emission shows a similar spatial distribution. A similar distribution between CN and CCH has been also observed in an LMC hot core by Shimonishi et al. (2020); they argue that CN and CCH would trace PDR-like outflow cavity structures that are irradiated by the UV light from a protostar associated with a hot core. We speculate that this is also the case for WB 89–789 SMM1.

Figure 9 shows the velocity maps (moment 1) of CN and CCH lines. CN and CCH emission are elongated in the southwest direction from the hot core (see also Figure 4). The figure also shows a possible direction of protostellar outflows expected from the spatial distribution of SiO. The elongated directions of CN and CCH coincide with the inferred direction of outflows. In addition, the elongated southwest parts of CN and CCH are blueshifted by  $\sim 1-2$  km s<sup>-1</sup> compared to the hotcore position. This may be due to outflow gas motion, although CN and CCH would trace an outflow cavity wall rather than the outflow gas itself. Actually, the observed velocity shift is smaller than a typical value of high-velocity wing components in massive protostellar outflows ( $\geq 5 \text{ km s}^{-1}$ ; e.g., Beuther et al. 2002; Maud et al. 2015). We note that a clear velocity structure is not seen in the SiO velocity map, except for the position of another embedded protostar discussed in Section 4.5. Future observations of optically thick outflow tracers such as CO are necessary to confirm the presence of high-velocity gas associated with protostellar outflows.

### 4.3. Molecular Abundances: Comparison with Galactic Hot Cores

Figure 10 shows a comparison of molecular abundances between WB 89–789 SMM1 and other known Galactic hot cores. The data for an intermediate-mass hot core, NGC 7192 FIRS2, are adopted from Fuente et al. (2014). The abundances are based on the 220 GHz region observations for a 0.009 pc diameter area centered at the hot core. The luminosity of NGC 7192 FIRS2 (~500  $L_{\odot}$ ) corresponds to that of a 5  $M_{\odot}$  ZAMS. The data for a high-mass source, the Orion hot core, are adopted from Sutton et al. (1995), based on the 340 GHz region



Figure 10. Comparison of molecular abundances between an outer Galactic hot core (black, WB 89–789 SMM1), an intermediate-mass hot core (green, NGC 7192 FIRS2), and a high-mass hot core (cyan, Orion). An abundance difference by a factor of 4 is indicated by the black solid line with hats. The area with thin vertical lines indicates the error bar. No data are available for HDO in NGC 7192 FIRS2. See Section 4.3 for details.



**Figure 11.** Comparison of molecular abundances normalized by the CH<sub>3</sub>OH column density for (a) WB 89–789 SMM1 versus NGC 7192 FIRS2 and (b) WB 89–789 SMM1 versus ST16 (LMC). Carbon- and oxygen-bearing species are shown by the blue squares, nitrogen-bearing species in green, and sulfur-bearing species in red. The dotted lines in panel (a) represent an abundance ratio of 2:1 and 1:2 for WB 89–789 SMM1: NGC 7192 FIRS2, while the solid line represents that of the 1:1 ratio. Similarly, the dotted lines in panel (b) represent a ratio of 100:1, 10:1, 1:10, and 1:100 for WB 89–789 SMM1:ST16, while the solid line represents a 1:1 ratio. The leftward triangles in panel (b) indicate the upper limit for ST16. See Section 4.3 for details.

observations for a 0.027 pc diameter area at the hot core. The abundance of HNCO is taken from Schutte & Greenberg (1997).

The molecular abundances in WB 89–789 SMM1 are generally lower than those of the inner Galactic counterparts. The degree of the abundance decrease is roughly consistent with the lower metallicity of the WB 89–789 region as indicated by the scale bar in Figure 10. Particularly, SMM1 and the intermediate-mass hot core NGC 7192 FIRS2 show similar molecular abundances after taking into account the four times lower metallicity of the former source. For the comparison with Orion, it seems that HC<sub>3</sub>N, C<sub>2</sub>H<sub>5</sub>CN, and SO<sub>2</sub> are significantly less abundant in SMM1 even taking into account the lower metallicity, while CH<sub>3</sub>OH is overabundant in SMM1 despite the low metallicity.

To further focus on chemical complexity at low metallicity, Figure 11 shows a comparison of fractional abundances of COMs normalized by the CH<sub>3</sub>OH column density for WB 89–789 SMM1 and NGC 7192 FIRS2. Such a comparison is useful for investigating the chemistry of organic molecules in warm and dense gas around protostars (Herbst & van Dishoeck 2009; Drozdovskaya et al. 2019) because  $CH_3OH$ is believed to be a parental molecule for the formation of even larger COMs (e.g., Nomura & Millar 2004; Garrod & Herbst 2006). In addition,  $CH_3OH$  is a product of grain surface reaction, thus warm  $CH_3OH$  gas mainly arises from a hightemperature region, where ices are sublimated and characteristic hot-core chemistry proceeds. Furthermore, the normalization by  $CH_3OH$  can cancel the metallicity effect in the abundance comparison.

The  $N(X)/N(CH_3OH)$  ratios are remarkably similar between WB 89–789 SMM1 and NGC 7192 FIRS2 as shown in Figure 11(a). The ratios of SMM1 coincide with those of NGC 7192 FIRS2 within a factor of 2 for the most molecular species. The correlation coefficient is calculated to be 0.94, while it is 0.96 if CH<sub>3</sub>CN is excluded. It seems that CH<sub>3</sub>CN deviates from the overall trend, although the uncertainty is large due to the



Figure 12. Comparison of molecular abundances between an outer Galactic hot core, WB 89–789 SMM1 (black), and three LMC hot cores, ST11 (red), ST16 (orange), and N113 A1 (light yellow). Abundances of SMM1 are calculated for a 0.1 pc diameter region. The area with the thin vertical lines indicates the error bar. The bar with a color gradient indicates an upper limit. The absence of bars indicates the lack of available data. See Section 4.4 for details.

opacity effect (see 3.3.4).  $C_2H_5OH$  also slightly deviates from the trend. The reason for their behavior is still unclear, but it may be related to the formation pathway of those molecules.

The above two comparisons suggest that chemical compositions of the hot core in the extreme outer Galaxy scale with the metallicity. In the WB 89–789 region, the metallicity is expected to be four times lower compared to the solar neighborhood. The observed abundances of COMs in the SMM1 hot core are lower than the other Galactic hot cores, but the decrease is proportional to this metallicity. Furthermore, similar  $N(\text{COMs})/N(\text{CH}_3\text{OH})$ ratios suggest that CH<sub>3</sub>OH is an important parental species for the formation of larger COMs in a hot core, as suggested by the aforementioned theoretical studies.

CH<sub>3</sub>OH ice is believed to form on grain surfaces, and several formation processes are proposed by laboratory experiments; i.e., hydrogenation of CO, ultraviolet photolysis, and radiolysis of ice mixtures (e.g., Hudson & Moore 1999; Watanabe et al. 2007). It is known that  $CH_3OH$  is already formed in quiescent prestellar cores before star formation occurs (Boogert et al. 2011). Solid CH<sub>3</sub>OH will chemically evolve to larger COMs through a combination of photolysis, radiolysis, and grain heating during the warm-up phase that leads to the formation of a hot core (Garrod & Herbst 2006). High-temperature gasphase chemistry of sublimated CH<sub>3</sub>OH would also contribute to the COM formation (Nomura & Millar 2004; Taquet et al. 2016). The present results suggest that various COMs can form even in a low-metallicity environment, if their parental molecule, CH<sub>3</sub>OH, is efficiently produced in a star-forming core. The detection of a chemically rich star-forming core in the extreme outer Galaxy has an impact on the understanding of the occurrence of the chemical complexity in a primordial environment of the early phase of the Galaxy formation. We here note that observations of ice mantle compositions have not been reported for the outer Galaxy so far. Future infrared observations of ice absorption bands toward embedded sources in the outer Galaxy are important.

### 4.4. Molecular Abundances: Comparison with LMC Hot Cores

It is still unknown if the observed simply metallicity-scaled chemistry of COMs in the WB 89–789 SMM1 hot core is common in other hot-core sources in the outer Galaxy. A comparison of the present data with those of hot cores in the LMC would provide a hint for understanding the universality of low-metallicity hot-core chemistry. The metallicity of the LMC is reported to be lower than the solar value by a factor of 2 to 3 (e.g., Dufour et al. 1982; Westerlund 1990; Russell & Dopita 1992; Choudhury et al. 2016), which is in common with the outer Galaxy.

Figure 12 shows a comparison of molecular abundances between WB 89-789 SMM1 and three LMC hot cores. The plotted molecular column densities for LMC hot cores are adopted from Shimonishi et al. (2016a) for ST11, Shimonishi et al. (2020) for ST16, and Sewiło et al. (2018) from N113 A1. Another LMC hot core in Sewiło et al. (2018), N113 B3, has similar molecular abundances to N113 A1. The  $N_{\rm H_2}$  value of ST11 and N113 A1 is reestimated using the same dust opacity data and dust temperature  $(T_d = 60 \text{ K})$  as in this work; we obtained  $N_{\text{H}_2} = 1.2 \times 10^{24} \text{ cm}^{-2}$  for ST11 and  $N_{\text{H}_2} = 9.2 \times 10^{23} \text{ cm}^{-2}$  for N113 A1. The dust temperature assumed in ST16 is 60 K as described in Section 3.3.3. Molecular column densities are estimated for circular/elliptical regions of  $0.12 \times 0.12$  pc,  $0.10 \times 0.10$  pc, and  $0.21 \times 0.13$  pc for ST11, ST16, and N113 A1, respectively. For a fair comparison, we have recalculated  $N_{\rm H_2}$  and molecular column densities of SMM1 for a 0.1 pc (1"93) diameter region. Those abundances are plotted in Figure 12 and summarized in Table 4.

The chemical composition of the outer Galaxy hot core does not resemble those of LMC hot cores as seen in Figure 12. The dissimilarity is also seen in the  $N(X)/N(CH_3OH)$  comparison between SMM1 and ST16 as shown in Figure 11(b), where the correlation coefficient is calculated to be 0.69.

Shimonishi et al. (2020) argue that SO<sub>2</sub> will be a good tracer of low-metallicity hot-core chemistry because (i) it is commonly detected in LMC hot cores with similar abundances, and (ii) it originated from a compact hot-core region. SO also shows similar abundances within LMC hot cores. In WB 89–789 SMM1, however, the abundances of SO<sub>2</sub> and SO relative to H<sub>2</sub> are lower by a factor of 28 and 5 compared with LMC hot cores. The measured rotation temperatures of SO<sub>2</sub> are similar between those hot cores, i.e., 166 K (SO<sub>2</sub>) for SMM1, 232 K (SO<sub>2</sub>) and 86 K (<sup>34</sup>SO<sub>2</sub>) for ST16, 190 K (SO<sub>2</sub>) and 95 K (<sup>34</sup>SO<sub>2</sub>) for ST11. The SO<sub>2</sub> column densities for ST16 and ST11 are estimated from <sup>34</sup>SO<sub>2</sub>, while that for SMM1 is from SO<sub>2</sub>. However, the SO<sub>2</sub> column density of SMM1 increases only by a factor of up to 3 when it is estimated from <sup>34</sup>SO<sub>2</sub> (see Section 3.3.4). Thus, the low  $SO_2$  abundance in the outer Galactic hot core would not be due to the optical thickness.

In contrast to the S-O bond-bearing species, the C-S bondbearing species such as CS, H<sub>2</sub>CS, and OCS do not show a significant abundance decrease in WB 89-789 SMM1. Thus, it is not straightforward to attribute the low abundance of  $SO_2$ (and perhaps SO) to the low elemental abundance ratio of sulfur in the outer Galaxy. Hot-core chemistry models suggest that SO<sub>2</sub> is mainly produced in high-temperature gas-phase reactions in warm gas, using H<sub>2</sub>S sublimated from ice mantles (Charnley 1997; Nomura & Millar 2004). This also applies to the SO<sub>2</sub> formation in low-metallicity sources as shown in astrochemical simulations for LMC hot cores (Shimonishi et al. 2020). We speculate that the different behavior of  $SO_2$  in the outer Galaxy and LMC hot cores may be related to differences in the evolutionary stage of hot cores. A different luminosity of host protostars may also contribute to the different sulfur chemistry, i.e.,  $\sim 8 \times 10^3 L_{\odot}$  for WB 89–789 SMM1, while several  $\times 10^5 L_{\odot}$  for LMC hot cores. A different cosmic-ray ionization rate between the outer Galaxy and the LMC may also affect the chemical evolution, although the rate is not known for the outer Galaxy.

Among nitrogen-bearing molecules, NO shows interesting behavior in LMC hot cores. After correcting for the metallicity, NO is overabundant in LMC hot cores compared with Galactic counterparts despite the low elemental abundance of nitrogen in the LMC (Shimonishi et al. 2020). Only NO shows such behavior among the nitrogen-bearing molecules observed in LMC hot cores. In WB 89-789 SMM1, however, such an overabundance of NO is not observed. The NO abundance of SMM1 is  $1.6 \times 10^{-9}$  for a 0.1 pc region data. This is a factor of 5 lower than a typical NO abundance in Galactic high-mass hot cores  $(8 \times 10^{-9}, \text{Ziurys et al. 1991})$ , which is consistent with a factor of 4 lower metallicity in WB 89-789. The present highspatial-resolution data have revealed that NO does not mainly arise from a hot-core region, as shown in Figure 4. It has an intensity peak at the south part of the hot core, where lowexcitation lines of SO and SO<sub>2</sub> also have a secondary peak (Section 4.2). Thus, shock chemistry or photochemistry, rather than high-temperature chemistry, would contribute to the production of NO in low-metallicity protostellar cores. In that case, a lower luminosity of SMM1 than those of LMC hot cores may contribute to the different behavior of NO.

For other nitrogen-bearing molecules, HNCO and  $CH_3CN$ , a clear difference is not identified between outer Galactic and LMC hot cores, although the number of data points is limited and the abundance uncertainty is large. The reason for the unusually low abundance of SiO in SMM1 is unknown. It may be related to different shock conditions or grain compositions because dust sputtering by shock is mainly responsible for the production of SiO gas.

The formation of COMs is one of the important standpoints for low-metallicity hot-core chemistry. It is reported that CH<sub>3</sub>OH shows a large abundance variation in LMC hot cores (Shimonishi et al. 2020). There are organic-poor hot cores such as ST11 and ST16, while N113 A1 and B3 are organic rich. The CH<sub>3</sub>OH abundance of WB 89–789 SMM1 is higher than those of any known LMC hot cores. The abundances of HCOOCH<sub>3</sub> and CH<sub>3</sub>OCH<sub>3</sub> in SMM1 are comparable with those of an organic-rich LMC hot core, N113 A1. The detection of many other COMs in SMM1 suggests the source has experienced rich organic chemistry despite its lowmetallicity nature.

Astrochemical simulations for LMC hot cores suggest that dust temperature at the initial ice-forming stage has a major effect on the abundance of CH<sub>3</sub>OH gas in the subsequent hotcore stage (Acharyya & Herbst 2018; Shimonishi et al. 2020). Simulations of grain surface chemistry dedicated to the LMC environment also suggest that dust temperature is one of the key parameters for the formation of CH<sub>3</sub>OH in dense cores (Acharyya & Herbst 2015; Pauly & Garrod 2018). This is because (i) CH<sub>3</sub>OH is mainly formed by the grain surface reaction, and (ii) the hydrogenation reaction of CO, which is a dominant pathway for the CH<sub>3</sub>OH formation, is sensitive to the dust temperature due to the high volatility of atomic hydrogen. For this reason, it is inferred that organic-rich hot cores had experienced a cold stage ( $\leq 10$ K) that is sufficient for CH<sub>3</sub>OH formation before the hot-core stage, while organic-poor ones might have missed such a condition for some reason. Alternatively, the slight difference in the hot core's evolutionary stage may contribute to the CH<sub>3</sub>OH abundance variation, because the high-temperature gas-phase chemistry is rapid, and it can decrease CH<sub>3</sub>OH gas at a late stage (e.g., Nomura & Millar 2004; Garrod & Herbst 2006; Vasyunin & Herbst 2013; Balucani et al. 2015).

Low-metallicity hot-core chemistry simulations in Shimonishi et al. (2020) argue that the maximum achievable abundances of CH<sub>3</sub>OH gas in a hot-core stage significantly decrease as the visual extinction of the initial ice-forming stage decreases. On the other hand, the simulations show that the CH<sub>3</sub>OH gas abundance is simply metallicity scaled if the initial ice-forming stage is sufficiently shielded. In a well-shielded initial condition, the grain surface is cold enough to trigger CO hydrogenation, and the resultant CH<sub>3</sub>OH abundance is roughly regulated by the elemental abundances. The observed metallicity-scaled chemistry of COMs in WB 89–789 SMM1 implies that the source had experienced such an initial condition before the hot-core stage.

Deuterium chemistry is widely used in interpreting the chemical and physical history of interstellar molecules (e.g., Caselli & Ceccarelli 2012; Ceccarelli et al. 2014). The measured CH<sub>2</sub>DOH/CH<sub>3</sub>OH ratio in WB 89–789 SMM1 is  $1.1\% \pm 0.2\%$ , which is comparable to the higher end of those ratios observed in high-mass protostars and the lower end of those in low-mass protostars (e.g., see Figure 2 in Drozdovskaya et al. 2021). The ratio is orders of magnitude higher than the deuterium-tohydrogen ratio in the solar neighborhood  $(2 \times 10^{-5})$ ; Linsky et al. 2006; Prodanović et al. 2010) and that in the big bang nucleosynthesis (3  $\times$  10<sup>-5</sup>; Burles 2002 and references therein). This suggests that the efficient deuterium fractionation occurred upon the formation of CH<sub>3</sub>OH in SMM1. The D<sub>2</sub>CO/HDCO ratio is  $45\% \pm 10\%$ , which is comparable to those observed in low-mass and high-mass protostars (e.g., Zahorecz et al. 2021). This would suggest that physical conditions for deuterium fractionation could be similar between WB 89-789 SMM1 and inner Galactic protostars. Note that higher-spatial-resolution observations and detailed multiline analyses would affect the measured abundance of deuterated species as reported in Persson et al. (2018) for the case of a nearby low-mass protostar. The H<sub>2</sub>CO column density derived in this work may be a lower limit because the line is often optically thick, thus we do not discuss the abundance ratio relative to H<sub>2</sub>CO.

It is known that the deuterium fractionation efficiently proceeds at low temperature (e.g., Roberts et al. 2003; Caselli

& Ceccarelli 2012; Taquet et al. 2014; Furuya et al. 2016). This is because the key reaction for the trigger of deuterium fractionation,  $H_3^+ + HD \rightarrow H_2D^+ + H_2 + 232$  K, is exothermic and its backward reaction cannot efficiently proceed below 20 K. In addition, gaseous neutral species such as CO and O efficiently destruct  $H_2D^+$ , thus their depletion at low temperature further enhances the deuterium fractionation (e.g., Caselli & Ceccarelli 2012). A sign of high deuterium fractionation observed in WB 89–789 SMM1 suggests that the source had experienced such a cold environment during its formation. This picture is consistent with the implication obtained from the metallicity-scaled chemistry of COMs, which also suggests the occurrence of a cold and well-shielded initial condition as discussed above.

Although the low metallicity is common between the outer Galaxy and the LMC, their star-forming environments would be different; the LMC has more harsh environments as inferred from active massive star formation over the whole galaxy, while that for the outer Galaxy might be quiescent due to its low star formation activity. Those environmental differences need to be taken into account for further understanding of the chemical evolution of star-forming regions at low metallicity. A future extensive survey of protostellar objects toward the outer Galaxy is thus vitally important for further discussion. Astrochemical simulations dedicated to the environment of the outer Galaxy, and the application to lower-mass protostars, are also important.

### 4.5. Another Embedded Protostar Traced by High-velocity SiO Gas

We have also detected a compact source associated with high-velocity SiO gas at the east side of WB 89–789 SMM1. Hereafter, we refer to this source as WB 89–789 SMM2. According to the SiO emission, the source is located at R.A. =  $06^{h}17^{m}24^{s}.246$  and decl. =  $14^{\circ}54'43''.25$  (ICRS), which is 2".7 (0.14 pc) away from SMM2. Figure 13(a) shows the SiO (6–5) spectrum extracted from a 0".6 diameter region centered at the above position. The SiO line is largely shifted to the blue and red sides relative to the systemic velocity in a symmetric fashion. The peaks of the shifted emission are located at  $V_{sys} \pm 25$  km s<sup>-1</sup>.

Figure 13(b) shows a velocity map and the integrated intensity distribution of SiO(6–5). In the figure, to focus on SiO in WB 89–789 SMM2, the intensity is integrated over a much wider velocity range (0–60 km s<sup>-1</sup>) compared with that adopted in Figure 4 (31–38 km s<sup>-1</sup>). The velocity map clearly indicates that the velocity structure of SiO in SMM2 is spatially symmetric to the SiO center. At this position, a local peak is seen in the 1200  $\mu$ m continuum as shown in the figure, suggesting the presence of an embedded source. SMM2 does not show any emission lines of COMs, and no alternative molecular lines are identified at the frequencies of Doppler-shifted SiO emission. Also taking into account the clear spectral and spatial symmetry, the observed lines must be attributed to high-velocity SiO gas.

The spectral characteristics of the observed high-velocity SiO resemble those of extremely high-velocity (EHV) outflows observed in Class 0 protostars (Bachiller et al. 1991; Tafalla et al. 2010, 2015; Tychoniec et al. 2019). The EHV flows are known to appear as a discrete high-velocity ( $V \gtrsim 30$  km s<sup>-1</sup>) peak and are observed in the youngest stage of star formation (Bachiller 1996; Matsushita et al. 2019 and references therein).



**Figure 13.** (a) SiO(6–5) spectrum of WB 89–789 SMM2. The dotted line indicates a systemic velocity of 34.5 km s<sup>-1</sup>. High-velocity ( $V_{\rm sys} \pm 25$  km s<sup>-1</sup>) SiO components are seen at the blue-/redshifted sides of the systemic velocity. (b) Velocity map (moment 1) of the SiO(6–5) line. The color scale indicates the offset velocity relative to the systemic velocity. Low signal-to-noise ratio regions (S/N < 5) are masked. Gray contours represent the intensity distribution of SiO(6–5) integrated from 0 to 60 km s<sup>-1</sup>, and the contour levels are  $1.5\sigma$ ,  $4\sigma$ , and  $12\sigma$  of the rms level. The yellow star indicates the SiO center of SMM2, while the blue cross indicates the hot-core position (SMM1). The subset panel shows the 1200  $\mu$ m continuum image for a 1."  $2 \times 1$ ." 2 region centered at SMM2. See Section 4.5 for details.

The EHV flows extend up to several thousands of astronomical units from the central protostar in SiO and usually have collimated bipolar structures (e.g., Bachiller et al. 1991; Hirano et al. 2010; Matsushita et al. 2019; Tychoniec et al. 2019). The beam size of the present data is about 5000 au, thus such structures will not be fully spatially resolved. Actually, a symmetric spatial distribution of blue-/redshifted SiO is only marginally resolved into two beam size regions (Figure 13(b)). The spatial extent of SiO emission is about 1" (0.052 pc). Assuming an outflow velocity of 25 km s<sup>-1</sup>, we estimate a dynamical timescale of EHV flows to be at least 2000 yr. This is roughly consistent with the dynamical timescales of other EHV sources, which range from a few hundred to a few thousand years (Bachiller 1996 and references therein).

A 1200  $\mu$ m continuum flux in a 0.00 diameter region centered at SMM2 is 0.60 ± 0.05 mJy beam<sup>-1</sup>. Assuming  $T_d = 20$  K, we obtain  $N_{\rm H_2} = 3.2 \times 10^{23}$  cm<sup>-2</sup>. This is equivalent to a gas number density of  $n_{\rm H_2} = 4.9 \times 10^6 \,\mathrm{cm}^{-3}$ . If we assume a higher  $T_d$ , i.e., 40 K, then the derived column density is 2.5 times lower than the 20 K case. In either case, the continuum data suggest the presence of high-density gas at this position. A column density and fractional abundance of SiO gas at the above position is estimated to be  $N(\text{SiO}) \sim 2 \times 10^{13} \,\mathrm{cm}^{-2}$  and  $N(\text{SiO})/N_{\rm H_2} \sim 6 \times 10^{-11}$ , where we assume optically thin emission in the LTE and the gas/dust temperature of 20 K. The fractional abundance will be two times higher if we assume the gas/dust temperature of 10 K or 40 K. The SiO abundance in SMM2 is at least 30 times higher than that observed in SMM1. The observed enhancement of SiO in SMM2 would be related to shock chemistry triggered by EHV outflows.

Previous single-dish observations of CO detected extended  $(\sim 20'')$  molecular outflows in the WB 89–789 region (Brand & Wouterloot 1994, 2007). The center of the outflow gas coincides with the position of the IRAS source (IRAS 06145 +1455;  $06^{h}17^{m}24^{s}2$ ,  $14^{\circ}54'42''$ , J2000). This position is consistent with those of SMM1 or SMM2, given the large beam size of CO(3-2) observations (14") in Brand & Wouterloot (2007). The observed CO outflow gas has an extended blueshifted component  $(20 < V_{LSR} < 31 \text{ km s}^{-1})$ toward the southeast direction from the center, while a redshifted component  $(37 < V_{LSR} < 55 \text{ km s}^{-1})$  is extended toward the northwest direction (see Figure 9 in Brand & Wouterloot 2007). This outflow direction coincides with that of the high-velocity SiO outflows observed in this work. The SiO outflows from SMM2 may have a common origin with the large-scale CO outflows.

In summary, it is likely that a compact, high-density, and embedded object is located at the position of WB 89–789 SMM2. Presumably, a protostar associated with SMM2 is driving the observed high-velocity SiO gas flows. Its short dynamical timescale and similarity to EHV flows suggest that the object is at the youngest stage of star formation (Class 0/I). Nondetection of warm gas emission also supports its young nature. We note that the detailed structure of high-velocity SiO gas is not fully spatially resolved, and CO lines, which often trace high-velocity outflows, are not covered in the present data. Future high-spatial-resolution observations of CO and other outflow tracers are key to further clarify the nature of WB 89–789 SMM2.

### 5. Summary

The extreme outer Galaxy is an excellent laboratory to study star formation and ISM in a Galactic low-metallicity environment. The following conclusions are obtained in this work.

- 1. A hot molecular core is for the first time detected in the extreme outer Galaxy (WB 89–789 SMM1), based on submillimeter observations with ALMA toward the WB 89–789 star-forming region located at the galactocentric distance of 19 kpc.
- 2. A variety of carbon-, oxygen-, nitrogen-, sulfur-, and silicon-bearing species, including COMs containing up to nine atoms and larger than  $CH_3OH$ , are detected toward a warm (>100 K) and compact (<0.03 pc) region associated

with a protostar ( $\sim 8 \times 10^3 L_{\odot}$ ). The results suggest that a great molecular complexity exists even in a lower-metallicity environment of the extreme outer Galaxy.

- 3. For deuterated species, we have detected HDO, HDCO, D<sub>2</sub>CO, and CH<sub>2</sub>DOH. HDO and CH<sub>2</sub>DOH arise from a compact and high-temperature ( $T_{\rm rot} = 155-220$ ) region, while HDCO and D<sub>2</sub>CO are in a lower-temperature ( $T_{\rm rot} \sim 40$  K) and slightly extended region. The measured ratios of CH<sub>2</sub>DOH/CH<sub>3</sub>OH and D<sub>2</sub>CO/HDCO are 1.1%  $\pm$  0.2% and 45%  $\pm$  10%, respectively.
- 4. Fractional abundances of  $CH_3OH$  and other COMs relative to  $H_2$  generally scale with the metallicity of WB 89–789, which is a factor of 4 lower than the solar value.
- 5. A comparison of fractional abundances of COMs relative to the CH<sub>3</sub>OH column density between the outer Galactic hot core and a Galactic intermediate-mass hot core shows a remarkable similarity. The results suggest a metallicityscaled chemistry for the formation of COMs in this source. CH<sub>3</sub>OH is an important parental molecule for COMs formation even in a lower-metallicity environment.
- 6. On the other hand, the molecular abundances of the present hot core do not resemble those of LMC hot cores. We speculate that different luminosities or star-forming environments between outer Galactic and LMC hot cores may contribute to this.
- 7. According to astrochemical simulations of low-metallicity hot cores, the observed metallicity-scaled chemistry of COMs in WB 89–789 SMM1 implies that the source had experienced a well-shielded and cold ice-forming stage before the hot-core stage.
- 8. We have also detected another compact source (WB 89–789 SMM2) associated with high-velocity SiO gas  $(V_{\rm sys} \pm 25 \text{ km s}^{-1})$  in the same region. The characteristics of the source resemble those of EHV outflows observed in Class 0 protostars. Physical properties and dynamical timescale of this outflow source are discussed.

This paper makes use of the following ALMA data: ADS/ JAO.ALMA#2017.1.01002.S and 2018.1.00627.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. This work has made extensive use of the Cologne Database for Molecular Spectroscopy and the molecular database of the Jet Propulsion Laboratory. This work makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/ California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation. This work was supported by JSPS KAKENHI grant Nos. 19H05067, 21H00037, and 21H01145. Finally, we would like to thank an anonymous referee for insightful comments, which substantially improved this paper.

Software: CASA (McMullin et al. 2007).

# Appendix A Measured Line Parameters

Tables A1–A9 summarize the measured line parameters (see Section 3.1 for details). The tabulated uncertainties and upper

limits are of  $2\sigma$  level and do not include systematic errors due to continuum subtraction. Upper limits are estimated assuming  $\Delta V = 4$  km s<sup>-1</sup>.

Table A1									
Line Parameters for HDO, H13CO+, HC18O+, CCH, c-C3H2, H2CO, HDCO, and D2CO									

Molecule	Transition	<i>E<sub>u</sub></i> (K)	Frequency (GHz)	T <sub>br</sub> (K)	$\Delta V$ (km s <sup>-1</sup> )	$\frac{\int T_{\rm br} dV}{({\rm K \ km \ s}^{-1})}$	$V_{\rm LSR}$ (km s <sup>-1</sup> )	rms (K)	Note
HDO	$2_{1, 1} - 2_{1, 2}$	95	241.56155	$0.99\pm0.03$	4.8	$5.05\pm0.29$	34.6	0.04	
HDO	73, 4-64, 3	837	241.97357	$0.28\pm0.02$	2.1	$0.63\pm0.12$	34.1	0.04	
$H^{13}CO^+$	3-2	25	260.25534	$5.85\pm0.02$	2.3	$14.23\pm0.13$	34.1	0.03	
$HC^{18}O^+$	4–3	41	340.63069	$0.64\pm0.05$	1.9	$1.29\pm0.20$	34.1	0.07	
CCH	$N = 4-3, J = \frac{9}{2}-\frac{7}{2}, F = 5-4$	42	349.33771	$4.39\pm0.04$	2.6	$12.32\pm0.24$	33.7	0.08	(1)
CCH	$N = 4-3, J = \frac{7}{2} - \frac{5}{2}, F = 4-3$	42	349.39928	$3.54\pm0.04$	2.8	$10.49\pm0.26$	33.7	0.08	(1)
c-C <sub>3</sub> H <sub>2</sub>	$3_{2, 1} - 2_{1, 2}$	18	244.22215	$0.23\pm0.02$	4.8	$1.18\pm0.27$	33.6	0.04	
c-C <sub>3</sub> H <sub>2</sub>	$5_{3, 2} - 4_{4, 1}$	45	260.47975	$0.09\pm0.02$	1.6	$0.15\pm0.10$	32.9	0.03	(2)
H <sub>2</sub> CO	$5_{1,5}-4_{1,4}$	62	351.76864	$7.02\pm0.05$	3.7	$27.32\pm0.40$	34.2	0.08	
HDCO	42 3-32 2	63	257.74870	$0.94\pm0.02$	2.8	$2.80\pm0.14$	34.3	0.03	
HDCO	$4_{2}, 2-3_{2}, 1$	63	259.03491	$0.97\pm0.02$	2.9	$3.00\pm0.18$	34.3	0.03	
D <sub>2</sub> CO	$4_{1}$ $3-3_{1}$ 2	35	245.53275	$0.64\pm0.03$	2.3	$1.54\pm0.15$	34.2	0.04	
$D_2CO$	$6_{2, 5} - 5_{2, 4}$	80	349.63061	$0.76\pm0.04$	2.4	$1.92\pm0.23$	33.9	0.08	

Note. (1) Blend of two hyperfine components. (2) Tentative detection.

 Table A2

 Line Parameters for N-bearing Molecules

Molecule	Transition	<i>Е</i> <sub>и</sub> (К)	Frequency (GHz)	T <sub>br</sub> (K)	$\Delta V$ (km s <sup>-1</sup> )	$\frac{\int T_{\rm br} dV}{({\rm K \ km \ s^{-1}})}$	$V_{\rm LSR}$ (km s <sup>-1</sup> )	rms (K)	Note
H <sup>13</sup> CN	3–2	25	259.01180	$3.25\pm0.02$	4.2	$14.45\pm0.19$	34.3	0.03	
HC <sup>15</sup> N	3–2	25	258.15700	$1.95\pm0.02$	3.6	$7.45\pm0.19$	34.3	0.03	
CN	$N = 3-2, J = \frac{5}{2} - \frac{5}{2}, F = \frac{3}{2} - \frac{3}{2}$	33	339.44678	$0.30\pm0.04$	2.6	$0.82\pm0.22$	34.6	0.07	
CN	$N = 3-2, J = \frac{5}{2} - \frac{5}{2}, F = \frac{5}{2} - \frac{5}{2}$	33	339.47590	$0.39\pm0.04$	1.7	$0.71\pm0.17$	34.0	0.07	
CN	$N = 3-2, J = \frac{5}{2} - \frac{5}{2}, F = \frac{7}{2} - \frac{7}{2}$	33	339.51664	$0.73\pm0.04$	1.8	$1.38\pm0.18$	34.1	0.07	
CN	$N = 3-2, J = \frac{5}{2} - \frac{3}{2}, F = \frac{5}{2} - \frac{5}{2}$	33	340.00813	$0.95\pm0.04$	2.1	$2.16\pm0.20$	33.9	0.07	
CN	$N = 3-2, J = \frac{5}{2} - \frac{3}{2}, F = \frac{3}{2} - \frac{3}{2}$	33	340.01963	$0.93\pm0.04$	1.8	$1.81\pm0.17$	34.1	0.07	
CN	$N = 3-2, J = \frac{5}{2} - \frac{3}{2}, F = \frac{7}{2} - \frac{5}{2}$	33	340.03155	$3.08\pm0.04$	2.7	$8.71\pm0.25$	33.8	0.07	
CN	$N = 3-2, J = \frac{5}{2} - \frac{3}{2}, F = \frac{5}{2} - \frac{3}{2}$	33	340.03541	$3.04\pm0.04$	2.1	$6.87\pm0.26$	33.7	0.07	(1)
CN	$N = 3-2, J = \frac{7}{2} - \frac{5}{2}, F = \frac{9}{2} - \frac{7}{2}$	33	340.24777	$4.38\pm0.03$	2.4	$11.32\pm0.22$	33.4	0.07	(1)
CN	$N = 3-2, J = \frac{7}{2} - \frac{5}{2}, F = \frac{5}{2} - \frac{5}{2}$	33	340.26177	$0.91\pm0.04$	1.9	$1.85\pm0.18$	34.1	0.07	
CN	$N = 3-2, J = \frac{7}{2} - \frac{5}{2}, F = \frac{7}{2} - \frac{7}{2}$	33	340.26495	$1.02\pm0.04$	2.0	$2.12\pm0.18$	33.9	0.07	
NO	$J = \frac{7}{2} - \frac{5}{2}, \ \Omega = \frac{1}{2}, \ F = \frac{9}{2} + \frac{7}{2}$	36	351.04352	$0.29\pm0.03$	2.5	$0.78\pm0.22$	33.7	0.08	
NO	$J = \frac{7}{2} - \frac{5}{2}, \ \Omega = \frac{1}{2}, \ F = \frac{7}{2} - \frac{5}{2}$	36	351.05171	$0.50\pm0.04$	2.1	$1.10\pm0.20$	34.3	0.08	(2)
HNCO	11 <sub>4, 7</sub> –10 <sub>4, 6</sub>	720	241.49864	$0.32\pm0.08$	4.8	$1.20\pm0.13$	33.8	0.04	(2)
HNCO	$11_{3, 9} - 10_{3, 8}$	445	241.61930	$0.51\pm0.02$	4.1	$2.19\pm0.25$	33.6	0.04	(2)
HNCO	11 <sub>2, 10</sub> -10 <sub>2, 9</sub>	240	241.70385	< 0.60		<2.6		0.04	(3)
HNCO	$11_{0, 11} - 10_{0, 10}$	70	241.77403	$0.93\pm0.02$	4.9	$4.87\pm0.26$	34.6	0.04	
HNCO	11 <sub>1, 10</sub> -10 <sub>1, 9</sub>	113	242.63970	$0.79\pm0.02$	5.0	$4.18\pm0.27$	34.7	0.04	
HNCO	$16_{1, 16} - 15_{1, 15}$	186	350.33306	$0.69\pm0.04$	5.1	$3.73\pm0.44$	34.5	0.08	
HNCO	164, 13-154, 12	794	351.24085	< 0.25	•••	<1.1		0.08	(3)
HNCO	16 <sub>3, 14</sub> –15 <sub>3, 13</sub>	518	351.41680	$0.33\pm0.04$	5.2	$1.83\pm0.45$	34.4	0.08	(2)
HNCO	$16_{2, 15} - 15_{2, 14}$	314	351.53780	$0.43\pm0.03$	5.4	$2.47\pm0.49$	34.1	0.08	
HNCO	$16_{2, 14} - 15_{2, 13}$	314	351.55157	$0.46\pm0.03$	5.8	$2.82\pm0.53$	35.2	0.08	
HNCO	$16_{0, 16} - 15_{0, 15}$	143	351.63326	$0.72\pm0.04$	4.0	$3.02\pm0.41$	34.6	0.08	
HNCO	231, 23-240, 24	333	351.99487	$0.33\pm0.03$	5.5	$1.91\pm0.47$	35.9	0.08	
CH <sub>3</sub> CN	14 <sub>10</sub> –13 <sub>10</sub>	806	257.03344	$0.14\pm0.02$	2.4	$0.36\pm0.10$	34.0	0.03	(2)
CH <sub>3</sub> CN	$14_{9}-13_{-9}$	671	257.12704	< 0.35		<1.5		0.03	(2) (4)
CH <sub>3</sub> CN	14 <sub>8</sub> –13 <sub>8</sub>	549	257.21088	$0.24\pm0.01$	6.3	$1.64\pm0.27$	34.9	0.03	(2)
CH <sub>3</sub> CN	14 <sub>7</sub> –13 <sub>7</sub>	442	257.28494	$0.42\pm0.02$	4.9	$2.20\pm0.21$	34.3	0.03	(2)
CH <sub>3</sub> CN	$14_{6} - 13_{-6}$	350	257.34918	$0.90\pm0.02$	4.7	$4.51\pm0.20$	34.4	0.03	(2)
$CH_3CN$	14 <sub>5</sub> –13 <sub>5</sub>	271	257.40358	<1.00	•••	<4.3		0.03	(2) (3)
CH <sub>3</sub> CN	144–134	207	257.44813	$1.14 \pm 0.02$	4.3	$5.22 \pm 0.19$	34.4	0.03	(2)
CH <sub>3</sub> CN	$14_{3}-13_{-3}$	157	257.48279	$1.55 \pm 0.02$	4.6	$7.55 \pm 0.20$	34.5	0.03	(2)
CH <sub>3</sub> CN	142-132	121	257.50756	$1.56 \pm 0.02$	4.4	$7.34 \pm 0.20$	34.6	0.03	(2)
CH <sub>3</sub> CN	141-131	100	257.52243	$1.63 \pm 0.02$	3.8	$6.61 \pm 0.18$	34.7	0.03	(2)
CH <sub>3</sub> CN	$14_0 - 13_0$	93	257.52738	$1.69 \pm 0.02$	4.3	$7.79 \pm 0.18$	34.4	0.03	
CH <sub>3</sub> CN	196-18-6	425	349.21231	$0.73 \pm 0.04$	3.9	$3.07 \pm 0.35$	34.2	0.08	(2)
CH <sub>3</sub> CN	19 <sub>5</sub> –18 <sub>5</sub>	346	349.28601	$0.81 \pm 0.04$	3.4	$2.97 \pm 0.30$	34.3	0.08	(2)
CH <sub>3</sub> CN	194–184	282	349.34634	$0.92 \pm 0.03$	4.3	$4.18 \pm 0.40$	34.4	0.08	(2)
CH <sub>3</sub> CN	193-18-3	232	349.39330	$1.24 \pm 0.03$	4.1	$5.38 \pm 0.39$	34.4	0.08	(5)
CH <sub>3</sub> CN	192-182	196	349.42685	$1.04 \pm 0.04$	4.2	$4.72 \pm 0.37$	34.6	0.08	(2)
CH <sub>3</sub> CN	191-181	175	349.44699	$1.25 \pm 0.03$	4.1	$5.42 \pm 0.38$	34.5	0.08	(5)
CH <sub>3</sub> CN	190-180	168	349.45370	$1.23 \pm 0.04$	3.9	$5.10 \pm 0.38$	34.2	0.08	
TCH <sub>3</sub> CN HC <sub>2</sub> N	$19_0 - 18_0$ 27 - 26	163 165	339.36630 245.60632	< 0.11 $1.55 \pm 0.03$	 4 2	< 0.45 7 02 + 0 25	 34 3	0.05	
110311	21 20	105	2-13.00032	$1.55 \pm 0.05$	7.4	1.02 ± 0.23	54.5	0.04	-

Note. (1) Blend of three hyperfine components. (2) Blend of three two components. (3) Blend with CH<sub>3</sub>OH. (4) Blend with HCOOCH<sub>3</sub>. (5) Blend of four hyperfine components.

Molecule	Transition	$E_u$ (K)	Frequency (GHz)	$T_{\rm br}$ (K)	$\Delta V$ (km s <sup>-1</sup> )	$\int T_{\rm br} dV$ (K km s <sup>-1</sup> )	$V_{\rm LSR}$ (km s <sup>-1</sup> )	rms (K)	Note
SiO	6.5	44	260 51801	$0.64 \pm 0.02$	27	$\frac{186 \pm 0.13}{186 \pm 0.13}$	34.1	0.03	
SO	$N_{r} = 6_{c} - 5_{c}$	56	258 25583	$5.04 \pm 0.02$ $5.34 \pm 0.02$	3.6	$20.20 \pm 0.19$	34.1	0.03	
50	$N_{1} = 0_{6} = 0_{5}$ $N_{2} = 3_{2} = 2_{2}$	26	339 34146	$0.49 \pm 0.02$	3.0	$1.76 \pm 0.34$	34.0	0.05	
SO	$N_{J} = 8_{3} - 7_{4}$	81	340 71416	$3.85 \pm 0.04$	3.9	$15.81 \pm 0.39$	34.2	0.07	
<sup>34</sup> SO	$N_{J} = 3_{2} - 2_{2}$	25	337.89225	<0.15		<0.6		0.07	
<sup>34</sup> SO	$N_{I} = 8_{0} - 7_{0}$		339.85727	$0.69 \pm 0.04$	44	$3.26 \pm 0.38$	33.0	0.07	
<sup>33</sup> SO	$N_1 = 6_7 - 5_6$	47	259.28403	$0.34 \pm 0.07$	6.8	$0.81 \pm 0.06$	33.5	0.03	(1)(2)
CS	5-4	35	244.93556	$14.57 \pm 0.03$	3.2	$49.51 \pm 0.20$	33.9	0.04	
C <sup>33</sup> S	5-4	35	242.91361	$1.31 \pm 0.02$	3.7	$5.18 \pm 0.21$	34.2	0.04	
C <sup>33</sup> S	7–6	65	340.05257	$1.05 \pm 0.04$	3.9	$4.35 \pm 0.34$	34.3	0.07	
C <sup>34</sup> S	7–6	65	337.39646	$2.46\pm0.04$	3.3	$8.65\pm0.31$	34.1	0.07	
H <sub>2</sub> CS	$7_{1} - 6_{1} - 5_{1}$	60	244.04850	$2.91\pm0.03$	3.0	$9.37\pm0.19$	34.2	0.04	
H <sub>2</sub> CS	$10_{1,10}-9_{1,9}$	102	338.08319	$1.68\pm0.04$	3.9	$7.04\pm0.36$	34.2	0.07	
OCS	20–19	123	243.21804	$1.82\pm0.03$	4.2	$8.17\pm0.24$	34.3	0.04	
OCS	28-27	237	340.44927	$1.26\pm0.04$	4.0	$5.40\pm0.39$	34.5	0.07	
OCS	29–28	254	352.59957	$1.05\pm0.04$	4.5	$5.01\pm0.40$	34.3	0.08	
O <sup>13</sup> CS	20-19	122	242.43543	$0.20\pm0.02$	4.8	$1.00\pm0.32$	34.9	0.04	
SO <sub>2</sub>	$5_{2, 4} - 4_{1, 3}$	24	241.61580	$0.88\pm0.02$	5.1	$4.79\pm0.28$	34.2	0.04	(3)
SO <sub>2</sub>	268, 18-277, 21	480	243.24543	< 0.10		< 0.4		0.04	
$SO_2$	$14_{0, 14} - 13_{1, 13}$	94	244.25422	$1.15\pm0.02$	6.3	$7.67\pm0.33$	34.2	0.04	
$SO_2$	263, 23-254, 22	351	245.33923	$0.41\pm0.02$	2.8	$1.21\pm0.15$	34.5	0.04	
$SO_2$	103, 7-102, 8	73	245.56342	$1.04\pm0.02$	5.3	$5.86 \pm 0.27$	34.3	0.04	
SO <sub>2</sub>	73, 5-72, 6	48	257.09997	$0.96\pm0.02$	5.6	$5.76\pm0.24$	34.2	0.03	(4)
SO <sub>2</sub>	324, 28-323, 29	531	258.38872	$0.46\pm0.02$	4.1	$2.01\pm0.21$	33.9	0.03	
SO <sub>2</sub>	207, 13-216, 16	313	258.66697	$0.32\pm0.07$	3.4	$0.76\pm0.08$	33.1	0.03	(2)
$SO_2$	93, 7-92, 8	63	258.94220	$0.91\pm0.02$	5.4	$5.26\pm0.23$	34.4	0.03	
SO <sub>2</sub>	184, 14-183, 15	197	338.30599	$0.65\pm0.03$	4.4	$3.09\pm0.37$	34.0	0.07	
SO <sub>2</sub>	201, 19-192, 18	199	338.61181	< 0.90		<3.8		0.07	(5)
SO <sub>2</sub>	282, 26-281, 27	392	340.31641	$0.48\pm0.03$	6.0	$3.02\pm0.50$	34.5	0.07	
SO <sub>2</sub>	53, 3-42, 2	36	351.25722	$0.75\pm0.04$	5.9	$4.73\pm0.51$	34.1	0.08	
SO <sub>2</sub>	$14_{4, 10}$ $-14_{3, 11}$	136	351.87387	$0.70\pm0.03$	4.4	$3.32\pm0.38$	34.0	0.08	
<sup>34</sup> SO <sub>2</sub>	$14_{0, 14} - 13_{1, 13}$	94	244.48152	$0.34\pm0.02$	1.5	$0.54\pm0.09$	33.6	0.04	
<sup>13</sup> CH <sub>3</sub> SH	14 <sub>1, 14</sub> –13 <sub>1, 13</sub> A	131	350.00956	< 0.15		< 0.7		0.08	

 Table A3

 Line Parameters for Si- and S-bearing Molecules

Note. (1) Blend of four hyperfine components. (2) The integrated intensity is calculated by directly integrating the spectrum. (3) Partial blend with HNCO. (4) Blend with HCOOCH<sub>3</sub>. (5) Blend with CH<sub>3</sub>OH.

 $\label{eq:table A4} \mbox{Line Parameters for CH}_3 OH, \ ^{13} CH_3 OH, \ and \ CH}_2 DOH$ 

Molecule	Transition	<i>E<sub>u</sub></i> (K)	Frequency (GHz)	T <sub>br</sub> (K)	$\Delta V$ (km s <sup>-1</sup> )	$\frac{\int T_{\rm br} dV}{({\rm K \ km \ s^{-1}})}$	$V_{\rm LSR}$ (km s <sup>-1</sup> )	rms (K)	Note
CH <sub>3</sub> OH	25 <sub>3</sub> A <sup>-</sup> -25 <sub>2</sub> A <sup>+</sup>	804	241.58876	$0.72\pm0.02$	4.5	$3.49\pm0.25$	34.5	0.04	
CH <sub>3</sub> OH	5 <sub>0</sub> E–4 <sub>0</sub> E	48	241.70016	$2.45\pm0.03$	4.0	$10.57\pm0.24$	34.2	0.04	
CH <sub>3</sub> OH	$5_{-1} E - 4_{-1} E$	40	241.76723	$3.70\pm0.03$	3.2	$12.53\pm0.20$	34.2	0.04	
CH <sub>3</sub> OH	$5_0 \text{ A}^+ - 4_0 \text{ A}^+$	35	241.79135	$4.15\pm0.03$	3.0	$13.29\pm0.19$	34.1	0.04	
CH <sub>3</sub> OH	$5_4 \text{ A}^ 4_4 \text{ A}^-$	115	241.80652	$1.46 \pm 0.02$	4.3	$6.65 \pm 0.23$	34.7	0.04	(1)
CH <sub>3</sub> OH	$5_{-4} E_{-4_{-4}} E_{-4_{-4}}$	123	241.81325	$1.33 \pm 0.02$	4.3	$6.13 \pm 0.23$	34.7	0.04	
CH <sub>3</sub> OH	$5_3 A' - 4_3 A'$	85	241.83272	$2.08 \pm 0.02$	4.2	$9.35 \pm 0.25$	34.3	0.04	(2)
CH <sub>3</sub> OH	$5_2 \mathbf{A} - 4_2 \mathbf{A}$	/3	241.84228	$2.13 \pm 0.02$	5.0	$11.37 \pm 0.26$ 7.12 + 0.22	33.7	0.04	(1)
	$5_{-3} E_{-4_{-3}} E_{-5_{-5}} E_{-4_{-5}} E_{-5_{-5}} E_{-5_{-5$	90 56	241.83230	$1.34 \pm 0.02$ $2.26 \pm 0.03$	4.4	$7.13 \pm 0.23$ 0.26 ± 0.23	34.0	0.04	
CH <sub>2</sub> OH	$5_1 L^{-4_1} L^{-4_2}$ $5_2 A^+ - 4_2 A^+$	73	241.87703	$1.82 \pm 0.03$	3.9	$7.20 \pm 0.23$ $7.63 \pm 0.23$	34.5	0.04	
CH <sub>2</sub> OH	$5_{2}E_{-4} = E_{-4}$	61	241.90415	$2.94 \pm 0.03$	3.8	$11.83 \pm 0.21$	34.0	0.04	(1)
CH <sub>3</sub> OH	$14_{-1} E - 13_{-2} E$	249	242.44608	$1.28 \pm 0.02$	4.8	$6.55 \pm 0.25$	34.6	0.04	(3)
CH <sub>3</sub> OH	$24_3 \text{ A}^ 24_2 \text{ A}^+$	746	242.49024	$0.88\pm0.02$	4.6	$4.30\pm0.25$	34.4	0.04	
CH <sub>3</sub> OH	$5_1 A^ 4_1 A^-$	50	243.91579	$2.75\pm0.02$	3.6	$10.69\pm0.21$	34.3	0.04	
CH <sub>3</sub> OH	22 <sub>3</sub> A <sup>-</sup> -22 <sub>2</sub> A <sup>+</sup>	637	244.33037	$1.06\pm0.02$	4.9	$5.54\pm0.27$	34.6	0.04	
CH <sub>3</sub> OH	$9_1 \text{ E} - 8_0 \text{ E}, \nu_t = 1$	396	244.33798	$1.08\pm0.02$	4.7	$5.38\pm0.25$	34.6	0.04	
CH <sub>3</sub> OH	$18_{-6} \text{ E}_{-17_{-7}} \text{ E}, \nu_t = 1$	889	245.09450	$0.31\pm0.02$	4.1	$1.35\pm0.26$	34.3	0.04	
CH <sub>3</sub> OH	$21_3 \text{ A}^ 21_2 \text{ A}^+$	586	245.22302	$1.22\pm0.03$	4.2	$5.50\pm0.24$	34.4	0.04	
CH <sub>3</sub> OH	$18_3 \text{ A}^+ - 18_2 \text{ A}^-$	447	257.40209	$1.50\pm0.02$	6.0	$9.52\pm0.25$	34.0	0.03	(4)
CH <sub>3</sub> OH	$19_3 \text{ A}^+ - 19_2 \text{ A}^-$	491	258.78025	$1.22 \pm 0.02$	5.4	$7.05 \pm 0.23$	34.1	0.03	
CH <sub>3</sub> OH	$17_2 \text{ A}^ 16_1 \text{ A}^-, \nu_t = 1$	653	259.27369	$0.79 \pm 0.02$	4.2	$3.54 \pm 0.19$	34.6	0.03	•••
CH <sub>3</sub> OH	$24_1 E - 24_0 E$	717	259.58140	$0.62 \pm 0.02$	4.4	$2.89 \pm 0.18$	34.7	0.03	
CH <sub>3</sub> OH	$20_{-8} \text{ E} = 21_{-7} \text{ E}$	808 527	260.06432	$0.43 \pm 0.02$	3.8	$1.75 \pm 0.17$	34.8	0.03	•••
	$20_3 \text{ A} - 20_2 \text{ A}$ 7 $A^+ 6 A^+ \mu - 2$	557 670	200.38140	$1.22 \pm 0.01$ 0.59 ± 0.04	4.7	$0.02 \pm 0.23$ 2.68 ± 0.40	54.5 34.5	0.05	(1)
CH <sub>3</sub> OH	$7_4 \text{ A} - 0_4 \text{ A} , \nu_t = 2$ 7 a E-6 a E $\mu = 2$	710	337.27350	$0.59 \pm 0.04$ 0.54 ± 0.03	4.5	$2.03 \pm 0.49$ 1 54 ± 0.48	34.8	0.07	(1)
CH <sub>2</sub> OH	$7_{-2} = 0_{-2} = 0_{-2} = 0_{-2}$ $7_0 = A^+ - 6_0 = A^+ = 0_{-2} = 2$	573	337 28432	$0.34 \pm 0.03$ $0.78 \pm 0.03$	53	$436 \pm 0.45$	34.7	0.07	
CH <sub>2</sub> OH	$7_0 A^+ - 6_1 A^+, \nu_t = 1$	390	337.29748	$0.97 \pm 0.03$	4.1	$4.25 \pm 0.19$	35.3	0.07	(1)
CH <sub>3</sub> OH	$7_2 \text{ E-}6_2 \text{ E}, \nu_t = 2$	651	337.30264	$0.65 \pm 0.03$	4.2	$2.94 \pm 0.39$	34.5	0.07	
CH <sub>3</sub> OH	$7_{-1} \text{ E}_{-6_{-1}} \text{ E}, \nu_t = 2$	597	337.31236	$0.57\pm0.04$	4.7	$2.87\pm0.41$	34.3	0.07	
CH <sub>3</sub> OH	$7_6 A^+ - 6_6 A^+, \nu_t = 1$	533	337.46370	$0.62\pm0.04$	5.5	$3.62\pm0.47$	34.6	0.07	(1)
CH <sub>3</sub> OH	$10_0 \text{ E-}9_{-9} \text{ E}, \nu_t = 1$	916	337.47259	$0.40\pm0.04$	5.6	$2.38\pm0.47$	33.8	0.07	
CH <sub>3</sub> OH	$7_{-6}$ E– $6_{-6}$ E, $\nu_t = 1$	558	337.49056	$0.71\pm0.04$	4.3	$3.23\pm0.36$	34.8	0.07	(5)
CH <sub>3</sub> OH	$7_3 \text{ E-}6_3 \text{ E}, \nu_t = 1$	482	337.51914	$0.80\pm0.04$	4.3	$3.68\pm0.38$	34.9	0.07	
CH <sub>3</sub> OH	$7_5 A^+ - 6_5 A^+, \nu_t = 1$	485	337.54612	$0.84 \pm 0.04$	4.7	$4.19 \pm 0.39$	34.7	0.07	(1)
CH <sub>3</sub> OH	$7_4 \text{ E6}_4 \text{ E}, \nu_t = 1$	428	337.58168	<1.00		<4.3		0.07	(6)
CH <sub>3</sub> OH	$7_{-2} \to 6_{-2} \to \nu_t = 1$	429	337.60529	$0.87 \pm 0.03$	3.8	$3.51 \pm 0.53$	35.0	0.07	
	$7_{-3} = 0$	262	227 62575	$1.01 \pm 0.03$ $1.02 \pm 0.04$	5.7	$4.05 \pm 0.32$ $3.71 \pm 0.30$	34.0 24.7	0.07	(1)
CH <sub>3</sub> OH	$7_2 A^ 6_2 A^-, \nu_t = 1$ $7_2 A^ 6_2 A^-, \nu_t = 1$	364	337 63575	$1.03 \pm 0.04$ $1.00 \pm 0.03$	5.4 4 1	$434 \pm 0.39$	34.6	0.07	
CH <sub>2</sub> OH	$7_2 \text{ K} = 6_2 \text{ K}, \nu_t = 1$	365	337 64391	$1.00 \pm 0.03$ $1.26 \pm 0.03$	79	$10.58 \pm 0.59$	34.3	0.07	(2)
CH <sub>2</sub> OH	$7_0 B^+ = 6_0 B^+, \nu_t = 1$	461	337.65520	$0.98 \pm 0.03$	3.2	$334 \pm 033$	34.4	0.07	(1)
CH <sub>3</sub> OH	$7_4 A^+ - 6_4 A^+, \nu_t = 1$	546	337.68561	$0.92 \pm 0.04$	4.0	$3.89 \pm 0.37$	34.9	0.07	(2)
CH <sub>3</sub> OH	$7_{-1}$ E- $6_{-1}$ E, $\nu_t = 1$	478	337.70757	$0.83\pm0.04$	4.9	$4.39\pm0.44$	34.5	0.07	
CH <sub>3</sub> OH	$7_0 A^+ - 6_0 A^+, \nu_t = 1$	488	337.74883	$0.88\pm0.04$	4.2	$3.96\pm0.36$	34.9	0.07	
CH <sub>3</sub> OH	20 <sub>-6</sub> E-21 <sub>-5</sub> E	676	337.83780	$0.45\pm0.04$	3.5	$1.69\pm0.30$	34.6	0.07	
CH <sub>3</sub> OH	$7_1 \text{ A}^ 6_1 \text{ A}^-, \nu_t = 2$	748	337.87755	$0.51\pm0.04$	3.2	$1.75\pm0.28$	34.6	0.07	
CH <sub>3</sub> OH	$7_1 \text{ A}^ 6_1 \text{ A}^-, \nu_t = 1$	390	337.96944	$0.89\pm0.04$	4.4	$4.13\pm0.38$	34.5	0.07	
CH <sub>3</sub> OH	$7_0 E - 6_0 E$	78	338.12449	$2.19 \pm 0.04$	3.4	$7.84 \pm 0.30$	34.4	0.07	
CH <sub>3</sub> OH	$7_{-1} E_{-6_{-1}} E_{-6_{-1$	71	338.34459	$2.91 \pm 0.04$	3.5	$10.81 \pm 0.32$	34.2	0.07	
CH <sub>3</sub> OH	$7_6 E - 6_6 E$	244	338.40461	$0.98 \pm 0.04$	3.8	$4.00 \pm 0.33$	34.7	0.07	
	$7_0 A^2 - b_0 A^2$	05 254	338.40870	$3.41 \pm 0.03$	2.9	$10.59 \pm 0.28$	34.1 24.6	0.07	•••
CH <sub>3</sub> OH	$7_{-6} = 0_{-6} = 0_{-6}$	254	338 44237	$0.88 \pm 0.03$ $1.04 \pm 0.04$	4.0	$4.23 \pm 0.38$ $4.79 \pm 0.36$	34.0 34.7	0.07	(1)
CH <sub>2</sub> OH	7 - F-6 - F	189	338 45654	$1.12 \pm 0.04$	4.3 4.7	$5.62 \pm 0.30$	34.5	0.07	
CH <sub>2</sub> OH	75 E-65 E	201	338 47523	$1.12 \pm 0.03$ $1.15 \pm 0.03$	4 1	$5.02 \pm 0.39$ $5.02 \pm 0.34$	34.6	0.07	
CH <sub>3</sub> OH	$7_5 A^+ - 6_5 A^+$	203	338.48632	$1.22 \pm 0.03$	4.9	$6.42 \pm 0.42$	34.5	0.07	(1)
CH <sub>3</sub> OH	7 <sub>-4</sub> E-6 <sub>-4</sub> E	153	338.50407	$1.31 \pm 0.03$	4.7	$6.52 \pm 0.41$	34.8	0.07	
CH <sub>3</sub> OH	7 <sub>4</sub> E–6 <sub>4</sub> E	161	338.53026	$1.30\pm0.04$	4.2	$5.87\pm0.35$	34.4	0.07	
CH <sub>3</sub> OH	7 <sub>3</sub> A <sup>+</sup> -6 <sub>3</sub> A <sup>+</sup>	115	338.54083	$1.95\pm0.04$	5.5	$11.45\pm0.47$	33.3	0.07	(1)
CH <sub>3</sub> OH	7 <sub>-3</sub> E-6 <sub>-3</sub> E	128	338.55996	$1.40\pm0.04$	4.5	$6.74\pm0.38$	34.4	0.07	
CH <sub>3</sub> OH	7 <sub>3</sub> E–6 <sub>3</sub> E	113	338.58322	$1.46\pm0.04$	4.3	$6.70\pm0.37$	34.6	0.07	

				(Continued)					
Molecule	Transition	<i>E<sub>u</sub></i> (K)	Frequency (GHz)	T <sub>br</sub> (K)	$\Delta V$ (km s <sup>-1</sup> )	$\int T_{\rm br} dV \\ ({\rm K \ km \ s^{-1}})$	$V_{\rm LSR}$ (km s <sup>-1</sup> )	rms (K)	Note
CH <sub>3</sub> OH	7 <sub>1</sub> E–6 <sub>1</sub> E	86	338.61494	$1.95\pm0.04$	4.4	$9.18\pm0.38$	34.4	0.07	
CH <sub>3</sub> OH	$7_2 \text{ A}^+ - 6_2 \text{ A}^+$	103	338.63980	$1.60\pm0.04$	4.1	$6.97\pm0.34$	34.5	0.07	
CH <sub>3</sub> OH	7 <sub>-2</sub> E-6 <sub>-2</sub> E	91	338.72290	$2.52\pm0.04$	4.1	$10.98\pm0.35$	34.9	0.07	(1)
CH <sub>3</sub> OH	$21_3 \text{ E} - 21_2 \text{ E}, \nu_t = 1$	951	339,42217	< 0.18		< 0.8		0.07	
CH <sub>3</sub> OH	$2_2 A^+ - 3_1 A^+$	45	340.14114	$1.08 \pm 0.03$	4.4	$5.05 \pm 0.38$	35.2	0.07	
CH <sub>3</sub> OH	$16_6 \text{ A}^ 17_5 \text{ A}^-$	509	340.39366	$0.90 \pm 0.04$	4.0	$3.87 \pm 0.34$	34.7	0.07	
CH <sub>2</sub> OH	$11_1 \text{ E} - 10_0 \text{ E}, \nu_t = 1$	444	340.68397	$0.98 \pm 0.03$	5.1	$5.29 \pm 0.46$	34.8	0.07	
CH <sub>3</sub> OH	$15_3 \text{ E} - 16_4 \text{ E}, \nu_t = 1$	695	350.28649	$0.70 \pm 0.03$	4.9	$3.65 \pm 0.42$	34.6	0.08	
CH <sub>3</sub> OH	$4_0 E = 3_1 E$	36	350.68766	$1.87 \pm 0.04$	4.6	$9.18 \pm 0.40$	34.1	0.08	
CH <sub>2</sub> OH	$18_2 \text{ E} - 18_2 \text{ E}, \nu_t = 1$	812	350.72388	< 0.25		<1.1		0.08	
CH <sub>2</sub> OH	$1 A^+ - 0 A^+$	17	350,90510	$2.38 \pm 0.04$	3.7	$9.29 \pm 0.33$	34.4	0.08	
СН3ОН	9 <sub>5</sub> E–10 <sub>4</sub> E	241	351.23648	$0.97 \pm 0.04$	4.7	$4.82 \pm 0.40$	34.5	0.08	
<sup>13</sup> CH <sub>3</sub> OH	$4_2 A^ 5_1 A^-$	60	242.37315	$0.17\pm0.02$	5.1	$0.93\pm0.27$	36.3	0.04	
<sup>13</sup> CH <sub>3</sub> OH	$15_3 \text{ A}^+ - 15_2 \text{ A}^-$	322	257.42179	$0.48\pm0.02$	3.9	$2.02\pm0.18$	34.5	0.03	
<sup>13</sup> CH <sub>3</sub> OH	$16_3 \text{ A}^+ - 16_2 \text{ A}^-$	358	258.15300	$0.59\pm0.02$	4.6	$2.90\pm0.19$	34.8	0.03	(7)
<sup>13</sup> CH <sub>3</sub> OH	$17_3 \text{ A}^+ - 17_2 \text{ A}^-$	396	259.03649	< 0.20		< 0.9		0.03	(8)
<sup>13</sup> CH <sub>3</sub> OH	$2_1 E - 1_0 E$	28	259.98653	$0.54\pm0.02$	2.9	$1.68\pm0.16$	34.5	0.03	(9)
<sup>13</sup> CH <sub>3</sub> OH	$13_0 \text{ A}^+ - 12_1 \text{ A}^+$	206	338.75995	$0.60\pm0.04$	3.7	$2.33\pm0.32$	34.4	0.07	
<sup>13</sup> CH <sub>3</sub> OH	$1_1 \text{ A}^+ - 0_0 \text{ A}^+$	17	350.10312	$0.58\pm0.04$	3.1	$1.87\pm0.28$	34.7	0.08	
<sup>13</sup> CH <sub>3</sub> OH	81 E-72 E	103	350.42158	$0.49\pm0.04$	4.6	$2.38\pm0.41$	34.0	0.08	
CH <sub>2</sub> DOH	$11_{2, 9}o_1 - 11_{1, 10}o_1$	177	242.03360	$0.32\pm0.03$	1.8	$0.60\pm0.14$	33.2	0.04	
CH <sub>2</sub> DOH	$5_{2, 3}e_0 - 5_{1, 4}e_0$	48	243.22599	$0.56\pm0.02$	2.9	$1.74 \pm 0.17$	35.5	0.04	
$CH_2DOH$	$4_{2, 2}e_0-4_{1, 3}e_0$	38	244.84113	$0.35\pm0.02$	4.2	$1.55\pm0.25$	34.4	0.04	
$CH_2DOH$	$10_{2, 8}o_1 - 10_{1, 9}o_1$	153	244.98885	$0.13\pm0.02$	3.9	$0.54 \pm 0.22$	34.7	0.04	
CH <sub>2</sub> DOH	$5_{2, 3}o_1 - 5_{1, 4}o_1$	68	257.39451	$0.26\pm0.02$	2.2	$0.61\pm0.10$	34.4	0.03	
CH <sub>2</sub> DOH	$4_{2, 3}e_1 - 3_{1, 3}o_1$	48	257.89567	$0.30\pm0.02$	2.3	$0.72\pm0.09$	34.6	0.03	
CH <sub>2</sub> DOH	$4_{2, 3}e_0 - 4_{1, 4}e_0$	38	258.33711	$0.42\pm0.02$	2.8	$1.25\pm0.12$	34.3	0.03	
CH <sub>2</sub> DOH	$9_{0, 9}e_0 - 8_{1, 8} e_0$	96	337.34866	$0.63\pm0.04$	2.8	$1.84\pm0.25$	35.1	0.07	
CH <sub>2</sub> DOH	$6_{1, 6}e_0 - 5_{0, 5}e_0$	48	338.95711	$0.39\pm0.04$	3.5	$1.46\pm0.32$	35.1	0.07	
CH <sub>2</sub> DOH	$15_{2, 14}o_1 - 15_{1, 14} e_1$	292	339.48572	$0.24\pm0.03$	2.2	$0.56\pm0.20$	34.9	0.07	
CH <sub>2</sub> DOH	$6_{2, 4}e_1 - 5_{1, 4}o_1$	72	340.12709	$0.42\pm0.03$	3.5	$1.55\pm0.43$	34.8	0.07	
CH <sub>2</sub> DOH	$13_{1,13}e_0 - 12_{0,12} e_1$	196	340.24344	$0.57\pm0.03$	2.9	$1.76\pm0.33$	34.2	0.07	(10)
CH <sub>2</sub> DOH	$2_{2, 1}e_0 - 1_{1, 0}e_0$	23	340.34829	$0.29\pm0.04$	3.7	$1.15\pm0.32$	34.1	0.07	
CH <sub>2</sub> DOH	$13_{4, 9}e_1 - 13_{3, 11}o_1$	267	349.18383	$0.24\pm0.04$	2.2	$0.57\pm0.22$	34.3	0.08	
CH <sub>2</sub> DOH	$12_{4, 8}e_1 - 12_{3, 10}o_1$	239	349.35613	$0.22\pm0.04$	3.1	$0.75\pm0.30$	35.3	0.08	
CH <sub>2</sub> DOH	$11_{4, 8}e_1 - 11_{3, 8}o_1$	213	349.49521	$0.22\pm0.04$	3.7	$0.85\pm0.32$	34.3	0.08	(11)
CH <sub>2</sub> DOH	$11_{4, 7}e_1 - 11_{3, 9}o_1$	213	349.50887	$0.47\pm0.04$	1.6	$0.80\pm0.22$	34.8	0.08	
CH <sub>2</sub> DOH	$10_{4, 6}e_1 - 10_{3, 8} o_1$	190	349.64360	$0.32\pm0.04$	2.8	$0.97\pm0.28$	34.4	0.08	
CH <sub>2</sub> DOH	$9_{4, 5}e_1 - 9_{3, 7}o_1$	168	349.76168	$0.30\pm0.04$	7.2	$2.31\pm0.62$	36.4	0.08	(12)
CH <sub>2</sub> DOH	$8_{4, 5}e_1 - 8_{3, 5}o_1$	149	349.86211	$0.34\pm0.04$	6.0	$2.15\pm0.55$	33.4	0.08	(12)
CH <sub>2</sub> DOH	$7_{4, 4}e_1 - 7_{3, 4}o_1$	132	349.95168	$0.48\pm0.03$	3.4	$1.73\pm0.29$	34.3	0.08	(12)
CH <sub>2</sub> DOH	$6_{4, 3}e_1 - 6_{3, 3}o_1$	117	350.02735	$0.64\pm0.04$	2.4	$1.60\pm0.26$	34.2	0.08	(12)
CH <sub>2</sub> DOH	$5_{4, 2}e_1 - 5_{3, 2} o_1$	104	350.09024	$0.57\pm0.04$	2.0	$1.21\pm0.23$	34.2	0.08	(12)
CH <sub>2</sub> DOH	$4_{4, 1}e_1 - 4_{3, 1}o_1$	94	350.14130	$0.33\pm0.03$	4.0	$1.41\pm0.37$	33.8	0.08	(12)
CH <sub>2</sub> DOH	$6_{2, 5}e_1 - 5_{1, 5}o_1$	72	350.45387	$0.53\pm0.03$	2.6	$1.46\pm0.28$	34.2	0.08	
CH <sub>2</sub> DOH	$5_{1, 4}e_1 - 5_{0, 5}e_0$	49	350.63207	$0.58\pm0.04$	3.2	$1.98\pm0.32$	35.2	0.08	
CH <sub>2</sub> DOH	$2_{2, 1}o_1 - 1_{1, 0}o_1$	42	351.60685	< 0.15		< 0.7		0.08	
CH <sub>2</sub> DOH	$8_{1, 8}e_0 - 7_{1, 7}e_0$	80	351.79643	$0.54\pm0.04$	2.5	$1.44\pm0.30$	34.4	0.08	
CH <sub>2</sub> DOH	$2_{2, 0}o_1 - 1_{1, 1}o_1$	42	352.34437	< 0.15		< 0.7		0.08	
CH <sub>2</sub> DOH	$8_{1, 8}e_1 - 7_{1, 7}e_1$	93	352.80196	$0.40\pm0.04$	2.6	$1.10\pm0.23$	34.4	0.08	

Table A4

**Note.** (1) Blend of two  $CH_3OH$  lines with similar spectroscopic constants. (2) Blend of three  $CH_3OH$  lines with similar spectroscopic constants. (3) Possible blend with  $C_2H_5OH$ . (4) Blend with  $CH_3CN$ . (5) Blend with HCOOCH<sub>3</sub>. (6) Blend with <sup>34</sup>SO. (7) Partial blend with  $HC^{15}N$ . (8) Possible blend with HDCO. (9) Blend with  $CH_3OCH_3$ . (10) Partial blend with CN. (11) Tentative detection. (12) Blend of two  $CH_2DOH$  lines with similar spectroscopic constants.

 $\begin{array}{c} \textbf{Table A5} \\ \text{Line Parameters for } C_2H_5OH \end{array}$ 

Molecule	Transition	$E_u$	Frequency	$T_{ m br}$	$\Delta V$	$\int T_{\rm br} dV$	VLSR	rms	Note
		(K)	(GHz)	(K)	$({\rm km \ s^{-1}})$	$(K \text{ km s}^{-1})$	$({\rm km}~{\rm s}^{-1})$	(K)	
C <sub>2</sub> H <sub>5</sub> OH	1411, 3-1311, 2	297	242.17548	$0.15\pm0.02$	5.4	$0.87\pm0.40$	34.7	0.04	(1)
C <sub>2</sub> H <sub>5</sub> OH	14 <sub>9, 5</sub> –13 <sub>9, 4</sub>	248	242.22129	$0.16\pm0.02$	5.5	$0.93\pm0.29$	33.7	0.04	(1)
C <sub>2</sub> H <sub>5</sub> OH	14 <sub>8,6</sub> –13 <sub>8,5</sub>	228	242.27115	$0.13\pm0.02$	4.1	$0.57\pm0.23$	34.6	0.04	(1)
C <sub>2</sub> H <sub>5</sub> OH	147, 8-137, 7	209	242.34984	$0.30\pm0.02$	4.1	$1.30\pm0.23$	35.7	0.04	(1)
C <sub>2</sub> H <sub>5</sub> OH	$14_{10, 4}$ - $13_{10, 3}$	266	242.42987	$0.36\pm0.02$	1.6	$0.62\pm0.08$	35.3	0.04	(2)
C <sub>2</sub> H <sub>5</sub> OH	146, 9–136, 8	193	242.47550	$0.35\pm0.02$	4.3	$1.60\pm0.23$	34.6	0.04	(1)
C <sub>2</sub> H <sub>5</sub> OH	14 <sub>7,8</sub> -13 <sub>7,7</sub>	204	242.52422	$0.37\pm0.02$	1.5	$0.57\pm0.08$	34.9	0.04	(1)
C <sub>2</sub> H <sub>5</sub> OH	146, 9–136, 8	188	242.62561	$0.42\pm0.02$	1.5	$0.67\pm0.08$	34.6	0.04	(1)
C <sub>2</sub> H <sub>5</sub> OH	145, 10-135, 9	180	242.68502	$0.13\pm0.02$	3.6	$0.51\pm0.19$	34.6	0.04	(1)
C <sub>2</sub> H <sub>5</sub> OH	145, 9-135, 8	180	242.69305	$0.35\pm0.02$	1.5	$0.56\pm0.08$	34.7	0.04	
C <sub>2</sub> H <sub>5</sub> OH	143, 12-133, 11	160	242.77011	$0.15\pm0.02$	3.4	$0.55\pm0.17$	35.2	0.04	
C <sub>2</sub> H <sub>5</sub> OH	145, 10-135, 9	175	242.81644	$0.09\pm0.02$	3.3	$0.33\pm0.18$	33.8	0.04	(3)
C <sub>2</sub> H <sub>5</sub> OH	145, 9-135, 8	175	242.82512	$0.10\pm0.02$	3.9	$0.42\pm0.21$	35.6	0.04	
C <sub>2</sub> H <sub>5</sub> OH	$14_{4,11} - 13_{4,10}$	169	242.99597	$0.28\pm0.03$	3.1	$0.91\pm0.19$	34.2	0.04	
C <sub>2</sub> H <sub>5</sub> OH	$14_{4,11} - 13_{4,10}$	164	243.12034	$0.38\pm0.02$	1.5	$0.58 \pm 0.08$	35.2	0.04	
C <sub>2</sub> H <sub>5</sub> OH	144, 10-134, 9	169	243.20653	$0.36\pm0.02$	1.7	$0.64\pm0.09$	34.3	0.04	
C <sub>2</sub> H <sub>5</sub> OH	141, 13-131, 12	152	244.63396	$0.24\pm0.02$	3.8	$0.99 \pm 0.21$	34.5	0.04	
C <sub>2</sub> H <sub>5</sub> OH	$14_{3}$ $11-13_{3}$ $10$	160	245.32715	$0.39\pm0.02$	1.4	$0.60\pm0.08$	34.6	0.04	
C <sub>2</sub> H <sub>5</sub> OH	$16_{1}$ $15-15_{2}$ $14$	117	257.06090	$0.26\pm0.02$	5.3	$1.49 \pm 0.23$	34.1	0.03	
C <sub>2</sub> H <sub>5</sub> OH	143 11-132 11	156	259.32264	$0.09 \pm 0.02$	4.3	$0.40 \pm 0.19$	34.2	0.03	(3)
C <sub>2</sub> H <sub>5</sub> OH	150 6-140 5	261	259,53913	$0.28\pm0.02$	2.4	$0.71 \pm 0.10$	34.4	0.03	(1)
C <sub>2</sub> H <sub>5</sub> OH	157 9-147 8	222	259.69790	$0.11 \pm 0.02$	4.7	$0.57 \pm 0.21$	34.4	0.03	(1)
C <sub>2</sub> H <sub>5</sub> OH	$15_{10}$ 5-14 <sub>10</sub> 4	279	259.75653	$0.27 \pm 0.02$	2.4	$0.69 \pm 0.14$	34.9	0.03	(1)
C <sub>2</sub> H <sub>5</sub> OH	150 6-140 5	255	259,77714	$0.28 \pm 0.02$	1.5	$0.43 \pm 0.07$	34.5	0.03	(1)
C <sub>2</sub> H <sub>5</sub> OH	$15_{8}$ $^{-14_{8}}$ $^{-7}$	235	259.81444	$0.29\pm0.02$	2.3	$0.72\pm0.10$	34.0	0.03	(1)
C <sub>2</sub> H <sub>5</sub> OH	156 10-146 0	206	259.85218	$0.30 \pm 0.02$	2.3	$0.74 \pm 0.10$	34.7	0.03	(1)
C <sub>2</sub> H <sub>5</sub> OH	157 0-147 8	216	259.88507	$0.28\pm0.02$	3.1	$0.93 \pm 0.13$	34.7	0.03	(1)
C <sub>2</sub> H <sub>5</sub> OH	$15_{3}$ $12-14_{3}$ $12$	172	260.04664	$0.28 \pm 0.02$	2.2	$0.64 \pm 0.10$	35.2	0.03	
C <sub>2</sub> H <sub>5</sub> OH	155 11-145 10	192	260.10761	$0.09 \pm 0.01$	4.7	$0.43 \pm 0.24$	34.5	0.03	(3)
C <sub>2</sub> H <sub>5</sub> OH	155 10-145 0	192	260.12276	$0.11 \pm 0.02$	4.6	$0.52 \pm 0.20$	34.5	0.03	
C <sub>2</sub> H <sub>5</sub> OH	153 13-143 12	168	260.14168	$0.29 \pm 0.02$	3.5	$1.06 \pm 0.15$	34.9	0.03	
C <sub>2</sub> H <sub>5</sub> OH	155 10-145 0	187	260.26613	$0.27 \pm 0.02$	2.5	$0.71 \pm 0.11$	33.9	0.03	
C <sub>2</sub> H <sub>5</sub> OH	154 12-144 11	181	260.45773	$0.12 \pm 0.02$	4.4	$0.57 \pm 0.19$	35.1	0.03	
C <sub>2</sub> H <sub>5</sub> OH	$15_{4,12} - 14_{4,11}$	176	260.59133	$0.28 \pm 0.02$	2.4	$0.74 \pm 0.10$	34.5	0.03	
C <sub>2</sub> H <sub>5</sub> OH	$20_{2}$ 10-192 18	234	338.88792	$0.39 \pm 0.04$	5.0	$2.07 \pm 0.43$	35.5	0.07	(4)
C <sub>2</sub> H <sub>5</sub> OH	$16_{7,0} - 16_{6,10}$	176	338 67173	$0.35 \pm 0.04$	47	$1.76 \pm 0.40$	33.4	0.07	(1)
C <sub>2</sub> H <sub>5</sub> OH	$14_7$ $7-14_6$ 8	150	339.06106	$0.28 \pm 0.03$	4.0	$1.21 \pm 0.34$	34.5	0.07	(1)
C <sub>2</sub> H <sub>5</sub> OH	$13_7 - 13_6 7$	138	339.20154	$0.38 \pm 0.03$	1.9	$0.79 \pm 0.25$	33.9	0.07	(1)
C <sub>2</sub> H <sub>5</sub> OH	127, 5-126, 6	127	339.31253	$0.24 \pm 0.03$	4.9	$1.24 \pm 0.40$	35.9	0.07	
C <sub>2</sub> H <sub>2</sub> OH	$11_{7,3} - 11_{6,5}$	117	339,39844	$0.25 \pm 0.03$	4.0	$1.07 \pm 0.33$	34.6	0.07	(1)
C <sub>2</sub> H <sub>5</sub> OH	87 1-86 2	92	339.54409	$0.30 \pm 0.04$	2.1	$0.67 \pm 0.20$	34.4	0.07	(1)
C <sub>2</sub> H <sub>2</sub> OH	$9_{4} = 8_{2} =$	58	339,97892	$0.24 \pm 0.04$	3.8	$0.97 \pm 0.32$	35.0	0.07	
C <sub>2</sub> H <sub>5</sub> OH	$20_{4, 16} - 19_{4, 15}$	252	350.36506	$0.40 \pm 0.04$	3.9	$1.65 \pm 0.33$	35.7	0.08	(5)
C <sub>2</sub> H <sub>2</sub> OH	$20_{2,10} - 19_{1,10}$	179	350.53435	$0.30 \pm 0.04$	3.3	$1.06 \pm 0.00$	34.9	0.08	
C <sub>2</sub> H <sub>5</sub> OH	$13_{5, 8} - 12_{4, 8}$	163	351.96548	$0.25\pm0.03$	2.0	$0.55\pm0.18$	35.3	0.08	

Note. (1) Blend of two  $C_2H_5OH$  lines with similar spectroscopic constants. (2) Blend of four  $C_2H_5OH$  lines with similar spectroscopic constants. (3) Tentative detection. (4) Blend of three  $C_2H_5OH$  lines with similar spectroscopic constants. (5) Possible blend with CH<sub>3</sub>CHO.

Table A6Line Parameters for HCOOCH3

Molecule	Transition	<i>E<sub>u</sub></i> (K)	Frequency (GHz)	T <sub>br</sub> (K)	$\Delta V$ (km s <sup>-1</sup> )	$\frac{\int T_{\rm br} dV}{(\rm K \ km \ s^{-1})}$	$V_{\rm LSR}$ (km s <sup>-1</sup> )	rms (K)	Note
HCOOCH <sub>3</sub>	$20_{4, 17}$ – $19_{4, 16}$ A $\nu_t = 1$	322	242.61007	$0.35\pm0.02$	2.4	$0.92\pm0.14$	34.3	0.04	
HCOOCH <sub>3</sub>	19 <sub>5, 14</sub> –18 <sub>5, 13</sub> A	130	242.89603	$0.74\pm0.02$	3.6	$2.85\pm0.19$	34.5	0.04	
HCOOCH <sub>3</sub>	$19_{4, 15} - 18_{4, 14} \text{ A } \nu_t = 1$	313	244.06667	$0.35\pm0.02$	3.4	$1.28\pm0.18$	34.4	0.04	
HCOOCH <sub>3</sub>	$20_{10, 10} - 19_{10, 9} \to \nu_t = 1$	378	244.11242	$0.13 \pm 0.02$	4.0	$0.56 \pm 0.22$	33.9	0.04	
HCOOCH <sub>3</sub>	$20_{12, 8} - 19_{12, 7} \text{ A } \nu_t = 1$	407	244.19830	$0.17 \pm 0.02$	4.8	$0.89 \pm 0.25$	34.5	0.04	(1)
HCOOCH <sub>3</sub>	$20_{10, 11} - 19_{10, 10} \text{ A } \nu_t = 1$	377	244.52854	$0.38 \pm 0.02$	3.0	$1.21 \pm 0.16$	34.7	0.04	(1)
HCOOCH <sub>3</sub>	$20_{4, 17} - 19_{4, 16} E$	135	244.58054	$0.74 \pm 0.02$ 0.78 ± 0.02	4.0	$3.04 \pm 0.24$ $3.02 \pm 0.10$	34.7 24.9	0.04	•••
HCOOCH <sub>3</sub>	204, 17-194, 16 A 20.4, 17-194, 16 A	301	244.39403	$0.78 \pm 0.02$ $0.29 \pm 0.03$	2.0	$3.02 \pm 0.19$ 0.67 ± 0.12	34.0	0.04	
HCOOCH <sub>3</sub>	$20_{11, 10} - 19_{11, 9} \pm \nu_t = 1$ $20_{0, 10} - 19_{0, 11} + 4 \nu_t = 1$	365	244.72900	$0.29 \pm 0.03$ $0.43 \pm 0.02$	2.2	$0.07 \pm 0.12$ 1 33 + 0 17	34.3	0.04	(1)
HCOOCH <sub>2</sub>	$19_{4,15} = 18_{4,14} \text{ E } \nu_t = 1$	313	244.90213	$0.49 \pm 0.02$ $0.30 \pm 0.02$	3.6	$1.03 \pm 0.17$ $1.17 \pm 0.19$	34.4	0.04	
HCOOCH <sub>3</sub>	$20_{10}$ $11-19_{10}$ $10 \text{ E } \nu_t = 1$	377	245.08271	$0.15 \pm 0.02$	4.0	$0.65 \pm 0.22$	35.3	0.04	
HCOOCH <sub>3</sub>	$20_{8,12}-19_{8,11} \to \nu_t = 1$	354	245.26174	$0.17\pm0.02$	5.0	$0.88 \pm 0.26$	34.7	0.04	
HCOOCH <sub>3</sub>	$20_{8, 13} - 19_{8, 12} \text{ A } \nu_t = 1$	354	245.34255	$0.34\pm0.02$	3.2	$1.14\pm0.19$	34.2	0.04	
HCOOCH <sub>3</sub>	$20_{9, 12}$ -19 <sub>9, 11</sub> E $\nu_t = 1$	365	245.54388	$0.28\pm0.02$	2.5	$0.75\pm0.13$	35.0	0.04	
HCOOCH <sub>3</sub>	20 <sub>15, 5</sub> –19 <sub>15, 4</sub> A	273	245.65121	$0.42\pm0.02$	3.2	$1.43\pm0.17$	34.7	0.04	(1)
HCOOCH <sub>3</sub>	20 <sub>15, 5</sub> –19 <sub>15, 4</sub> E	273	245.65678	$0.29\pm0.02$	3.1	$0.98\pm0.17$	34.5	0.04	
HCOOCH <sub>3</sub>	20 <sub>15, 6</sub> –19 <sub>15, 5</sub> E	273	245.67298	$0.33\pm0.02$	2.4	$0.83\pm0.13$	34.1	0.04	
HCOOCH <sub>3</sub>	$23_{2, 22} - 22_{2, 21} \text{ A } \nu_t = 1$	343	256.99936	$0.36 \pm 0.02$	4.2	$1.62 \pm 0.18$	34.8	0.03	
HCOOCH <sub>3</sub>	$23_{1, 22} - 22_{1, 21} \text{ A } \nu_t = 1$	343	257.01547	$0.36 \pm 0.02$	3.6	$1.39 \pm 0.16$	34.3	0.03	•••
HCOOCH <sub>3</sub>	$21_{9, 12} - 20_{9, 11} \to \nu_t = 1$	3//	257.04978	$0.46 \pm 0.02$	4.5	$2.18 \pm 0.19$	34.2	0.03	
HCOOCH <sub>3</sub>	$20_{5, 15} - 19_{5, 14} E$	143	257.22001	$0.69 \pm 0.02$	4.1	$3.03 \pm 0.17$	34.6	0.03	(1)
HCOOCH <sub>3</sub>	$20_{5, 15} - 19_{5, 14} \text{ A}$	145	257.25207	$0.70 \pm 0.02$ $0.42 \pm 0.02$	4.4	$5.38 \pm 0.21$ 1.66 ± 0.16	34.4	0.03	(1)
HCOOCH <sub>3</sub>	$219, 13-209, 12 \text{ A } \nu_t = 1$ 20 = 19 E $\nu_t = 1$	325	257 58889	$0.42 \pm 0.02$ 0.38 ± 0.02	3.7 4.6	$1.00 \pm 0.10$ $1.86 \pm 0.21$	35.4	0.03	(1)
HCOOCH <sub>2</sub>	$204, 16 194, 15 10 v_t = 1$ 222, 20 = 212, 10 E	152	257.69033	$0.30 \pm 0.02$ $0.72 \pm 0.02$	3.7	$2.88 \pm 0.16$	34.6	0.03	
HCOOCH <sub>3</sub>	$22_{3}, 20, 21_{3}, 19, 20$ $22_{3}, 20-21_{3}, 19, A$	152	257.69949	$0.72 \pm 0.02$ $0.73 \pm 0.02$	3.5	$2.00 \pm 0.10$ $2.75 \pm 0.15$	34.5	0.03	
HCOOCH <sub>3</sub>	$21_{8,13} - 20_{8,12} \to \nu_t = 1$	366	257.83109	$0.27 \pm 0.02$	3.7	$1.05 \pm 0.16$	34.1	0.03	
HCOOCH <sub>3</sub>	$21_{8, 14} - 20_{8, 13} \text{ A } \nu_t = 1$	366	257.88987	$0.24\pm0.02$	2.3	$0.59\pm0.11$	33.8	0.03	
HCOOCH <sub>3</sub>	$21_{8, 13} - 20_{8, 12} \text{ A } \nu_t = 1$	366	257.90613	$0.26\pm0.02$	2.4	$0.66\pm0.11$	35.3	0.03	
HCOOCH <sub>3</sub>	21 <sub>16, 5</sub> –20 <sub>16, 4</sub> E	306	257.91989	$0.25\pm0.02$	3.5	$0.93\pm0.15$	34.0	0.03	
HCOOCH <sub>3</sub>	21 <sub>16, 6</sub> –20 <sub>16, 5</sub> E	306	257.93383	$0.21\pm0.02$	3.2	$0.73\pm0.15$	34.7	0.03	
HCOOCH <sub>3</sub>	21 <sub>15, 6</sub> –20 <sub>15, 5</sub> A	285	258.00176	$0.46\pm0.02$	3.2	$1.55\pm0.14$	34.4	0.03	(1)
HCOOCH <sub>3</sub>	$24_{1, 24} - 23_{1, 23} \text{ A } \nu_t = 1$	345	258.01075	$0.63 \pm 0.01$	3.9	$2.58\pm0.18$	34.5	0.03	(2)
HCOOCH <sub>3</sub>	$2I_{15, 7}-20_{15, 6}$ E	285	258.02424	$0.30 \pm 0.02$	2.2	$0.69 \pm 0.11$	35.0	0.03	
HCOOCH <sub>3</sub>	$21_{9, 13} - 20_{9, 12} \to \nu_t = 1$	3//	258.03797	$0.31 \pm 0.02$	1.4	$0.48 \pm 0.06$	33.7	0.03	
	$24_{1, 24} - 25_{1, 23} \ge \nu_t = 1$	545 152	258.05504	$0.09 \pm 0.02$ 0.85 $\pm$ 0.02	4.9	$3.37 \pm 0.21$	33.0	0.03	(1)
HCOOCH <sub>3</sub>	$22_{2}, 20-21_{2}, 19$ E	152	258.08104	$0.85 \pm 0.02$ $0.76 \pm 0.02$	3.4	$4.93 \pm 0.23$ 3 14 + 0 18	34.5	0.03	
HCOOCH <sub>2</sub>	$21_{22}, 20, 21_{22}, 19, 14$	266	258 12119	$0.70 \pm 0.02$ $0.69 \pm 0.02$	4.5	$3.26 \pm 0.20$	33.9	0.03	(2)
HCOOCH <sub>3</sub>	$21_{14}$ / $20_{14}$ 6 11 $21_{14}$ 8-20 <sub>14</sub> 7 E	266	258.14209	$0.05 \pm 0.02$ $0.35 \pm 0.02$	3.8	$1.41 \pm 0.16$	34.7	0.03	(2)
HCOOCH <sub>3</sub>	$21_{13}$ $8^{-20_{13}}$ 7 A	248	258.27743	$0.84\pm0.01$	6.3	$5.64\pm0.36$	36.0	0.03	(2)
HCOOCH <sub>3</sub>	21 <sub>12, 9</sub> –20 <sub>12, 8</sub> E	232	258.47645	$0.47\pm0.01$	5.1	$2.58\pm0.24$	35.3	0.03	
HCOOCH <sub>3</sub>	21 <sub>12, 9</sub> -20 <sub>12, 8</sub> A	232	258.48298	$0.62\pm0.02$	5.8	$3.84\pm0.27$	34.9	0.03	(1)
HCOOCH <sub>3</sub>	23 <sub>2, 22</sub> –22 <sub>2, 21</sub> E	156	258.49087	$0.79\pm0.02$	3.9	$3.27\pm0.17$	34.7	0.03	
HCOOCH <sub>3</sub>	23 <sub>2, 22</sub> –22 <sub>2, 21</sub> A	156	258.49624	$0.83\pm0.01$	5.0	$4.38\pm0.28$	34.4	0.03	(1)
HCOOCH <sub>3</sub>	23 <sub>1, 22</sub> -22 <sub>1, 21</sub> E	156	258.50273	$0.81 \pm 0.01$	3.5	$3.00 \pm 0.18$	34.6	0.03	
HCOOCH <sub>3</sub>	$23_{1, 22}$ - $22_{1, 21}$ A	156	258.50818	$0.85 \pm 0.02$	3.3	$2.97 \pm 0.14$	34.5	0.03	
HCOOCH <sub>3</sub>	$21_{5, 17} - 20_{5, 16} \text{ A } \nu_t = 1$	341	258.70105	$0.33 \pm 0.02$	2.7	$0.93 \pm 0.12$	34.3	0.03	
HCOOCH <sub>3</sub>	$21_{11, 10} - 20_{11, 9} E$	217	258.74625	$0.50 \pm 0.02$ 0.62 ± 0.02	3.5	$1.84 \pm 0.15$ $2.20 \pm 0.21$	35.0	0.03	(1)
HCOOCH <sub>3</sub>	$21_{11}, 11-20_{11}, 10$ A $21_{11}, 20_{11}, 10$ F	217	258.75007	$0.02 \pm 0.02$ 0.59 ± 0.02	4.9	$3.20 \pm 0.21$ $3.03 \pm 0.20$	34.9	0.03	(1)
HCOOCH <sub>2</sub>	$21_{11}, 11-20_{11}, 10$ E $21_{2}, 10-20_{2}, 17$ A $\nu = 1$	333	258 77532	$0.39 \pm 0.02$ $0.35 \pm 0.02$	4.8 2.9	$1.07 \pm 0.20$	35.1	0.03	(1)
HCOOCH <sub>3</sub>	$21_{3}, 1_{8}, 20_{3}, 17, 17, \nu_{t} = 1$ $21_{7}, 1_{4}-20_{7}, 1_{3}, A, \nu_{t} = 1$	356	259.00387	$0.39 \pm 0.02$ $0.39 \pm 0.02$	4.3	$1.07 \pm 0.12$ $1.77 \pm 0.32$	34.2	0.03	
HCOOCH <sub>3</sub>	$21_{7, 14} - 20_{7, 13} \to \nu_t = 1$	356	259.02583	$0.29 \pm 0.02$	2.2	$0.67 \pm 0.09$	34.6	0.03	
HCOOCH <sub>3</sub>	21 <sub>10, 11</sub> -20 <sub>10, 10</sub> E	203	259.11395	$0.46\pm0.02$	4.3	$2.09\pm0.19$	34.6	0.03	
HCOOCH <sub>3</sub>	21 <sub>10, 12</sub> -20 <sub>10, 11</sub> A	203	259.12818	$0.77\pm0.02$	4.1	$3.37\pm0.17$	34.7	0.03	(1)
HCOOCH <sub>3</sub>	21 <sub>10, 12</sub> -20 <sub>10, 11</sub> E	203	259.13793	$0.45\pm0.02$	3.4	$1.63\pm0.14$	34.6	0.03	
HCOOCH <sub>3</sub>	21 <sub>3, 18</sub> –20 <sub>3, 17</sub> E $\nu_t = 1$	333	259.26499	$0.28\pm0.02$	3.3	$0.99\pm0.14$	34.2	0.03	
HCOOCH <sub>3</sub>	20 <sub>4, 16</sub> –19 <sub>4, 15</sub> A	139	259.52181	$0.68\pm0.02$	4.1	$2.98\pm0.17$	35.0	0.03	
HCOOCH <sub>3</sub>	21 <sub>9, 12</sub> -20 <sub>9, 11</sub> E	190	259.62930	$0.46 \pm 0.02$	3.6	$1.76\pm0.16$	34.7	0.03	•••
HCOOCH <sub>3</sub>	$21_{9, 13}$ - $20_{9, 12}$ A	190	259.64653	$0.85 \pm 0.02$	4.8	$4.37 \pm 0.21$	33.8	0.03	(1)
$HCOOCH_3$	21 <sub>9, 13</sub> –20 <sub>9, 12</sub> E	190	259.65308	$0.53 \pm 0.02$	3.5	$2.01 \pm 0.15$	34.4	0.03	

(Continued)										
Molecule	Transition	$E_u$ (K)	Frequency (GHz)	T <sub>br</sub> (K)	$\Delta V$ (km s <sup>-1</sup> )	$\int T_{\rm br} dV (\rm K \ km \ s^{-1})$	$V_{\rm LSR}$ (km s <sup>-1</sup> )	rms (K)	Note	
HCOOCH <sub>3</sub>	21 <sub>3, 18</sub> -20 <sub>3, 17</sub> E	147	260.24450	$0.66\pm0.02$	4.1	$2.89\pm0.17$	34.7	0.03		
HCOOCH <sub>3</sub>	21 <sub>8, 14</sub> -20 <sub>8, 13</sub> A	179	260.39273	$0.59\pm0.02$	3.5	$2.22\pm0.15$	34.6	0.03		
HCOOCH <sub>3</sub>	21 <sub>8, 13</sub> –20 <sub>8, 12</sub> A	179	260.41533	$0.57\pm0.02$	4.0	$2.42\pm0.17$	34.6	0.03		
HCOOCH <sub>3</sub>	27 <sub>8, 20</sub> –26 <sub>8, 19</sub> A	267	337.50352	$0.39\pm0.04$	2.9	$1.19\pm0.29$	34.8	0.07		
HCOOCH <sub>3</sub>	27 <sub>8, 19</sub> –26 <sub>8, 18</sub> A	267	338.35579	$0.37\pm0.04$	3.4	$1.33\pm0.31$	34.7	0.07		
HCOOCH <sub>3</sub>	27 <sub>7, 21</sub> –26 <sub>7, 20</sub> E	258	338.39632	$0.53\pm0.03$	4.4	$2.46\pm0.39$	34.9	0.07	(1)	
HCOOCH <sub>3</sub>	137, 7–126, 6 A	86	339.18591	$0.19\pm0.04$	1.5	$0.30\pm0.14$	34.3	0.07	(3)	
HCOOCH <sub>3</sub>	13 <sub>7,6</sub> –12 <sub>6,7</sub> A	86	339.19634	$0.21\pm0.03$	2.7	$0.63\pm0.25$	34.7	0.07	(3)	
HCOOCH <sub>3</sub>	29 <sub>3, 26</sub> –28 <sub>3, 25</sub> A $\nu_t = 1$	450	339.88222	$0.24\pm0.04$	3.8	$0.99\pm0.34$	34.6	0.07		
HCOOCH <sub>3</sub>	28 <sub>5, 24</sub> –27 <sub>5, 23</sub> E	257	340.74199	$0.58\pm0.04$	4.9	$3.03\pm0.42$	34.3	0.07		
HCOOCH <sub>3</sub>	28 <sub>5, 24</sub> -27 <sub>5, 23</sub> A	257	340.75476	$0.41\pm0.03$	5.3	$2.33\pm0.45$	34.7	0.07		
HCOOCH <sub>3</sub>	29 <sub>5, 25</sub> –28 <sub>5, 24</sub> E $\nu_t = 1$	460	349.68548	$0.26\pm0.04$	2.1	$0.58\pm0.21$	35.1	0.08		
HCOOCH <sub>3</sub>	$30_{4, 27}$ – $29_{4, 26}$ A $\nu_t = 1$	467	350.13257	$0.71\pm0.03$	2.0	$1.48\pm0.30$	33.5	0.08		
HCOOCH <sub>3</sub>	$30_{3, 27}$ – $29_{3, 26}$ A $\nu_t = 1$	467	350.30254	$0.33\pm0.04$	4.2	$1.48\pm0.39$	34.0	0.08		
HCOOCH <sub>3</sub>	$30_{4, 27}$ – $29_{4, 26} \to \nu_t = 1$	467	350.55020	$0.33\pm0.04$	3.7	$1.27\pm0.37$	33.9	0.08		
HCOOCH <sub>3</sub>	27 <sub>6, 21</sub> –26 <sub>6, 20</sub> E	252	350.91952	$0.49\pm0.03$	4.4	$2.27\pm0.52$	34.6	0.08		
HCOOCH <sub>3</sub>	27 <sub>6, 21</sub> –26 <sub>6, 20</sub> A	252	350.94733	$0.53\pm0.04$	3.9	$2.21\pm0.35$	34.4	0.08		
HCOOCH <sub>3</sub>	28 <sub>7, 22</sub> –27 <sub>7, 21</sub> E	275	350.99804	$0.50\pm0.04$	4.3	$2.29\pm0.37$	34.8	0.08		
HCOOCH <sub>3</sub>	28 <sub>7, 22</sub> -27 <sub>7, 21</sub> A	275	351.01591	$0.49\pm0.04$	4.9	$2.57\pm0.43$	35.2	0.08		
HCOOCH <sub>3</sub>	29 <sub>5, 25</sub> –28 <sub>5, 24</sub> E	274	351.51710	$0.40\pm0.04$	4.7	$1.99\pm0.40$	35.2	0.08		
HCOOCH <sub>3</sub>	29 <sub>5, 25</sub> –28 <sub>5, 24</sub> A	274	351.52916	$0.41\pm0.04$	4.6	$2.02\pm0.39$	35.0	0.08		
HCOOCH <sub>3</sub>	28 <sub>8, 20</sub> –27 <sub>8, 19</sub> E	284	351.82345	$0.39\pm0.04$	4.0	$1.67\pm0.35$	34.6	0.08		
HCOOCH <sub>3</sub>	28 <sub>8, 20</sub> –27 <sub>8, 19</sub> A	284	351.84219	$0.44\pm0.04$	3.4	$1.59\pm0.30$	35.0	0.08		
HCOOCH <sub>3</sub>	30 <sub>4, 27</sub> –29 <sub>4, 26</sub> E	281	352.28276	$0.41\pm0.04$	3.0	$1.31\pm0.28$	34.6	0.08		
HCOOCH <sub>3</sub>	30 <sub>4, 27</sub> –29 <sub>4, 26</sub> A	281	352.29258	$0.40\pm0.04$	4.5	$1.87\pm0.38$	34.7	0.08		
HCOOCH <sub>3</sub>	30 <sub>3, 27</sub> –29 <sub>3, 26</sub> E	281	352.40468	$0.51\pm0.04$	2.0	$1.09\pm0.17$	34.1	0.08		
HCOOCH <sub>3</sub>	30 <sub>3, 27</sub> –29 <sub>3, 26</sub> A	281	352.41414	$0.53\pm0.04$	3.7	$2.09\pm0.32$	34.4	0.08		
HCOOCH <sub>3</sub>	$33_{1, 33} - 32_{1, 32}$ A $\nu_t = 1$	479	352.81684	$0.32\pm0.04$	3.0	$1.00\pm0.26$	33.7	0.08	(1)	

Table A6

Note. (1) Blend of two HCOOCH<sub>3</sub> lines with similar spectroscopic constants. (2) Blend of three HCOOCH<sub>3</sub> lines with similar spectroscopic constants. (3) Tentative detection.

 Table A7

 Line Parameters for CH<sub>3</sub>OCH<sub>3</sub>

Molecule	Transition	$E_u$	Frequency (GHz)	$T_{\rm br}$	$\Delta V$	$\int T_{\rm br} dV$ (K km s <sup>-1</sup> )	$V_{\rm LSR}$ (km s <sup>-1</sup> )	rms (K)	Note
CULOCU	5 4 EE	(R)	241 52872	(K)	(KIII 3 )		(KIII 3 )	(K)	(1)
CH <sub>3</sub> OCH <sub>3</sub>	$5_{3, 2}-4_{2, 3}$ EE	20	241.52872	$0.59 \pm 0.02$	5.0	$3.12 \pm 0.20$	33.3	0.04	(1)
CH <sub>3</sub> OCH <sub>3</sub>	$5_{3, 2}-4_{2, 3}$ AA	26	241.53103	$0.58 \pm 0.02$	5.2	$3.23 \pm 0.32$	36.3	0.04	
$CH_3OCH_3$	$21_{3, 18}$ - $20_{4, 17}$ EE	226	241.63730	$0.25 \pm 0.02$	4.7	$1.25 \pm 0.29$	34.8	0.04	(1)
CH <sub>3</sub> OCH <sub>3</sub>	13 <sub>1, 13</sub> –12 <sub>0, 12</sub> EE	81	241.94654	$0.92\pm0.02$	4.2	$4.12 \pm 0.23$	34.5	0.04	(2)
$CH_3OCH_3$	23 <sub>2, 22</sub> –23 <sub>1, 23</sub> EE	253	244.50830	$0.16 \pm 0.02$	4.2	$0.72\pm0.24$	33.5	0.04	
CH <sub>3</sub> OCH <sub>3</sub>	23 <sub>2, 22</sub> –23 <sub>1, 23</sub> AA	253	244.51274	$0.12\pm0.02$	3.3	$0.40\pm0.17$	34.5	0.04	
CH <sub>3</sub> OCH <sub>3</sub>	18 <sub>2, 16</sub> –17 <sub>3, 15</sub> EE	164	257.04988	$0.46\pm0.02$	4.4	$2.16\pm0.19$	34.4	0.03	(2)
CH <sub>3</sub> OCH <sub>3</sub>	27 <sub>3, 25</sub> –27 <sub>2, 26</sub> EE	356	257.61453	$0.09\pm0.02$	8.1	$0.79\pm0.37$	34.0	0.03	(2) (3)
CH <sub>3</sub> OCH <sub>3</sub>	14 <sub>1, 14</sub> –13 <sub>0, 13</sub> EE	93	258.54906	$1.17\pm0.02$	4.4	$5.43\pm0.19$	34.2	0.03	(2)
CH <sub>3</sub> OCH <sub>3</sub>	17 <sub>5, 12</sub> -17 <sub>4, 13</sub> EE	175	259.31195	$0.46\pm0.07$	9.0	$3.34\pm0.16$	35.0	0.03	(2)
CH <sub>3</sub> OCH <sub>3</sub>	63. 4-52. 3 EE	32	259.48973	$0.47\pm0.01$	3.0	$1.48\pm0.20$	34.4	0.03	(1)
CH <sub>3</sub> OCH <sub>3</sub>	63, 4-52, 3 AA	32	259.49375	$0.39\pm0.01$	2.9	$1.21\pm0.19$	34.4	0.03	
CH <sub>3</sub> OCH <sub>3</sub>	235, 19-234, 20 EE	287	259.69007	$0.41\pm0.02$	4.3	$1.87\pm0.18$	34.1	0.03	(2)
CH <sub>3</sub> OCH <sub>3</sub>	21 <sub>5, 17</sub> -21 <sub>4, 18</sub> EE	246	259.73215	$0.47\pm0.02$	5.8	$2.87\pm0.25$	34.4	0.03	(2)
CH <sub>3</sub> OCH <sub>3</sub>	20 <sub>5, 16</sub> –20 <sub>4, 17</sub> EE	227	259.98441	$0.53\pm0.01$	3.5	$1.99\pm0.20$	35.6	0.03	(2)
CH <sub>3</sub> OCH <sub>3</sub>	24 <sub>5, 20</sub> -24 <sub>4, 21</sub> EE	309	260.00439	$0.43\pm0.02$	5.0	$2.33\pm0.21$	34.0	0.03	(2)
CH <sub>3</sub> OCH <sub>3</sub>	195, 15-194, 16 EE	208	260.32922	$0.46\pm0.02$	4.1	$2.03\pm0.21$	34.4	0.03	(2)
CH <sub>3</sub> OCH <sub>3</sub>	25 <sub>5, 21</sub> –25 <sub>4, 22</sub> EE	332	260.61685	$0.35\pm0.02$	3.0	$1.13\pm0.15$	35.0	0.03	(2)
CH <sub>3</sub> OCH <sub>3</sub>	21 <sub>2, 19</sub> -20 <sub>3, 18</sub> AA	220	337.42046	$0.57\pm0.04$	3.2	$1.95\pm0.32$	34.6	0.07	
CH <sub>3</sub> OCH <sub>3</sub>	74, 4-63, 3 AE	48	337.72300	$0.55\pm0.04$	2.3	$1.33\pm0.28$	35.1	0.07	
CH <sub>3</sub> OCH <sub>3</sub>	7 <sub>4.3</sub> –6 <sub>3.3</sub> EE	48	337.73219	$0.40\pm0.04$	4.5	$1.88\pm0.38$	35.4	0.07	
CH <sub>3</sub> OCH <sub>3</sub>	74, 4-63, 4 EE	48	337.77802	$0.40\pm0.03$	3.8	$1.59\pm0.32$	33.8	0.07	
CH <sub>3</sub> OCH <sub>3</sub>	$7_{4}$ 3-63 4 AA	48	337.78721	$0.71\pm0.03$	5.8	$4.41\pm0.51$	34.8	0.07	
CH <sub>3</sub> OCH <sub>3</sub>	191 18-182 17 EE	176	339.49153	$0.60 \pm 0.04$	3.9	$2.50 \pm 0.33$	34.5	0.07	
CH <sub>3</sub> OCH <sub>3</sub>	$10_{3}$ 7-9 <sub>2</sub> 8 EE	63	340.61262	$0.45\pm0.03$	7.0	$3.35 \pm 0.59$	35.1	0.07	
CH <sub>3</sub> OCH <sub>3</sub>	$11_{2,9}-10_{1,10}$ EE	66	349.80618	$0.31\pm0.04$	4.6	$1.52\pm0.41$	33.6	0.08	
	<u>_, , 1, 10</u>								

Note. (1) Blend of three CH<sub>3</sub>OCH<sub>3</sub> lines with similar spectroscopic constants. (2) Blend of four CH<sub>3</sub>OCH<sub>3</sub> lines with similar spectroscopic constants. (3) Tentative detection.

				2 5	2				
Molecule	Transition	<i>E<sub>u</sub></i> (K)	Frequency (GHz)	T <sub>br</sub> (K)	$\frac{\Delta V}{(\text{km s}^{-1})}$	$\frac{\int T_{\rm br} dV}{(\rm K \ km \ s^{-1})}$	$V_{\rm LSR}$ (km s <sup>-1</sup> )	rms (K)	Note
C <sub>2</sub> H <sub>5</sub> CN	273, 25-263, 24	173	241.62587	$0.13\pm0.02$	4.9	$0.69\pm0.29$	33.3	0.04	
C <sub>2</sub> H <sub>5</sub> CN	279, 18-269, 17	253	241.93218	$0.23\pm0.03$	3.6	$0.86\pm0.21$	33.9	0.04	(1)
C <sub>2</sub> H <sub>5</sub> CN	2712, 15-2612, 14	322	241.95905	$0.12\pm0.02$	3.1	$0.40\pm0.16$	34.2	0.04	(2)
C <sub>2</sub> H <sub>5</sub> CN	27 <sub>8, 20</sub> -26 <sub>8, 19</sub>	234	241.97045	$0.30\pm0.02$	1.8	$0.56\pm0.10$	33.5	0.04	(2)
C <sub>2</sub> H <sub>5</sub> CN	2713, 14-2613, 13	350	241.99710	$0.12\pm0.02$	3.2	$0.40\pm0.17$	33.2	0.04	(2)
C <sub>2</sub> H <sub>5</sub> CN	277, 21-267, 20	217	242.05249	$0.23\pm0.02$	4.0	$0.97\pm0.22$	34.2	0.04	(2)
C <sub>2</sub> H <sub>5</sub> CN	276, 22-266, 21	203	242.20698	$0.30\pm0.02$	6.3	$2.03\pm0.34$	31.7	0.04	(2)
C <sub>2</sub> H <sub>5</sub> CN	274, 24-264, 23	181	242.66469	$0.32\pm0.03$	2.4	$0.83\pm0.17$	33.9	0.04	
C <sub>2</sub> H <sub>5</sub> CN	14 <sub>3, 11</sub> -13 <sub>2, 12</sub>	55	245.02365	$0.32\pm0.02$	2.3	$0.77\pm0.14$	35.1	0.04	
C <sub>2</sub> H <sub>5</sub> CN	300, 30-290, 29	194	257.31064	$0.11\pm0.02$	3.7	$0.43\pm0.16$	34.2	0.03	
C <sub>2</sub> H <sub>5</sub> CN	301, 30-290, 29	194	257.58361	$0.20\pm0.02$	1.5	$0.32\pm0.06$	33.6	0.03	
C <sub>2</sub> H <sub>5</sub> CN	299, 21-289, 20	277	259.86276	$0.11\pm0.02$	3.5	$0.42\pm0.15$	33.9	0.03	(2)
C <sub>2</sub> H <sub>5</sub> CN	2912, 17-2812, 16	347	259.86989	$0.35\pm0.02$	1.4	$0.53\pm0.08$	33.4	0.03	(2)
C <sub>2</sub> H <sub>5</sub> CN	2913, 16-2813, 15	374	259.90664	$0.09\pm0.02$	3.2	$0.31\pm0.14$	33.5	0.03	(2) (3)
C <sub>2</sub> H <sub>5</sub> CN	296, 24-286, 23	227	260.22166	$0.24\pm0.02$	3.1	$0.80\pm0.15$	34.8	0.03	
C <sub>2</sub> H <sub>5</sub> CN	295, 25-285, 24	215	260.53569	$0.27\pm0.02$	3.7	$1.04\pm0.16$	34.3	0.03	
NH <sub>2</sub> CHO	130, 13-121, 12	91	244.85421	< 0.08		< 0.3		0.04	
NH <sub>2</sub> CHO	13 <sub>2, 12</sub> -13 <sub>1, 13</sub>	104	258.63638	$0.10\pm0.02$	3.9	$0.40\pm0.17$	35.6	0.03	(3)
NH <sub>2</sub> CHO	122, 10-112, 9	92	260.18909	$0.36\pm0.02$	4.4	$1.67\pm0.19$	34.7	0.03	
NH <sub>2</sub> CHO	169, 7-159, 6	380	339.68606	$0.36\pm0.03$	4.3	$1.63\pm0.36$	33.2	0.07	(4)
NH <sub>2</sub> CHO	16 <sub>8,8</sub> -15 <sub>8,7</sub>	329	339.71519	$0.30\pm0.04$	3.9	$1.27\pm0.34$	35.2	0.07	(4)
NH <sub>2</sub> CHO	167, 10-157, 9	284	339.77954	$0.36\pm0.04$	3.3	$1.26\pm0.29$	33.9	0.07	(5)
NH <sub>2</sub> CHO	16 <sub>6, 11</sub> -15 <sub>6, 10</sub>	246	339.90250	$0.29\pm0.04$	4.9	$1.49\pm0.42$	34.0	0.07	(5)
NH <sub>2</sub> CHO	16 <sub>3, 14</sub> -15 <sub>3, 13</sub>	166	340.48963	$0.37\pm0.04$	4.2	$1.65\pm0.36$	34.0	0.07	
NH <sub>2</sub> CHO	164, 13-154, 12	186	340.53439	$0.36\pm0.04$	5.2	$1.98\pm0.44$	34.1	0.07	
NH <sub>2</sub> CHO	164, 12-154, 11	186	340.69074	$0.46\pm0.03$	2.5	$1.19\pm0.27$	33.7	0.07	
NH <sub>2</sub> CHO	162, 14-152, 13	153	349.47820	$0.36\pm0.04$	3.6	$1.41\pm0.33$	33.9	0.08	
NH <sub>2</sub> CHO	9 <sub>2, 8</sub> -8 <sub>1, 7</sub>	58	349.63403	< 0.30		<1.3		0.08	

 Table A8

 Line Parameters for C2H5CN and NH2CHO

Note. (1) Blend of four  $C_2H_5CN$  lines with similar spectroscopic constants. (2) Blend of two  $C_2H_5CN$  lines with similar spectroscopic constants. (3) Tentative detection. (4) Blend of four  $NH_2CHO$  lines with similar spectroscopic constants. (5) Blend of two  $NH_2CHO$  lines with similar spectroscopic constants.

Line Parameters for HCOOH, H <sub>2</sub> CCO, and c-C <sub>2</sub> H <sub>4</sub> O										
Molecule	Transition	<i>E<sub>u</sub></i> (K)	Frequency (GHz)	T <sub>br</sub> (K)	$\Delta V$ (km s <sup>-1</sup> )	$\int T_{\rm br} dV \\ ({\rm K \ km \ s^{-1}})$	$V_{\rm LSR}$ (km s <sup>-1</sup> )	rms (K)	Note	
trans-HCOOH	12 <sub>1, 12</sub> -11 <sub>1, 11</sub>	84	257.97501	$0.52\pm0.02$	5.5	$3.00\pm0.23$	34.5	0.03		
trans-HCOOH	154, 12-144, 11	181	338.14384	$0.42\pm0.03$	5.0	$2.26\pm0.43$	34.6	0.07		
trans-HCOOH	15 <sub>3, 13</sub> -14 <sub>3, 12</sub>	158	338.20186	$0.36\pm0.03$	4.4	$1.70\pm0.39$	34.7	0.07		
trans-HCOOH	154, 11-144, 10	181	338.24882	$0.35\pm0.04$	2.8	$1.04\pm0.26$	34.7	0.07		
trans-HCOOH	153, 12-143, 11	159	340.22910	$0.31\pm0.04$	5.8	$1.92\pm0.49$	35.1	0.07		
cis-HCOOH	130, 13-121, 12	95	244.23510	$0.33\pm0.02$	1.6	$0.57\pm0.09$	35.7	0.04		
cis-HCOOH	91, 9-80, 8	49	244.24786	$0.27\pm0.02$	2.5	$0.73\pm0.16$	34.2	0.04	(1)	
H <sub>2</sub> CCO	124, 9-114, 8	284	242.30938	$0.12\pm0.02$	3.0	$0.36\pm0.16$	34.3	0.04	(2)	
H <sub>2</sub> CCO	$12_{0, 12}$ -11 <sub>0, 11</sub>	76	242.37573	$0.23\pm0.02$	4.0	$0.99\pm0.27$	33.8	0.04		
H <sub>2</sub> CCO	$12_{3, 10} - 11_{3, 9}$	193	242.39845	$0.41\pm0.03$	3.1	$1.35\pm0.19$	34.4	0.04	(2)	
H <sub>2</sub> CCO	$12_{2, 11} - 11_{2, 10}$	128	242.42466	< 0.10		< 0.4		0.04		
H <sub>2</sub> CCO	$12_{2, 10} - 11_{2, 9}$	128	242.53616	$0.13\pm0.02$	3.2	$0.43\pm0.19$	35.5	0.04		
H <sub>2</sub> CCO	$12_{1, 11} - 11_{1, 10}$	89	244.71227	$0.61\pm0.03$	3.4	$2.24\pm0.20$	34.4	0.04		
H <sub>2</sub> CCO	131,13-121, 12	100	260.19198	$0.67\pm0.02$	3.1	$2.21\pm0.18$	34.6	0.03		
H <sub>2</sub> CCO	17 <sub>1, 17</sub> –16 <sub>1, 16</sub>	160	340.19308	$0.41\pm0.03$	4.8	$2.08\pm0.61$	34.6	0.07	(3)	
c-C <sub>2</sub> H <sub>4</sub> O	11 <sub>2, 10</sub> -10 <sub>1, 9</sub>	104	338.77198	$0.35\pm0.03$	4.2	$1.57\pm0.35$	34.6	0.07	(4)	

 Table A9

 Line Parameters for HCOOH. H2CCO. and c-C2H4O

Note. (1) Partial blend with  $SO_2$ . (2) Blend of two  $H_2CCO$  lines with similar spectroscopic constants. (3) Partial blend with  $C_2H_5OH$ . (4) Blend of two c- $C_2H_4O$  lines with similar spectroscopic constants.

# Appendix B Fitted Spectra

Figures B1–B11 show the results of the spectral line fitting (see Section 3.1 for details).



Figure B1. ALMA spectra of the detected molecular emission lines. The blue lines represent fitted Gaussian profiles. For the molecules with multiple line detection, the spectra are sorted in ascending order of the upper state energy (the emission line with the lowest upper state energy is shown in the upper left panel and that with the highest energy is in the lower right panel). For SiO, the positions of primary and secondary peaks are indicated by arrows.



Figure B2. Same as in Figure B1 but for nitrogen-bearing molecules.



Figure B3. Same as in Figure B1 but for nitrogen-bearing molecules (continued).



Figure B4. Same as in Figure B1 but for sulfur-bearing molecules.



Figure B5. Same as in Figure B1 but for CH<sub>3</sub>OH.



Figure B6. Same as in Figure B1 but for CH<sub>3</sub>OH (continued) and <sup>13</sup>CH<sub>3</sub>OH.



Figure B7. Same as in Figure B1 but for  $C_2H_5OH$ .



Figure B8. Same as in Figure B1 but for HCOOCH<sub>3</sub>.



Figure B9. Same as in Figure B1 but for HCOOCH<sub>3</sub> (continued).



Figure B10. Same as in Figure B1 but for HCOOCH<sub>3</sub> (continued), CH<sub>3</sub>OCH<sub>3</sub>, and CH<sub>3</sub>CHO.



Velocity (km s<sup>-1</sup>)

Figure B11. Same as in Figure B1 but for HCOOH, H<sub>2</sub>CCO, and c-C<sub>2</sub>H<sub>4</sub>O.

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