Millimetre spectral line mapping observations towards four massive star-forming H II regions

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ABSTRACT

We present spectral line mapping observations towards four massive star-forming regions – Cepheus A, DR21S, S76E and G34.26+0.15 – with the IRAM 30-m telescope at the 2 and 3 mm bands. In total, 396 spectral lines from 51 molecules, one helium recombination line, 10 hydrogen recombination lines and 16 unidentified lines were detected in these four sources. An emission line of nitrosyl cyanide (ONCN, $14_0, 14-13_{0, 13}$) was detected in G34.26+0.15, as the first detection in massive star-forming regions. We found that $c\text{-C}_3\text{H}_2$ and NH_2D show enhancement in shocked regions, as suggested by the evidence of SiO and/or SO emission. The column density and rotational temperature of CH_3CN were estimated with the rotational diagram method for all four sources. Isotope abundance ratios of $^{12}\text{C}/^{13}\text{C}$ were derived using HC_3N and its ^{13}C isotopologue, which were around 40 in all four massive star-forming regions and slightly lower than the local interstellar value (~ 65). The $^{14}\text{N}/^{15}\text{N}$ and $^{16}\text{O}/^{18}\text{O}$ abundance ratios in these sources were also derived using the double isotopic method, which were slightly lower than in the local interstellar medium. Except for Cep A, the $^{33}\text{S}/^{34}\text{S}$ ratios in the other three targets were derived, which were similar to that in the local interstellar medium. The column density ratios of $\text{N}(\text{DCN})/\text{N}(\text{HCN})$ and $\text{N}(\text{DCO}^+)/\text{N}(\text{HCO}^+)$ in these sources were more than two orders of magnitude higher than the elemental $[\text{D}]/[\text{H}]$ ratio, which is 1.5×10^{-5} . Our results show that the later stage sources, G34.26+0.15 in particular, present more molecular species than earlier stage sources. Evidence of shock activity is seen in all stages studied.

Key words: stars: formation – stars: massive – stars: winds, outflows – ISM: clouds – radio lines: stars – submillimetre: stars.

1 INTRODUCTION

Massive stars play an important role in galaxy evolution. The formation of massive stars is difficult to study because of the large distances, complex cluster environments and rapid time-scales in evolution (e.g. Zinnecker & Yorke 2007; Herbst & van Dishoeck 2009). Massive star formation involves different physical and astrochemical properties in various evolutionary stages,

such as starless cores, hot molecular cores (HMCs), hyper-compact H II, (HCH II), ultra-compact H II (UCH II), compact H II (CH II) and evolved H II regions (Kurtz et al. 2000; Churchwell 2002). Feedback from massive stars in turn affects surrounding molecular clouds through energetic stellar winds, powerful outflows, ultraviolet (UV) radiation, expansion of H II regions and supernova explosions (Kennicutt 1998). Emissions of radio continuum and recombination lines have been used to investigate HCH II, UCH II and H II regions (Churchwell 2002). Molecular probes are also essential for investigating the physical and chemical conditions of massive star-forming regions (e.g. temperature, density, radiation field, etc.).

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They are also utilized to study chemical evolution in massive star formation regions (van Dishoeck & Blake 1998).

The millimetre wavelength window is important for studying massive star formation, because it contains many useful molecular probes, such as shock tracers (SiO, SO, HNC and H₂CO; Schilke et al. 1997; Esplugues et al. 2013; Rizzo, Fuente & García-Burillo 2005), long carbon chain molecules (*c*-C₃H₂, HC₃N and HC₅N; Morris, Snell & vanden Bout 1977; Chung, Osamu & Masaki 1991; Bergin, Snell & Goldsmith 1996), deuterated molecules (DCN, DCO⁺, C₂D and NH₂D; Shah & Wootten 2001; Pety et al. 2007; Parise et al. 2009) and dense gas traces (HCN, HCO⁺, CS and C₂H; Padovani et al. 2009), etc.

The various molecules can probe different physical and chemical components. Thus, molecular tracers offer a powerful tool for investigating the physical and chemical conditions of star-forming regions. The study of physical and chemical evolutions in various scales is essential to develop a picture of massive star formation, and these are the main focus of this paper. To achieve these main goals, we map four massive star formation regions, at different evolutionary stages from HCH II to H II, with a total 11.8-GHz bandwidth coverage.

In this paper, we present observational results of four massive star-forming regions, which were carried out by the IRAM 30-m telescope. In Section 2, we describe the observations and the data reduction. Observational results are introduced in Section 3, including molecular lines, velocity-integrated maps of molecular lines, isotope abundance ratios and long carbon chain molecules. In Section 4, we derive the rotational temperature and column density of CH₃CN for each source, and we investigate the properties of shocked regions with shock tracers and deuterated molecules. A brief summary is given in Section 5.

2 SOURCE SELECTION AND OBSERVATIONS

2.1 Sources

We select four well-studied massive star formation regions from Wu et al. (2010), which are representative of different evolutionary stages. Cepheus A (hereafter Cep A), DR21S, G34.26+0.15 (hereafter G34) and S76E lie at different distances from 0.7 to 3.3 kpc, and are associated with HCH II (Hughes & Wouterloot 1984), cometary-shaped H II (Immer et al. 2014), CH II (Reid & Ho 1985; Mookerjee et al. 2007) and an extended H II region (Li et al. 2012), respectively, according to radio observations. These regions provide ideal laboratories to study the properties of massive star-forming regions using mapping observations, because they have high mass and luminosity.

The Cep A molecular cloud complex is the second nearest star formation region after the Orion complex, located at a distance of 700 ± 40 pc (Moscadelli et al. 2009). Herbig–Haro objects (Hartigan et al. 1986), HCH II regions (Hughes & Wouterloot 1984) and two bipolar molecular outflow aligned east–west and north–east–south–west (NE–SW) (Rodríguez et al. 1980; Gómez et al. 1999) have been detected in Cep A. The bolometric luminosity of this region is $2.5 \times 10^4 L_{\odot}$ with a mass of $\sim 330 M_{\odot}$ (Evans et al. 1981; Narayanan & Walker 1996). Our mapping centre of Cep A is located in the radio source HW2, which is a massive protostar (Cunningham, Moeckel & Bally 2009; Dzib et al. 2011), with a mass of $\sim 18 M_{\odot}$ (Torrelles et al. 2011). There is a fast, bipolar, highly collimated radio jet ejected from the HW2 young stellar object (YSO), with well-aligned NE–SW direction and a scale of ~ 1500 au (Curiel et al. 2006). Furthermore, a rotating disc around HW2 has been identified from submillimetre observations (Patel et al. 2005).

The infrared observations towards HW2 show that there are strong shocks, implying that the object is at an early evolutionary stage.

DR21S is a massive star-forming region within the Cygnus X molecular cloud at a distance of 1.5 ± 0.08 kpc (Rygl et al. 2012). This region has been studied in multiple wavelength observations (Wilson & Mauersberger 1990; Liechti & Walmsley 1997; Schneider et al. 2006, 2010; Jakob et al. 2007). It has a molecular gas mass of about $4.7 \times 10^6 M_{\odot}$ and a far-infrared luminosity of $1.5 \times 10^5 L_{\odot}$ (Campbell et al. 1982; Schneider et al. 2006). The cloud also hosts one of the strong energetic outflows, with a mass of about $3000 M_{\odot}$ (Cruz-González, Salas & Hiriart 2007). Our mapping observations have covered two cometary H II regions (Immer et al. 2014) and several regions with ongoing shock activity (Davis et al. 2007) towards DR21S.

The G34 molecular cloud complex is a massive star-forming region at a distance of 3.3 kpc (Kuchar & Bania 1994), and its envelope scale is 8.1×10^4 au. The cloud contains $1.1 \times 10^4 M_{\odot}$ of dense gas (Hill et al. 2005), and has a luminosity of $3.2 \times 10^5 L_{\odot}$ (van der Tak et al. 2013), with an age of a few $\times 10^4$ yr (Paron et al. 2009). From radio continuum observations, this source shows two very condensed UCH II regions (called A and B), a more evolved CH II region with a cometary shape (called C) and an extended ring-like H II region (called D) (Reid & Ho 1985; Mookerjee et al. 2007). There are several outflows in G34, as evidenced by SiO emission extending to the north-west, south-east and north-east of the CH II region (Hatchell, Fuller & Millar 2001).

S76E is a massive star-forming region containing an extended H II region (Li et al. 2012), with an emitting region size of about 2 arcmin (i.e. about 1.2 pc given a distance of 2.11 kpc; Plume et al. 1992). This region has an IRAS total IR (TIR) luminosity of $2.3 \times 10^4 L_{\odot}$ (Zinchenko, Henning & Schreyer 1997), with a molecular mass of $1.64 \times 10^3 M_{\odot}$ (Zinchenko et al. 1994).

2.2 IRAM 30-m observations and VLA archive data

We carried out mapping observations with the IRAM 30-m telescope at Pico Veleta, Spain,¹ in 2012 January. The on-the-fly (OTF) mapping mode was used for all four objects, with a mapping size of 120×120 arcsec². The mapping centres are listed in Table 1. The Eight Mixer Receiver (EMIR) and Fourier Transform Spectrometer (FTS) backends were used. These observations cover the frequency range between 84.5 and 92.3 GHz in the 3-mm atmospheric window, and between 143.7 and 147.7 GHz in the 2-mm atmospheric window. A variety of molecular lines are covered simultaneously, which can improve observational efficiency and avoid deviation of relative position and flux calibration. The reasonable frequency resolution (Guzmán et al. 2013) of the FTS with 195-kHz sampling corresponds to ~ 0.67 km s^{−1} and ~ 0.4 km s^{−1} at 87 and 145 GHz, respectively. The data were converted to the main beam temperature T_{mb} using $T_{\text{mb}} = (F_{\text{eff}}/B_{\text{eff}})T_A^*$, where B_{eff} is the main beam efficiency and F_{eff} is forward efficiency. The main beam efficiencies are 0.81 for 86 GHz and 0.73 for 145 GHz. The forward efficiencies are 95 per cent at 3 mm and 93 per cent at 2 mm. The beam sizes are about 17 and 28 arcsec, and τ values are about 0.05 and 0.1, while the typical system temperatures are about 125 and 95 K at 2 and 3 mm, respectively. All data were re-gridded to steps of 15 arcsec, and we have assumed that the beam-filling factor is unity for the following analysis.

¹ Based on observations carried out with the IRAM 30-m telescope. IRAM is supported by INSU/CNRS (France), MPG (Germany) and IGN (Spain).

Table 1. 3.6-cm radio continuum emission of the four sources. Columns are: (1) source name; (2) right ascension; (3) declination; (4) Galactic latitude; (5) distance D and the reference; (6) galactocentric distance D_g ; (7) local standard of rest velocity; (8) peak intensities S_p of radio continuum emission; (9) flux densities S_v of radio continuum emission; (10) Synthesized beam of radio continuum emission.

Source	RA (J2000)	Dec. (J2000)	Gal. lat. (deg)	D (Ref. ^a) (kpc)	D_g (kpc)	v_{LSR} (km s ⁻¹)	S_p (mJy beam ⁻¹)	S_v (mJy)	Synthesized beam (arcsec ² , °)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Cep A	22:56:18.1	62:01:46.2	2.1	0.7 ± 0.04 (1)	8.7	-11	4.81 ± 0.05	10.3 ± 0.1	$8.8 \times 6.6, -22$
DR21S	20:39:00.8	42:19:29.8	0.5	1.5 ± 0.08 (2)	8.6	-2	5781 ± 6	13932 ± 19	$8.8 \times 7.2, 89$
G34	18:53:18.5	01:14:56.7	0.1	3.3 (3)	5.8	58	2051 ± 3	2512 ± 5	$12 \times 9, -23$
S76E	18:46:10.4	07:53:14.1	4.7	2.11 (4)	7.0	33	133 ± 1	2437 ± 28	$14.4 \times 8.7, 50$

^aReferences are: (1) Moscadelli et al. (2009); (2) Rygl et al. (2012); (3) Kuchar & Bania (1994); (4) Plume et al. (1992).

Free-free emission at centimetre wavelengths is a useful tool to study HCH II, UCH II and H II regions. Radio continuum data at the X band (3.6 cm) observed with the Very Large Array (VLA) were obtained from Li et al. (2012). In Table 1, we list the peak intensity S_p in Column 7, the flux density S_v in Column 8 and the deconvolved size in Column 9.

3 RESULTS

3.1 Line identification

To increase the sensitivity of weak lines, we averaged the spectrum over the map of 30×30 arcsec² for each source (Fig. 1). The molecular lines were identified using the Splatalogue data base² (see Pickett et al. 1998) and the Cologne Database for Molecular Spectroscopy (CDMS)³ (see Müller et al. 2005). Most of the molecular lines have similar linewidths and central velocities, while several lines are more broad than the typical linewidths, such as radio recombination lines (RRLs) and SiO lines. RRLs were detected in DR21S, G34 and S76E, but not detected in Cep A, where the radio continuum emission was dominated by a high-velocity ionized jet (Jiménez-Serra et al. 2011). The line parameters derived from Gaussian fitting are listed in Tables B2, B3, B4 and B5, including velocity integrated intensity (A), local standard of rest velocity v_{LSR} , linewidth (full width at half-maximum, FWHM) and emission peak temperature (in T_{mb}). Detailed information of the molecular lines for each source are described below.

Cep A

In total, 61 lines from 35 molecules were identified (see Table B2), including long carbon chain molecules (e.g. HC_{2n-1}N, CH₃C₂H, H¹³C_{2n-1}N, c-C₃H₂, C₄H, $n = 2, 3$), deuterated molecules (DCN, DCO⁺, C₂D, NH₂D) and shock tracers (SiO, SO, etc.), etc. Most of these lines velocities are around $v_{\text{LSR}} \sim -11$ km s⁻¹, while the linewidth (FWHM) ranges from 3.3 to 4.5 km s⁻¹.

DR21S

We identified 78 spectral features corresponding to 43 different molecular species, including long carbon chain molecules, deuterated molecules, photo-dissociation regions (PDRs) and shock tracers, etc. In addition, one helium recombination (He42 α), six RRLs and one unidentified line were detected (see Table B3). A complex oxygen-bearing molecule of acetone (CH₃)₂CO 23_{11,13}-22_{12,10} AE

was detected for the first time in this massive star-forming region. These line velocities are around $v_{\text{LSR}} \sim -2$ km s⁻¹, while the typical FWHM ranges from 3 to 5 km s⁻¹.

G34

A total of 169 spectral features were detected (Table B4). We identified 78 molecular species and three RRLs, including long carbon chain molecules, deuterated molecules, PDRs and shock tracers, etc. In addition, nine unidentified lines were detected. Most of these molecular line velocities are around $v_{\text{LSR}} \sim 58$ km s⁻¹ and the typical FWHM ranges from 3.5 to 4.5 km s⁻¹. Several molecules were detected in this source, but were absent in the other three sources (e.g. SiC₂, H₂CN, HDCS, N¹⁵NH⁺, ¹⁵NNH⁺, ¹³C³⁴S, SO₂, ONCN and HCO). The linewidth of SiC₂ is 6.23 km s⁻¹ (FWHM), which is significantly broader than the typical FWHM.

S76E

We detected 71 spectral lines from 44 molecules, and one RRL (Table B5), including long carbon chain molecules, deuterated molecules, several well-known PDRs and shock tracers, etc. In addition, we found six unidentified lines. These lines are around $v_{\text{LSR}} \sim 33$ km s⁻¹, while the typical FWHM ranges from 2.8 to 3.5 km s⁻¹.

In summary, many fundamental molecules were detected in all four sources, such as long carbon chain molecules, deuterated molecules, sulphur-bearing molecules, PDRs and shock tracers, etc. Both C₂S and HCO were detected in DR21S and G34, while SO₂, ONCN, SiC₂, C₃S, NH₂CO and H₂NCH₂CN were only detected in G34 and (CH₃)₂CO was only detected in DR21S. In addition, the number of molecules in G34 is significantly more than in the other sources. This indicates that the chemical environment in G34 is more complicated than the other three sources. Molecules detected in all four sources might have been formed or might have existed at the early stage of massive star formation. The molecules, which were only detected in DR21S and/or G34, but were absent in Cep A and S76E, likely only form in specific environments. The physical and chemical environments can be affected by interaction between two CH II regions in DR21S. The G34 molecular cloud complex is interacting with a supernova remnant, which could affect the chemical environment of the molecular cloud, could accelerate the chemical reaction and could produce complicated molecules. These sources exhibit different radio continuum specific intensities and chemical complexities, indicating that they might be in a different evolutionary stage. G34 and DR21S show more chemical complexity than Cep A and S76E, which is consistent with the evolutionary stages as suggested by evidence of radio continuum and RRLs. The comparison between our results and previous line surveys, towards infrared dark clouds (IRDCs), high-mass protostellar objects

² www.splatalogue.net

³ <http://www.astro.uni-koeln.de/cdms>

Figure 1. Comparison of the Cep A, DR21S, S76E and G34 survey at 3- and 2-mm wavelengths. The spectrum is averaged over the map of 30×30 arcsec² for each source. The spectra velocity (frequency) resolution is 0.65 km s^{-1} (0.195 MHz) and 0.4 km s^{-1} (0.195 MHz) at 3 and 2 mm, respectively, while the unit is K for the main-beam temperature.

Figure 1 – *continued.*

Figure 1 – continued.

(HMPOs), HMCs and UCH II regions at 3 mm, show that the molecular abundances in our sources are significantly higher than in IRDCs and HMPOs (Marseille et al. 2008; Sanhueza et al. 2012), but are generally in agreement with HMCs and UCH II regions (Gerner et al. 2014).

3.2 Velocity-integrated intensity maps

In each target, most molecular lines show similar spatial distributions, with their emission peaking at the core position, while some other lines exhibit distinct morphologies. For example, both $c\text{-C}_3\text{H}_2$ and DCO^+ have multiple emission peaks in all four sources, while a few cases – HCO , ONCN and $(\text{CH}_3)_2\text{CO}$ – show anticorrelation with the RRLs (or free-free continuum emission) in the velocity-integrated intensity maps.

Cep A

Our mapping centre is located at the radio source HW2. The velocity-integrated intensity map of DCO^+ 2–1 shows three main condensations, as well as $c\text{-C}_3\text{H}_2$ 2–1 (Fig. 2), which is discussed in Sections 3.4.1 and 4.3. Fig. 3 shows the velocity-integrated intensity maps of the deuterated molecules and shock tracers. The SiO 2–1 emission is stretched along the NE–SW direction, which is consistent with what was found in the literature (Codella et al. 2006).

DR21S

Velocity-integrated intensity maps and spectra of deuterated molecules are shown in Fig. 4. Some of these show slightly different morphologies compared with the corresponding hydrogenated molecules. The deuterated molecules are discussed in detail in Section 4.3. The large oxygen-bearing molecule of acetone $(\text{CH}_3)_2\text{CO}$ shows strong emission in several positions, with a cavity around the emission peak of $\text{H41}\alpha$ (Fig. 7), which is similar to the results of Friedel & Snyder (2008). The $c\text{-C}_3\text{H}_2$ 2–1 emission also shows a cavity around the radio continuum emission peak, which is discussed in Section 3.4.1. $\text{He42}\alpha$ emission was detected towards the core region (Fig. 7).

G34

Fig. 8 shows different spatial distributions between $\text{H41}\alpha$ and HC_3N . $\text{H41}\alpha$ emission is extended in the south-east, while HC_3N is extended in the west. HCO and $c\text{-C}_3\text{H}_2$ show significantly different morphologies compared to RRLs. HCO shows anticorrelation with $\text{H41}\alpha$ (Fig. 8), while $c\text{-C}_3\text{H}_2$ shows a cavity feature in the emission peak of RRL, which is discussed in Section 3.4.1.

S76E

As shown in Fig. 2, $c\text{-C}_3\text{H}_2$ 2–1 and $c\text{-C}_3\text{H}_2$ 3–2 transitions exhibit slightly different morphologies. The velocity-integrated intensity maps and spectra of deuterated molecules are presented in Fig. 6, and are discussed in Section 4.3.

3.3 Isotopic abundances

$^{12}\text{C}/^{13}\text{C}$

Because the millimetre HC_3N lines are optically thin in most molecular clouds (Li et al. 2012), the line intensity ($I = \int T dv$) ratios between HC_3N 10–9 and its isotopologues (HCC^{13}CN 10–9 and

HC^{13}CCN 10–9) can be used to determine the abundance ratios of these molecules. The $^{12}\text{C}/^{13}\text{C}$ isotope abundance ratios were derived from the line ratio between HC_3N and its isotopologues, assuming similar astrochemical processes. The $^{12}\text{C}/^{13}\text{C}$ isotope ratios are about 40 in all four sources (Table 2), which are slightly lower than the ratio of 60–70 found in the local interstellar medium (ISM; Milam et al. 2005), but agree well with the result in Orion (~ 40 ; Persson et al. 2007; Tercero et al. 2010). The rarer isotope ^{13}C is a secondary element that can be produced from ^{12}C in the carbon–nitrogen–oxygen (CNO) cycle in low- and intermediate-mass stars (Prantzos, Aubert & Audouze 1996), while the main isotope of carbon ^{12}C , as a primary element, is mainly produced by the triple alpha reaction (Timmes, Woosley & Weaver 1995). A positive gradient along the Galactic radius is apparent in the $^{12}\text{C}/^{13}\text{C}$ ratios, which are ~ 25 to > 100 from the Galactic Centre to the outer disc, following the relationship $^{12}\text{C}/^{13}\text{C} = 6.21 D_{\text{GC}} + 18.71$, where D_{GC} is the distance from the Galactic Centre (Milam et al. 2005). The $^{12}\text{C}/^{13}\text{C}$ ratios that are calculated from HC_3N and its isotopologues seem to exhibit a gradient with D_{GC} , except for DR21S and S76E, as the ratio is lower than the prediction of Milam et al. (2005) for the former and the Galactic latitude is much higher than 2° for the latter. The discrepancy of isotope abundance ratios between our sources and the local ISM might arise from Galactic chemical evolution, because the solar value represents the ISM 4.5 Gyr ago. The $^{12}\text{C}/^{13}\text{C}$ ratios can also be affected by isotope selective photodissociation from UV photons because both ^{12}C and ^{13}C have different self-shielding (Wilson & Rood 1994; Milam et al. 2005). The ^{13}C is more easily photodissociated than ^{12}C , which can result in a lower $^{12}\text{C}/^{13}\text{C}$ ratio in the star-forming region compared with the local ISM (e.g. Szűcs, Glover & Klessen 2014).

$^{14}\text{N}/^{15}\text{N}$

The HCN molecule and its isotopologues have large Einstein coefficients, making their line emission easily optically thick. To accurately estimate the abundance ratios from lines with high optical depths, we used the double isotope method, in which one of the isotope abundances is either measured from different species or fixed with the local ISM value. We estimated the isotope abundance ratios of $^{14}\text{N}/^{15}\text{N}$, which were calculated from the observed line ratios of $\text{H}^{13}\text{CN}(1\text{--}0)$ and $\text{HC}^{15}\text{N}(1\text{--}0)$, after adopting the ratio of $^{12}\text{C}/^{13}\text{C}$ derived from HC_3N 10–9 and its isotopologues.

The $^{14}\text{N}/^{15}\text{N}$ isotope ratios in these sources range from 109 to 304, which are lower than ~ 400 found in the local ISM (Terzieva & Herbst 2000) and 1000 ± 200 found in the prototypical starless cloud core L1544 (Bizzocchi et al. 2013). The $^{14}\text{N}/^{15}\text{N}$ ratio in S76E is 304 ± 15 , which is roughly consistent with 300 ± 50 in Barnard 1 (Daniel et al. 2013). The HC^{15}N abundance could be enhanced in the early stages of molecular dense cores (Rodgers & Charnley 2008), while the effect can be neglected in our sources because they are all H II regions. The ^{15}N element is believed to be formed in the synthesis of massive stars and potential can be destroyed in low-mass stars (Wang et al. 2009). This indicates that a part of the ^{15}N element can be destroyed in the local ISM. Adande & Ziurys (2012) found that the $^{14}\text{N}/^{15}\text{N}$ ratio shows a positive gradient with distance of D_{GC} , $^{14}\text{N}/^{15}\text{N} = 21.1(5.2) \text{ kpc}^{-1} D_{\text{GC}} + 123.8(37.1)$, which likely supports the Galactic chemical evolution model that ^{15}N has a secondary origin in novae. The results of Cep A and G34 are consistent with the above scenario. The Galactic chemical evolution can be used to explain the discrepancy of $^{14}\text{N}/^{15}\text{N}$ ratios between our sources and the local ISM.

Figure 2. Images of $c\text{-C}_3\text{H}_2$ emissions in four sources. The grey-scale is radio continuum (VLA 8.4 GHz) and range indicated in the wedge is in Jy beam^{-1} . The upper panel shows $c\text{-C}_3\text{H}_2$ emissions in Cep A: (left) velocity-integrated intensity maps of SiO 2–1 (red dashed line, -13.5 to -1.3 km s^{-1}) overlaid on $c\text{-C}_3\text{H}_2$ 2–1 (-15 to -7 km s^{-1}); (middle) velocity-integrated intensity maps of $c\text{-C}_3\text{H}_2$ 3–2 (red dashed line, -15 to -7 km s^{-1}) overlaid on $c\text{-C}_3\text{H}_2$ 2–1; (right) spectra of $c\text{-C}_3\text{H}_2$ 2–1 at four different positions. The contour levels are 30–100 per cent, in steps of 15 per cent of the peak intensities, for SiO and $c\text{-C}_3\text{H}_2$ 2–1. $c\text{-C}_3\text{H}_2$ 3–2 are 45–100 per cent, in steps of 15 per cent of the peak intensity. The middle panel shows $c\text{-C}_3\text{H}_2$ emissions in DR21S: (left) velocity-integrated intensity maps of $c\text{-C}_3\text{H}_2$ 3–2 (red dashed line, -6.5 to 2 km s^{-1}) overlaid on $c\text{-C}_3\text{H}_2$ 2–1 (-6.5 to 2 km s^{-1}); (right) spectrum of $c\text{-C}_3\text{H}_2$ overlaid on velocity-integrated intensity map of $c\text{-C}_3\text{H}_2$ 2–1 absorption component (5.6 – 12 km s^{-1}). The contour levels are 30–100 per cent, in steps of 15 per cent of the peak intensity, for $c\text{-C}_3\text{H}_2$ 3–2 and $c\text{-C}_3\text{H}_2$ 2–1. The lower panel shows: (left) velocity-integrated intensity maps of $c\text{-C}_3\text{H}_2$ 3–2 (red dash line) overlaid on $c\text{-C}_3\text{H}_2$ 2–1 in G34; (right) velocity-integrated intensity maps of $c\text{-C}_3\text{H}_2$ 3–2 (red dashed line) and CS 3–2 (green dashed line) overlaid on $c\text{-C}_3\text{H}_2$ 2–1 (blue line) in S76E. The contour levels are 30–100 per cent, in steps of 15 per cent of the peak intensity, for $c\text{-C}_3\text{H}_2$ 3–2 and $c\text{-C}_3\text{H}_2$ 2–1. CS are 80, 90 and 100 per cent. The ellipse and circle in the bottom-left corner show the beam sizes (HPBW) of the observations. (A colour version of this figure is available in the online version.)

$^{16}\text{O}/^{18}\text{O}$

With the double isotope method, we derived the $^{16}\text{O}/^{18}\text{O}$ isotopic ratios with $\text{H}^{13}\text{CO}^+(1-0)$, $\text{HC}^{18}\text{O}^+(1-0)$ and the ratio of $^{12}\text{C}/^{13}\text{C}$. The local ISM value (557 ± 30) is slightly higher than our results (Wilson 1999), which are about 422, 415, 532 and 288 in Cep A,

S76E DR21S and G34, respectively. The ratio of ~ 288 found in G34 is consistent with 287 ± 27 found in Orion derived from OCS and its isotopologues (Tercero et al. 2010). The fractionation of oxygen can be ignored because of its high first ionization potential (Langer et al. 1984).

Figure 3. Shock tracers and deuterated molecules in Cep A. The grey-scale is radio continuum (VLA 8.4 GHz) and the range indicated in the wedge is in Jy beam⁻¹. The upper panel shows, from left to right: velocity-integrated intensity maps of SiO 2–1 (–13.5 to –1.3 km s⁻¹), SO 2–1 (–14 to –4 km s⁻¹) and CS 3–2 (red dashed line, –17 to 0 km s⁻¹) overlaid on SiO 2–1 (blue line). The middle panel shows, from left to right: channel map of SO 2–1, the spectra of SO 2–1 (black line) overlaid on HCO⁺ 1–0 (red line). The lower panel shows, from left to right: velocity-integrated intensity maps of DCN 1–0 (–15 to –5 km s⁻¹), NH₂D 1–1 (red dashed line, –20 to –5 km s⁻¹) overlaid on DCO⁺ 2–1 (blue line, –15 to –5 km s⁻¹). The contour levels are 30–100 per cent, in steps of 15 per cent of the peak intensities, for these molecular lines. The ellipse and circle in the bottom-left corner show the beam sizes of the observations.

³⁴S/³³S

The C³³S 3–2 and C³⁴S 3–2 lines are optically thin (Goicoechea et al. 2006), and thus their flux ratio can be used to derive the ratios of ³⁴S/³³S. The ratios of ³⁴S/³³S are 5.1, 4.7 and 5.5 in DR21S,

G34 and S76E, respectively. These values are in agreement with the local ISM (~6) and Orion KL (~5) isotope abundance ratios (Chin et al. 1996; Persson et al. 2007; Tercero et al. 2010). For Cep A, the ³⁴S/³³S isotope ratio was not derived, because the C³³S 3–2 line was not detected.

Figure 4. Shock tracers and deuterated molecules in DR21S. The grey-scale is radio continuum (VLA 8.4 GHz) and the range indicated in the wedge is in Jy beam⁻¹. The upper panel shows, from left to right: velocity-integrated intensity maps of SiO 2–1 (–20 to 20 km s⁻¹), HNC 4–3 (–8 to 3 km s⁻¹), SO 2–1 (–8 to 3 km s⁻¹), where the red triangle indicates the position of the CH₃OH 5_{-1,5}–4_{0,4} E maser. The contour levels are 30–100 per cent, in steps of 15 per cent of the peak intensity, for SiO 2–1, HNC 4–3, SO 2–1 and HCO⁺ 1–0. The middle panel shows the spectra of HCO⁺ 1–0 and CH₃OH 5_{-1,5}–4_{0,4} E. The lower panel shows, from left to right: velocity-integrated intensity maps of DCN 2–1 (–9 to 5 km s⁻¹), SO 2–1 (red dashed line) overlaid on DCO⁺ 2–1 (–5.5 to 2 km s⁻¹), NH₂D 1–1 (–7.5 to 5 km s⁻¹) and spectra of C₂D 2–1. The contour levels are 30–100 per cent, in steps of 15 per cent of the peak intensity, for these molecular lines. The ellipse and circle in the bottom-left corner show the beam sizes of the observations.

Table 2. Isotope abundance ratios. The errors of isotope ratios were calculated by the error propagation equation in Bevington & Robinson (2003).

Source	¹² C/ ¹³ C	¹⁴ N/ ¹⁵ N	¹⁶ O/ ¹⁸ O	³⁴ S/ ³³ S	N(DCN)/N(HCN)	N(DCO ⁺)/N(HCO ⁺)
Cep A	49.0 ± 8.6	214.1 ± 41.3	422.1 ± 87.9		(2.4 ± 0.5) × 10 ⁻³	(7.9 ± 1.6) × 10 ⁻⁴
DR21S	32.8 ± 2.4	109.9 ± 11.2	532.9 ± 113.1	5.1 ± 0.8	(3.6 ± 0.4) × 10 ⁻³	(1.5 ± 0.2) × 10 ⁻³
G34	38.7 ± 2.7	289.2 ± 23.6	287.9 ± 27.4	4.7 ± 0.3	(1.3 ± 0.1) × 10 ⁻³	(3.5 ± 0.7) × 10 ⁻⁴
S76E	46.4 ± 4.2	304.2 ± 31.9	415.9 ± 60.1	5.5 ± 0.4	(1.1 ± 0.1) × 10 ⁻³	(9.8 ± 4.8) × 10 ⁻⁴
Local interstellar medium	60–70 (1) ^a	400 (2) ^a	557 ± 30 (3) ^a	6.3 ± 1 (4) ^a		

^aReferences are: (1) Milam et al. (2005); (2) Terzieva & Herbst (2000); (3) Wilson (1999); (4) Chin et al. (1996).

D/H

Several deuterated molecules were found in all four sources. DCN, DCO⁺, H¹³CN and H¹³CO⁺ are adopted to derive the abundance ratios of N(DCN)/N(HCN) and N(DCO⁺)/N(HCO⁺), and the ¹²C/¹³C

ratios are obtained with HC₃N and its isotopologues. To derive the abundance ratio of D/H, we adopt several assumptions. First, we assume local thermal equilibrium (LTE) conditions and optically thin for all these lines. In addition, these lines have similar excitation

temperatures, emitting regions and filling factors. With the above assumptions, we derived the abundance (column density) ratio using the formula from Sakai et al. (2012):

$$\begin{aligned} \frac{N(\text{DCN})}{N(\text{H}^{13}\text{CN})} &= \left(\frac{\mu_{0,\text{H}^{13}\text{CN}}}{\mu_{0,\text{DCN}}} \right)^2 \left(\frac{\nu_{\text{H}^{13}\text{CN}}}{\nu_{\text{DCN}}} \right)^2 \\ &\times \exp \left(\frac{E_{u,\text{DCN}} - E_{u,\text{H}^{13}\text{CN}}}{kT_{\text{ex}}} \right) \\ &\times \frac{1 - [J_{\text{H}^{13}\text{CN}}(T_{\text{BB}})/J_{\text{H}^{13}\text{CN}}(T_{\text{ex}})]}{1 - [J_{\text{DCN}}(T_{\text{BB}})/J_{\text{DCN}}(T_{\text{ex}})]} \\ &\times \frac{I_{\text{DCN}}}{I_{\text{H}^{13}\text{CN}}}. \end{aligned} \quad (1)$$

Here, N is the column density, μ_0 is the dipole moment, ν is the rest frequency of the line, E_u is the upper state energy, T_{ex} is the excitation temperature, T_{BB} is the background radiation temperature (2.7 K), I is the velocity-integrated in T_{mb} and $J(T)$ is the Planck function written as

$$J(T) = \frac{(h\nu)/k}{\exp(h\nu/kT) - 1}. \quad (2)$$

The values of μ_0 , ν and E_u are shown in Table B1. Equation (1) can be reduced to

$$\frac{N(\text{DCN})}{N(\text{H}^{13}\text{CN})} \simeq 0.42 \exp \left(\frac{6.28}{T_{\text{ex}}} \right) \frac{I_{\text{DCN}}}{I_{\text{H}^{13}\text{CN}}}. \quad (3)$$

We can also derive the $N(\text{DCO}^+)/N(\text{H}^{13}\text{CO}^+)$ ratio with the same method:

$$\frac{N(\text{DCO}^+)}{N(\text{H}^{13}\text{CO}^+)} \simeq 0.29 \exp \left(\frac{6.21}{T_{\text{ex}}} \right) \frac{I_{\text{DCO}^+}}{I_{\text{H}^{13}\text{CO}^+}}. \quad (4)$$

We take T_{ex} from the highest value of the rotational temperature of CH_3CN (Table 3), which is discussed in Section 4.1.

The column density ratios of $N(\text{DCN})/N(\text{HCN})$ and $N(\text{DCO}^+)/N(\text{HCO}^+)$ are converted by $N(\text{DCN})/N(\text{H}^{13}\text{CN})$ and $N(\text{DCO}^+)/N(\text{H}^{13}\text{CO}^+)$, with the $^{12}\text{C}/^{13}\text{C}$ ratios derived from the aforementioned method for each source. The ratios of $N(\text{DCN})/N(\text{HCN})$ are slightly higher than $N(\text{DCO}^+)/N(\text{HCO}^+)$, while these values are two orders of magnitude higher than the elemental $[\text{D}]/[\text{H}] \sim 1.5 \times 10^{-5}$ ratio (Linsky et al. 2006). These ratios are consistent with 0.018–0.08 from a study of DNC and HNC towards UCH II regions, which are an order of magnitude lower than the high-mass starless core candidates (HMSCs; Fontani

et al. 2014). This result confirms the theoretical prediction that the deuterated fraction (column density ratio between a deuterated molecule and its hydrogenated counterpart, D_{frac}) decreases with the core evolution after the YSO formed (Caselli 2002). The high D_{frac} found in our sources is likely because the abundances of deuterated molecules were enhanced in cold molecular clouds before the formation of the protostar or warm deuterium chemistry derived by CH_2D^+ and/or C_2HD^+ (Parise et al. 2009). These ratios are summarized in Table 2.

3.4 Long carbon chain molecules

3.4.1 $c\text{-C}_3\text{H}_2$

Two lines of $c\text{-C}_3\text{H}_2$ ($2_{1,2}\text{-}1_{0,1}$, $3_{1,2}\text{-}2_{2,1}$) were detected in all four sources. As a small cyclic hydrocarbon, $c\text{-C}_3\text{H}_2$ was first detected towards Sgr B2 (Thaddeus, Vrtillek & Gottlieb 1985), and then was detected in a variety of sources (Vrtillek, Gottlieb & Thaddeus 1987; Madden et al. 1989; Lucas & Liszt 2000; Qi et al. 2013). $c\text{-C}_3\text{H}_2$ is easily dissociated by radiation from the central star (Qi et al. 2013). Acetylene (C_2H_2), which is released from polycyclic aromatic hydrocarbons (PAHs), has been used to explain the $c\text{-C}_3\text{H}_2$ enhancement in UV exposed regions (Fuente et al. 2003).

The velocity-integrated intensity map of $c\text{-C}_3\text{H}_2$ 2–1 shows a cavity around the emission peak of the 8.4-GHz radio continuum in DR21S (Fig. 2). However, the $c\text{-C}_3\text{H}_2$ 3–2 emission peaks at the radio continuum emission peak, which implies that the abundance of $c\text{-C}_3\text{H}_2$ in the radio continuum emission peak region should not be lower than its surrounding region. In addition, the spectra of $c\text{-C}_3\text{H}_2$ 2–1 have an absorption feature towards the cavity region as shown in Fig. 2. Therefore, the cavity feature of $c\text{-C}_3\text{H}_2$ 2–1 towards the radio continuum emission peak should be caused by absorption. The velocity-integrated intensity map of $c\text{-C}_3\text{H}_2$ 2–1 in G34 also shows an absorption feature similar to that in DR21S (Fig. 2). In Fig. 2, we also show the velocity-integrated intensity map of $c\text{-C}_3\text{H}_2$ in S76E, with two emission peaks. The slightly different spatial distributions between $c\text{-C}_3\text{H}_2$ 2–1 and 3–2 might be because both transitions have different excitation conditions.

As shown in Fig. 2, the $c\text{-C}_3\text{H}_2$ 2–1 emission in CepA is resolved into three main condensations, which are labelled P1, P2 and P3 in a clockwise direction. Similar to DR21S and G34, the $c\text{-C}_3\text{H}_2$ cavity on top of the radio continuum peak is caused by absorption.

Table 3. Results of the rotation diagram analysis for CH_3CN with multiple transitions. From the mapping results, we only selected the positions that detected three transitions of CH_3CN for calculating T_{rot} and N_{tot} .

Position (arcsec)	Cep A		DR21S		G34		S76E	
	T_{rot} (K)	N_{tot} ($\times 10^{13} \text{ cm}^{-2}$)	T_{rot} (K)	N_{tot} ($\times 10^{13} \text{ cm}^{-2}$)	T_{rot} (K)	N_{tot} ($\times 10^{13} \text{ cm}^{-2}$)	T_{rot} (K)	N_{tot} ($\times 10^{13} \text{ cm}^{-2}$)
(0, 0)	39 ± 9	1.0 ± 0.3	47 ± 4	4.0 ± 0.5				
(0, 15)			45 ± 9	2.6 ± 0.8			40 ± 4	53.7 ± 8
(0, 30)			33 ± 6	1.6 ± 0.4				
(0, −15)			20 ± 2	1.9 ± 0.3			47 ± 13	1.9 ± 0.7
(0, −30)			24 ± 4	1.4 ± 0.3				
(15, 0)							35 ± 4	3.0 ± 0.4
(15, 15)	71 ± 27	1.1 ± 0.6						
(−15, 15)					68 ± 2	15.4 ± 0.1		
(−15, 30)					38 ± 3	3.8 ± 0.4		
(−15, 45)					26 ± 3	1.0 ± 0.2		
(−15, 60)					33 ± 7	1.1 ± 0.3		
(−30, 15)	45 ± 15	0.7 ± 0.3						
(−30, −15)							44 ± 13	0.9 ± 0.3

The $c\text{-C}_3\text{H}_2$ emission is associated with CS 3–2 emission in P1 and P3, while CS emission is weaker in P2. The $c\text{-C}_3\text{H}_2$ line emission in P1 is stronger and narrower than in P2 and P3. Because $c\text{-C}_3\text{H}_2$ has a similar spatial distribution and line profile compared to SO, which is considered to be a low-velocity shock tracer in massive star-forming regions (Podio et al. 2015), we suggest that the main mechanism that enhances the abundance of $c\text{-C}_3\text{H}_2$ in the P2 region is likely to be low-velocity shock activity.

3.4.2 Other long carbon chain molecules

We also detected some other long carbon chain molecules, including the cyanopolynes (HC_{2n+1}N), such as cyanoacetylene (HC_3N), cyanodiacetylene (HC_5N) and C_4H . Three high- J excitation lines of HC_3N ($J = 34\text{--}33$, $J = 33\text{--}32$ and $J = 32\text{--}31$), two transitions of HC_5N (10–9 and 16–15) and their isotopologues (HCC^{13}CN 10–9 and HC^{13}CCN 10–9) were detected in these targets. The HC_3N isomer molecule of HCCNC and C_3S 15–14 was only detected in DR21S and G34, respectively. $\text{CH}_3\text{C}_5\text{N}$ was only detected in G34, which is the largest molecule in this observation. We present these spectra in Fig. A1.

3.5 ONCN

Nitrosyl cyanide ONCN ($14_{0,14}\text{--}13_{0,13}$, 145 397.59 MHz) emission, which has an upper level energy E_u of 52.4 K and an Einstein A coefficient A_{ij} of 2.66×10^{-5} , was detected in G34. It is the first detection of ONCN in massive star formation regions. Fig. 9 presents the spectra and the velocity-integrated intensity map of ONCN, which shows an anticorrelation with the ionized gas tracer H41 α . ONCN emission not associated with either the core or the shock activity. The ONCN line was not detected in previous observations probably because its emission is not focused on the centre of source, and previous observations did not cover this frequency.

4 DISCUSSION

4.1 Excitation and column densities

In all four sources, we have detected several transitions of CH_3CN (methyl cyanide), which is an excellent probe of gas temperature in warm dense environments (Goldsmith & Langer 1999). We estimated the excitation conditions of CH_3CN using the population diagram method introduced by Goldsmith & Langer (1999):

$$\ln\left(\frac{N_u}{g_u}\right) = \ln\left(\frac{N_{\text{tot}}}{Q_{\text{rot}}}\right) - \frac{E_u}{kT_{\text{ex}}} - \ln\left(\frac{\Omega_{\text{source}}}{\Omega_{\text{beam}}}\right) - \ln(C_\tau). \quad (5)$$

Here, $f_{\text{beam}} = \Omega_{\text{source}}/\Omega_{\text{beam}}$ is the beam filling factor and $C_\tau = \tau/(1 - e^{-\tau})$, where τ is the optical depth. For a uniform beam filling ($\Omega_{\text{beam}} \sim \Omega_{\text{source}}$) and low optical depth, the population diagram reduces to a rotational diagram with a rotational temperature T_{rot} and total column density N_{tot} . Column density (N_{tot}) and rotational temperature (T_{rot}) can be estimated based on

$$\ln\left(\frac{N_u}{g_u}\right) = \ln\left(\frac{N_{\text{tot}}}{Q_{\text{rot}}}\right) - \frac{E_u}{kT_{\text{rot}}}. \quad (6)$$

Here, N_u is the observed upper state column density of the molecule including line opacity and beam–source coupling effects, g_u is the degeneracy of the upper state, Q_{rot} is the rotational partition function, k is the Boltzmann constant and E_u is the upper level energy.

The rotation diagrams are shown in Fig. A2. Under the LTE assumption, the excitation temperature is the same as the rotational temperature. The excitation temperatures of CH_3CN in G34

(~ 68 K) and Cep A (~ 71 K) are higher than DR21S (~ 47 K) and S76E (~ 47 K). While the total column density of CH_3CN in G34 ($\sim 1.5 \times 10^{14} \text{ cm}^{-2}$) and S76E ($\sim 5.4 \times 10^{14} \text{ cm}^{-2}$) are higher than in Cep A ($\sim 1.1 \times 10^{13} \text{ cm}^{-2}$) and DR21S ($\sim 4.0 \times 10^{13} \text{ cm}^{-2}$). CH_3CN in G34 has a higher excitation temperature and higher column density than those in the other three sources, indicating that G34 is in a more evolved stage. The high excitation temperature of CH_3CN found in Cep A might be affected by the radio jet from HW2. We summarize the diagnostic results of CH_3CN in Table 3.

4.2 Shock-related molecules

Cep A

Fig. 3 shows the velocity-integrated intensity map of SiO 2–1, which is a fast shock tracer (e.g. Qiu et al. 2007). The SiO emission stretches along the direction of NE–SW, indicating that the shock is in the NE–SW direction, which is consistent with the results in the literature (Codella et al. 2006). SiO emission peaks are located at two positions: offset (0 arcsec, 0 arcsec) with v_{LSR} of -9.77 km s^{-1} , and offset (30 arcsec, 30 arcsec) with v_{LSR} of -8.38 km s^{-1} , which gives a velocity gradient of $\sim 0.66 \text{ km s}^{-1} \text{ kau}^{-1}$ (1 arcsec = 700 au at the given distance of 0.7 kpc). The linewidth of the second peak (8.57 km s^{-1}) is broader than that of the first peak (5.55 km s^{-1}).

SO is an important shock tracer in star formation regions (Podio et al. 2015), and it can be significantly enhanced by low-velocity shocks (Chernin, Masson & Fuller 1994). From the channel map of SO (Fig. 3), it appears that the -5.36 km s^{-1} component of SO shows similar spatial distribution as SiO. This might be because both emissions are affected by a central star, as they are emissions associated with radio continuum. SO also shows strong emission in the northern region (P2) of the core at a velocity of -9.44 km s^{-1} , and its spectra profile shows a blueshifted line wing with high T_{mb} and a narrow linewidth. The HCO^+ 1–0 emission in P2 also shows a blue profile; the spectrum presents a blueshifted emission and redshifted absorption, which are considered as a signature of infalling gas (Liu, Wu & Zhang 2013). Thus, low-velocity shocks likely dominate gas properties here, because of the gas infall.

DR21S

Fig. 4 shows the velocity-integrated intensity maps of shock tracers (SiO 2–1, HNC 4–3, SO 2–1). They show strong emission on the south side of the core with narrow linewidth. This region likely has shock activity, which is consistent with previous observations (see Fig. A1: A 4–2 in Davis et al. 2007). As shown in Fig. 4, a blueshifted line wing with an inverse P Cygni profile of HCO^+ can be seen in the western region of the core, while SiO, HNC and SO are without obvious emission in this region. Class I CH_3OH maser emission at 84.5 GHz was also detected in this region, and it was considered to be associated with outflows/inflows in the star-forming region (Sobolev 1993). These results are consistent with previous high spatial resolution observations that detected several shock activities (see Fig. A2: B 1–1, B 1–2 and B 1–3 in Davis et al. 2007).

G34

We detected several shock gas tracers in G34, including SO 2–1, HNC 4–3, SiO 2–1 and its isotopologues (^{29}SiO 2–1 and

Figure 5. Shock tracers and deuterated molecules in G34. The grey-scale is radio continuum (VLA 8.4 GHz) and the range indicated in the wedge is in Jy beam⁻¹. The upper panel shows, from left to right: velocity-integrated intensity maps of SiO 2-1 (50–70 km s⁻¹), HNC 4-3 (52–65 km s⁻¹) and SO 2-1 (52–70 km s⁻¹). The contour levels are 30–100 per cent, in steps of 15 per cent of the peak intensity, for SiO 2-1, HNC 4-3, SO 2-1 and HCO⁺ 1-0. The middle panel shows the spectra of HCO⁺ 1-0 (first row), CS 3-2 (second row) and SiO 2-1 (third row). The lower panel shows, from left to right: velocity-integrated intensity maps of DCN 2-1 (50–65 km s⁻¹), DCO⁺ 2-1 (53–61 km s⁻¹), SiO 2-1 (red dashed line) overlaid on NH₂D 1-1 (50–65 km s⁻¹), the spectra of HDCS 3-2. The contour levels are 30–100 per cent, in steps of 15 per cent of the peak intensity, for DCN 2-1, DCO⁺ 2-1, SiO 2-1 and NH₂D 1-1. The ellipse and circle in the bottom-left corner show the beam sizes of the observations.

³⁰SiO 2-1). They show strong emission in the west region of the core (Fig. 5); this shocked region and the tracer velocity are in agreement with the results of the study of SiO in Hatchell et al. (2001). Their emitting region corresponds to a cometary CH_{II} region, which is called C in the literature (Mookerjee et al. 2007). Fig. 5 shows that the spectra of HCO⁺ present a blueshifted line wing with an inverse P Cygni profile in the western region. CS 3-2 emission also shows a redshifted absorption feature in the same region. These features

might be the result of the gas infalling towards the cometary H_{II} region called C (e.g. Liu et al. 2013).

S76E

Fig. 6 shows the velocity-integrated intensity maps of SiO 2-1 and SO 2-1. Their emission is only associated with part of the radio continuum emission, in the south-west side of the core. The

Figure 6. Shock tracers and deuterated molecules in S76E. The grey-scale is radio continuum (VLA 8.4 GHz) and the range indicated in the wedge is in Jy beam⁻¹. The upper panel shows, from left to right: velocity-integrated intensity maps of SiO 2-1 (25–55 km s⁻¹), SO 2-1 (30–40 km s⁻¹). The contour levels are 30–100 per cent, in steps of 15 per cent of the peak intensity, for SiO 2-1 and SO 2-1. The middle panel shows, from left to right: velocity-integrated intensity maps of redshift velocity component (25–33.5 km s⁻¹) of SiO 2-1 overlaid on its blueshift velocity component (33.5–55 km s⁻¹) and the position-velocity diagram of SiO 2-1 (PA = 90°). The contour levels are 30–100 per cent, in steps of 15 per cent of the peak intensity, for SiO 2-1. The lower panel shows: (left) velocity-integrated intensity maps of SiO 2-1 (green dashed line) and NH₂D 1-1 (red dashed line, 28–38 km s⁻¹) overlaid on DCN 2-1 (blue line, 30–38 km s⁻¹), where the contour levels are 30–100 per cent, in steps of 15 per cent of the peak intensity, for SiO 2-1, NH₂D 1-1 and DCN 2-1; (middle) DCO⁺ 2-1 line profile; (right) C₂D 2-1 line profile. The ellipse and circle in the bottom-left corner show the beam sizes of the observations.

velocity-integrated intensity map of SiO redshifted emission, integrated from 33.5 to 47 km s⁻¹, shows similar spatial distribution to the blueshifted emission, integrated from 28.2 to 33.5 km s⁻¹. In Fig. 6, we show the position-velocity diagram of SiO, which presents a strong blueshifted emission.

In all four sources, we have detected several shock gas tracers, including SO, HNC, SiO and its isotopologues, at a level of $>5\sigma$. The SiO emission is usually associated with strong shocks, and it is an ideal probe for revealing the processes of jet/outflow activity associated with young protostars, such as in the case of Cep A. SO can be enhanced not only in hot cores, but also in shocked regions. This emission likely can be enhanced by low-velocity shocks, be-

cause of the gas infall, such as in the P2 region of Cep A. These tracers provide a powerful tool to investigate the shock processes in star formation regions.

4.3 Deuterium-bearing molecules

The deuterated molecules are widespread in massive star-forming regions (Caselli et al. 2012). High D_{frac} towards these regions provide a chemical ‘fingerprint’ of physical conditions (Shah & Wootten 2001). We have detected DCN 2-1, DCO⁺ 2-1 and NH₂D 1-1 in all four sources, C₂D 2-1 in three sources, except for G34, and HDCS (3-2) in G34.

Figure 7. $(CH_3)_2CO$ and $He42\alpha$ in DR21S. The left panel shows velocity-integrated intensity maps of $H41\alpha$ (red dashed line, -35 to 35 $km\ s^{-1}$) overlaid on $(CH_3)_2CO$ (-6 to 1 $km\ s^{-1}$). The contour levels are 15–100 per cent, in steps of 15 per cent of the peak intensity, for $(CH_3)_2CO$ 23–22 and $H41\alpha$. The ellipse in the bottom-left corner shows the beam sizes of the observations. The right panel shows the $He42\alpha$ line profile at offset (0, 0).

Figure 8. HCO , HC_3N and $H41\alpha$ in G34. The left panel shows velocity-integrated intensity map of $H41\alpha$ (red dashed line, -10 to 105 $km\ s^{-1}$) overlaid on HCO 1–0 (55 – 64 $km\ s^{-1}$). The right panel shows velocity-integrated intensity map of $H41\alpha$ (red dashed line) overlaid on HC_3N 10–9 (52 – 64 $km\ s^{-1}$). The contour levels are 30–100 per cent, in steps of 15 per cent of the peak intensity, for HCO 1–0, HC_3N 10–9 and $H41\alpha$. The circle in the bottom-left corner shows the beam sizes of the observations.

Figure 9. Velocity-integrated intensity map and spectra of $ONCN$ 14–13 in G34. Velocity-integrated intensity map of $H41\alpha$ (red dashed line) overlaid on $ONCN$ 14–13 (52.5 – 58.5 $km\ s^{-1}$). The contour levels are 15–100 per cent, in steps of 15 per cent of the peak intensity, for $ONCN$ 14–13 and $H41\alpha$. The ellipse in the bottom-right corner shows beam sizes of the observations.

Cep A

The velocity-integrated intensity maps of DCN 2–1 and DCO^+ 2–1 show different spatial distributions compared to the radio continuum emission (Fig. 3). DCO^+ emissions are resolved into three main condensations surrounding the emission peak of radio continuum with different line central velocities, which are labelled M1, M2 and M3 in a clockwise direction. The velocity is -12.0 km s^{-1} in M1, -10.1 km s^{-1} in M2 and -9.7 km s^{-1} in M3. The DCO^+ emission in M1 and M3 has comparable linewidths (FWHM) of $\sim 1.4 \text{ km s}^{-1}$, which is broader than 1.0 km s^{-1} in M2. DCN and NH_2D also show strong emission around the M1 region, and DCN presents a similar spatial distribution to DCO^+ in M1. The deuterated molecules have likely been enhanced around the M1 region, as there is strong emission of DCO^+ , DCN and NH_2D . As discussed in Section 4.2, there is strong shock activity in the M1 region and low-velocity shock activity in the M2 region. Moreover, weak emission of SiO towards M3 indicates that there is likely to be an association with intermediate shock activity.

Two main pathways are considered for forming deuterated molecules in different temperature ranges: at a low temperature of $T \sim 10\text{--}30 \text{ K}$, the dominant pathway is via H_3^+ isotopologues; at a slightly higher temperature of $T \sim 30\text{--}80 \text{ K}$, the dominant pathway is via light hydrocarbons (CH_2D^+ and C_2HD^+) (Albertsson et al. 2013). The DCO^+ is considered to form mainly at low temperatures through H_3^+ isotopologues, and thus it is expected to be formed during the pre-stellar phase and to be sensitive to freeze-out (Albertsson et al. 2013). One possible explanation why DCO^+ shows strong emission around the M2 and M3 regions is that its abundance has been enhanced by shock, as it is likely to be injected into the gas phase from the grain mantles through shock activity (Mangum, Plambeck & Wootten 1991). The DCO^+ emission around M1 is not only associated with radio continuum emission, but also in the vicinity of the shocked region with the same velocity compared to SiO (-9.7 km s^{-1}), as well as the DCN emission. The DCN is considered to be formed by light hydrocarbons at a relatively high temperature of $T \sim 30\text{--}80 \text{ K}$ (Albertsson et al. 2013), and it is not mainly formed on a grain surface. The gas, in the surrounding areas of a central young protostar, will be warming with the shock activity and evolution of dense cores. This might be responsible for the enhancement of DCO^+ and DCN emission around the M1 region, as DCO^+ can be released into the gas phase from dust grains and DCN can be formed with an increase in temperature. DCO^+ shows a cavity in the vicinity of the emission peak of radio continuum, which might be because there are low abundances or it was destroyed by high temperatures (heated by the central star), as DCO^+ can be destroyed in a high-temperature environment (Pety et al. 2007). NH_2D is considered to be formed at low-temperature ($<30 \text{ K}$) and high-density ($\simeq 10^6 \text{ cm}^{-3}$) regions (e.g. starless cores, protostars), and it can be formed not only via gas-phase reactions but also via grain-surface reactions with D atoms (Tielens 1983). The NH_2D shows strong emission around the shocked region (M1), implying that it likely has been released into the gas phase from dust grains through shock activity (e.g. Mookerjee et al. 2009).

DR21S

As shown in Fig. 4, the emission peaks of DCN 2–1, DCO^+ 2–1 and NH_2D 1–1 are away from the emission peak of radio continuum. In addition, both DCO^+ and NH_2D show obvious emission on the south side of the core, where they are likely dominated by shock activity considering the aforementioned shock tracers. The

shock interacts with ambient gas/dust, which can affect the chemical composition of the grain mantles and of the molecular gas, and is possibly responsible for the enhancement of DCO^+ and NH_2D emission on the south side of the core. For $C_2D(2\text{--}1)$, the signal-to-noise ratio is not good enough to make a velocity-integrated map, and its spectrum is shown in Fig. 4.

G34

The velocity-integrated intensity maps and spectra of deuterated molecules are presented in Fig. 5. Both DCN 2–1 and NH_2D 1–1 show obvious emission on the west side of the core, where it is associated with shock activity as suggested by evidence of SiO and SO. This indicates that the shock activity is likely responsible for the enhancement of DCO^+ and NH_2D emission in this region, as the gas temperature can be increased in the shocked region, and both molecules can be evaporated to gas phase from the dust grain with an increase in temperature. DCO^+ 2–1 shows obvious emission on the north side of the core, as well as NH_2D . The gas temperature in this region is around 30 K derived from CH_3CN . Both DCO^+ and NH_2D lines can be excited in such high-temperature environments. We present the spectrum of HDCS 3–2 in Fig. 5 instead of the velocity-integrated intensity map, because of the low signal-to-noise ratio.

S76E

Fig. 6 shows the velocity-integrated intensity maps of DCN 2–1 and NH_2D 1–1. Both NH_2D and DCN emissions are in the vicinity of the radio continuum emission, although the emission looks more extended in NH_2D . NH_2D shows obvious emission in the southwestern region of the radio continuum emission, where we also found obvious SiO emission. This indicates that the NH_2D emission is likely associated with shock activity in this region. We show the spectra of DCO^+ 2–1 and C_2D 2–1 in Fig. 6 instead of velocity-integrated intensity maps, because of the low signal-to-noise ratio.

From the above analysis, we note that the NH_2D emission has been enhanced by shock activity towards all sources, while DCO^+ and DCN emission have been enhanced by shock activity only in some cases (e.g. Cep A and DR21S for DCO^+ ; Cep A and G34 for DCN).

5 SUMMARY AND FUTURE PROSPECTUS

We have carried out spectral line mapping observations towards four massive star-forming regions (CepA, DR21S, G34 and S76E) with the IRAM 30-m telescope. Our main results are summarized as follows.

(i) A total of 395 spectral features were detected in four massive star-forming regions. In total, we identified 61 lines from 25 molecules in Cep A; 78 lines from 43 molecules, an unidentified line, a helium combination line and six RRLs in DR21S; 169 lines from 86 molecules, three RRLs and nine unidentified lines in G34; 78 lines from 44 molecules, one RRLs and six unidentified lines in S76E.

(ii) We detected a large oxygen-bearing molecule of acetone ($(CH_3)_2CO$) in DR21S. For all four sources, we detected three transitions of HC_5N , two transitions of HC_3N and its isotopologues of $HCC^{13}CN$ and $HC^{13}CCN$ in all four sources. The HC_3N isomeride molecule $HCCNC$ was only detected in DR21S, while C_3S was

detected in G34 and C₄H was detected in DR21S and S76E. The nitrosyl cyanide ONCN(14_{0,14}-13_{0,13}) emission, as the first detection of ONCN in a massive star-forming region, was detected in G34, and its emission shows anticorrelation with the RRLs.

(iii) We derived several isotope abundance ratios in each source (e.g. ¹²C/¹³C, ¹⁴N/¹⁵N, ¹⁶O/¹⁸O and ³³S/³⁴S). The ¹²C/¹³C ratios are about 40, which is slightly lower than the ratio of 60–70 found in the local ISM (Milam et al. 2005). The ¹⁴N/¹⁵N ratios are from 109 to 304, and the ¹⁶O/¹⁸O ratios are from 287 to 532. The ³³S/³⁴S ratios are about 5, except for CepA, in which the C³³S 3–2 line is not detected. The ratios of N(DCN)/N(HCN) and N(DCO⁺)/N(HCO⁺) in each source are two orders of magnitude higher than the elemental [D]/[H] ratio (1.5×10^{-5}), which is consistent with results in the literature (Parise et al. 2009).

(iv) Several shock tracers (SiO, SO and HNC) were detected and used to investigate the shock properties in these star-forming regions. Comparing these shock tracers and deuterated molecules, we found that NH₂D emission can be enhanced in the shocked region, and both DCO⁺ and DCN emissions can also be enhanced towards the shocked region in some cases (e.g. Cep A and DR21S/G34).

(v) The CH₃CN lines are used to derive the rotational temperature and column density of this line in each source, which show the highest excitation temperature and column density in G34.

Mapping observations of multiple lines towards massive star-forming regions at different evolutionary stages allows detailed studies of chemical properties, shock activities and physical conditions. Sensitive high-angular resolution observations with (sub)millimetre interferometers, such as ALMA, will be a powerful tool to constrain chemical and physical properties during the massive star formation process.

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APPENDIX A: MOLECULAR LINE PROFILES

Figure A1. Spectra of long carbon chain molecules.

Figure A2. Rotation diagrams for the $\text{CN}_3\text{CN } J = 5_k-4_k$ lines observed at Cep A, DR21S, G34 and S76E, respectively. Offset position and source name are given in the upper-right corners.

APPENDIX B: PARAMETERS OF MOLECULAR LINES

Table B1. The line information. The parameters of molecular lines were assigned using CDMS.

Species	Transition	Rest frequency (MHz)	E_u/k	$(\mu_0)^2$ (D)
DCN	2–1	144828.11	10.43	13.42
H^{13}CN	1–0	86342.26	4.14	15.85
DCO^+	2–1	144077.29	10.37	7.89
H^{13}CO^+	1–0	86754.29	4.16	6.34

Table B2. Cep A.

Molecule	Transition	Frequency (MHz)	$\int T_{\text{mb}} dv$ (K km s ⁻¹)	v_{LSR} (km s ⁻¹)	FWHM (km s ⁻¹)	T_{mb} (K)
CH ₃ OH	$vt = 0, 1\ 5(-1, 5)-4(0, 4)\text{E}$	84521.16	0.63 ± 0.05	-10.80 ± 0.13	3.66 ± 0.32	0.16
HC ¹⁸ O ⁺	1-0	85162.22	0.39 ± 0.04	-10.85 ± 0.19	3.52 ± 0.39	0.11
HC ₅ N	$v = 0\ 32-31$	85201.34	0.29 ± 0.05	-11.62 ± 0.24	3.15 ± 0.66	0.05
<i>c</i> -C ₃ H ₂	2(1,2)-1(0,1)	85338.89	1.01 ± 0.04	-10.49 ± 0.07	3.38 ± 0.17	0.28
HCS ⁺	2-1	85347.89	0.34 ± 0.04	-10.81 ± 0.22	3.61 ± 0.48	0.09
CH ₃ CCH	5(3)-4(3)	85442.60	0.22 ± 0.06	-10.73 ± 0.67	4.71 ± 1.91	0.04
CH ₃ CCH	5(2)-4(2)	85450.76	0.49 ± 0.05	-10.77 ± 0.18	3.55 ± 0.38	0.13
CH ₃ CCH	5(1)-4(1)	85455.66	0.90 ± 0.04	-10.70 ± 0.07	2.81 ± 0.15	0.30
CH ₃ CCH	5(0)-4(0)	85457.29	1.18 ± 0.04	-10.77 ± 0.05	3.11 ± 0.13	0.36
C ₄ H	9-8 $J = 17/2-15/2$	85672.58	0.13 ± 0.04	-10.66 ± 0.32	2.37 ± 0.71	0.05
NH ₂ D	1(1,1)0+-1(0,1)0- $F=1-2$	85926.27	1.02 ± 0.09	-11.86 ± 0.24	5.99 ± 0.79	0.06
HC ¹⁵ N	$v = 0\ 1-0$	86054.96	0.53 ± 0.04	-10.69 ± 0.12	3.24 ± 0.27	0.15
SO	$v = 0N, J = 2, 2-1, 1$	86093.95	0.89 ± 0.05	-10.45 ± 0.09	3.69 ± 0.24	0.23
H ¹³ CN	1-0 $F = 1-1$	86338.73	0.67 ± 0.04	-10.55 ± 0.09	3.01 ± 0.24	0.21
H ¹³ CN	1-0 $F = 2-1$	86340.17	1.28 ± 0.05	-10.60 ± 0.06	3.70 ± 0.17	0.33
H ¹³ CN	1-0 $F = 0-1$	86342.25	0.26 ± 0.04	-10.46 ± 0.32	3.76 ± 0.71	0.07
H ¹³ CO ⁺	1-0	86754.28	3.38 ± 0.05	-10.71 ± 0.02	3.41 ± 0.05	0.93
SiO	$v = 0-6\ 2-1\ v = 0$	86846.96	0.50 ± 0.07	-10.21 ± 0.53	7.51 ± 1.36	0.06
HN ¹³ C	1-0 $F = 1-1$	87090.82	0.86 ± 0.04	-10.40 ± 0.06	2.92 ± 0.14	0.28
CCH	$v = 0\ 1-0\ 3/2-1/2\ F = 1-1$	87284.10	0.74 ± 0.04	-10.81 ± 0.09	3.24 ± 0.22	0.22
CCH	$v = 0\ 1-0\ 3/2-1/2\ F = 2-1$	87316.89	4.95 ± 0.18	-10.88 ± 0.06	3.35 ± 0.14	1.39
CCH	$v = 0\ 1-0\ 3/2-1/2\ F = 1-0$	87328.58	2.72 ± 0.05	-10.82 ± 0.02	3.31 ± 0.06	0.79
CCH	$v = 0\ 1-0\ 1/2-1/2\ F = 1-1$	87401.98	2.87 ± 0.05	-10.82 ± 0.02	3.38 ± 0.06	0.81
CCH	$v = 0\ 1-0\ 1/2-1/2\ F = 0-1$	87407.16	1.34 ± 0.05	-10.62 ± 0.05	3.42 ± 0.13	0.37
CCH	$v = 0\ 1-0\ 1/2-1/2\ F = 1-0$	87446.47	0.65 ± 0.04	-10.89 ± 0.09	3.27 ± 0.20	0.19
HC ₅ N	$v = 0\ 33-32$	87863.63	0.14 ± 0.04	-12.37 ± 0.21	1.54 ± 0.68	0.09
HNCO	4(0,4)-3(0,3)	87925.23	0.41 ± 0.05	-10.69 ± 0.25	4.07 ± 0.70	0.10
HCN	1-0 $F = 1-1$	88630.41	12.67 ± 0.43	-12.53 ± 0.14	8.66 ± 0.31	1.38
HCN	1-0 $F = 2-1$	88631.84	4.52 ± 0.23	-12.17 ± 0.02	2.23 ± 0.07	1.90
HCN	1-0 $F = 0-1$	88633.93	3.74 ± 0.20	-10.71 ± 0.11	4.74 ± 0.25	0.74
HCO ⁺	$v = 0\ 1-0$	89188.52	13.02 ± 0.43	-12.13 ± 0.05	4.07 ± 0.20	3.01
HC ₅ N	$v = 0\ 34-33$	90525.88	0.21 ± 0.04	-10.53 ± 0.45	3.35 ± 0.87	0.04
HNC	$v = 0\ 1-0$	90663.56	11.39 ± 0.04	-10.91 ± 0.00	4.40 ± 0.01	2.43
CCS	7-6	90686.38	0.18 ± 0.04	-10.32 ± 0.36	3.57 ± 0.77	0.05
HCCCN	$v = 0\ 10-9$	90979.02	3.44 ± 0.04	-10.43 ± 0.01	2.95 ± 0.03	1.09
CH ₃ CN	$v = 0\ 5(1)-4(1)$	91985.31	0.22 ± 0.05	-10.47 ± 0.28	3.29 ± 0.90	0.07
CH ₃ CN	$v = 0\ 5(0)-4(0)$	91987.08	0.21 ± 0.04	-10.24 ± 0.25	2.91 ± 0.59	0.07
³³ SO ₂	4(2,2)-4(1,3) $F = 5.5-5.5$	143793.88	0.27 ± 0.04	-11.25 ± 0.26	3.39 ± 0.57	0.08
³³ SO ₂	4(2,2)-4(1,3)	143795.86	0.22 ± 0.04	-10.65 ± 0.34	3.15 ± 0.74	0.06
CH ₃ OH	3(1,3)-2(1,2) A++	143865.79	0.25 ± 0.04	-11.11 ± 0.26	3.33 ± 0.47	0.07
DCO ⁺	2-1	144077.28	0.46 ± 0.04	-10.60 ± 0.17	3.37 ± 0.32	0.13
CH ₃ C ₃ N	35(19)-34(19)	144087.77	0.33 ± 0.04	-9.32 ± 0.31	4.09 ± 0.53	0.08
CH ₃ OH	$vt = 0\ 24(-6, 18)-25(-5, 20)$	144194.75	0.33 ± 0.04	-4.79 ± 0.21	3.62 ± 0.47	0.09
CCD	2-1 $J = 5/2-3/2\ F = 7/2-5/2$	144241.96	0.27 ± 0.04	-11.83 ± 0.36	4.30 ± 0.73	0.04
CCD	2-1 $J = 5/2-3/2\ F = 3/2-1/2$	144243.05	0.13 ± 0.03	-14.87 ± 0.27	2.14 ± 0.56	0.05
C ³⁴ S	2-1	144617.10	0.73 ± 0.03	-10.55 ± 0.06	2.73 ± 0.14	0.25
DCN	2-1 $F1 = 2-1$	144828.00	0.61 ± 0.05	-10.71 ± 0.18	4.66 ± 0.45	0.13
<i>c</i> -C ₃ H ₂	3(1,2)-2(2,1)	145089.62	0.23 ± 0.03	-10.33 ± 0.18	2.64 ± 0.39	0.09
CH ₃ OH	3(0,3)-2(0,2) E	145093.76	0.54 ± 0.05	-11.55 ± 0.31	5.78 ± 0.82	0.09
CH ₃ OH	3(-1,3)-2(-1,2) E	145097.44	1.48 ± 0.05	-10.71 ± 0.05	3.67 ± 0.16	0.38
CH ₃ OH	3(0,3)-2(0,2) A++	145103.19	1.86 ± 0.04	-10.69 ± 0.04	3.75 ± 0.11	0.47
CH ₃ OH	3(-2,2)-2(-2,1) E	145126.39	0.23 ± 0.17	-10.14 ± 1.53	3.81 ± 2.89	0.06
CH ₃ OH	3(1,2)-2(1,1) E	145131.87	0.25 ± 0.04	-11.08 ± 0.37	4.57 ± 0.79	0.05
HCCCN	16-15	145560.95	1.04 ± 0.04	-10.56 ± 0.05	2.97 ± 0.12	0.33
H ₂ CO	2(0,2)-1(0,1)	145602.95	4.19 ± 0.04	-10.76 ± 0.02	4.38 ± 0.05	0.90
OCS	12-11	145946.81	0.11 ± 0.04	-10.09 ± 0.33	1.90 ± 1.05	0.05
CH ₃ OH	3(1,2)-2(1,1) A-	146368.34	0.46 ± 0.08	-10.55 ± 0.48	6.36 ± 1.82	0.07
(CH ₃) ₂ CO	$v = 0\ 43(16, 27)-42(19, 24)\text{EE}$	146599.28	0.17 ± 0.04	-9.28 ± 0.26	2.23 ± 0.73	0.07
CS	3-2	146969.02	9.80 ± 0.09	-10.65 ± 0.02	4.57 ± 0.04	2.01
<i>c</i> -HCCCD	19(6,13)-18(8,10)	147021.69	0.47 ± 0.09	-12.81 ± 0.38	4.19 ± 1.10	0.11

Table B3. DR21S.

Molecule	Transition	Frequency (MHz)	$\int T_{\text{mb}} dv$ (K km s ⁻¹)	v_{LSR} (km s ⁻¹)	FWHM (km s ⁻¹)	T_{mb} (K)
CH ₃ OH	5(-1, 5)-4(0, 4)	84521.20	0.62 ± 0.05	-2.03 ± 0.10	2.74 ± 0.32	0.22
H γ	H60 γ	84914.39	3.80 ± 0.16	-0.16 ± 0.68	30.80 ± 1.68	0.05
HC ¹⁸ O ⁺	1-0	85162.22	0.15 ± 0.02	-1.69 ± 0.16	1.60 ± 0.46	0.10
HC ₅ N	32-31	85201.34	0.35 ± 0.04	-2.07 ± 0.12	2.32 ± 0.28	0.14
C ¹³ CH	1-0 3/2-1/2 $F = 2, 2.5-1, 1.5$	85229.27	0.12 ± 0.02	-2.00 ± 0.14	1.30 ± 0.48	0.09
C ¹³ CH	1-0 3/2-1/2 $F = 2, 1.5-1, 0.5$	85232.76	0.95 ± 0.04	-2.84 ± 0.39	1.97 ± 0.83	0.04
C ¹³ CH	1-0 3/2-1/2 $F = 1, 1.5-0, 0.5$	85256.96	0.14 ± 0.05	-2.10 ± 0.69	3.36 ± 1.99	0.03
c-C ₃ H ₂	2(1,2)-1(0,1)	85338.90	2.36 ± 0.05	-2.13 ± 0.03	3.44 ± 0.08	0.64
HCS ⁺	2-1	85347.86	0.34 ± 0.04	-1.99 ± 0.19	3.19 ± 0.46	0.10
CH ₃ CCH	5(3)-4(3)	85442.60	0.13 ± 0.02	-1.91 ± 0.26	2.02 ± 0.52	0.06
CH ₃ CCH	5(2)-4(2)	85450.76	0.34 ± 0.04	-1.77 ± 0.11	2.27 ± 0.28	0.14
CH ₃ CCH	5(1)-4(1)	85455.66	0.81 ± 0.04	-1.87 ± 0.05	2.30 ± 0.13	0.33
CH ₃ CCH	5(0)-4(0)	85457.29	0.90 ± 0.04	-1.84 ± 0.05	2.37 ± 0.13	0.36
C4H	9-8 $J = 19/2-17/2$	85634.00	0.25 ± 0.04	-2.34 ± 0.18	2.48 ± 0.53	9.58
c-C ₃ H ₂	4(3,2)-4(2,3)	85656.41	0.25 ± 0.05	-3.57 ± 0.63	5.59 ± 1.40	0.04
He α	He42 α	85723.31	5.55 ± 0.40	-0.74 ± 0.12	32.51 ± 0.64	0.02
H α	H42 α	85688.39	26.20 ± 0.20	0.78 ± 1.16	37.49 ± 2.87	0.34
SO	$N, J = 2, 2-1, 1$	86093.98	0.63 ± 0.05	-2.30 ± 0.12	3.29 ± 0.34	0.18
CCS	$N, J = 7, 6-6, 5$	86181.41	0.16 ± 0.04	-2.07 ± 0.31	2.69 ± 0.79	0.06
H ¹³ CN	1-0 $F = 1-1$	86338.73	1.07 ± 0.05	-2.03 ± 0.06	2.75 ± 0.17	0.36
H ¹³ CN	1-0 $F = 2-1$	86340.17	1.90 ± 0.05	-2.02 ± 0.03	2.83 ± 0.10	0.63
H ¹³ CN	1-0 $F = 0-1$	86342.25	0.50 ± 0.07	-1.66 ± 0.17	3.06 ± 0.66	0.16
H ϵ	H70 ϵ	86488.42	1.08 ± 0.14	-1.99 ± 1.80	27.62 ± 4.42	0.03
HCO	1(0,1)-0(0,0) 3/2-1/2 $F = 2-1$	86670.82	0.57 ± 0.04	-2.17 ± 0.11	3.04 ± 0.25	0.18
HCO	1(0,1)-0(0,0) 3/2-1/2 $F = 1-0$	86708.35	0.40 ± 0.05	-2.29 ± 0.18	3.18 ± 0.46	0.12
H ¹³ CO ⁺	1-0	86754.28	2.57 ± 0.04	-2.00 ± 0.02	2.72 ± 0.05	0.89
HCO	1(0,1)-0(0,0) 1/2-1/2 $F = 1-1$	86777.43	0.35 ± 0.04	-2.52 ± 0.20	3.28 ± 0.51	0.10
SiO	2-1 $v = 0$	86846.99	2.79 ± 0.08	-1.51 ± 0.22	5.06 ± 0.59	0.17
HN ¹³ C	1-0 $F = 2-1$	87090.85	1.30 ± 0.04	-1.60 ± 0.03	2.39 ± 0.09	0.51
CCH	1-0 3/2-1/2 $F = 1-1$	87284.15	1.01 ± 0.04	-2.03 ± 0.05	2.77 ± 0.15	0.34
CCH	1-0 3/2-1/2 $F = 2-1$	87316.92	7.67 ± 0.05	-2.14 ± 0.01	3.11 ± 0.02	2.32
CCH	1-0 3/2-1/2 $F = 1-0$	87328.62	4.16 ± 0.05	-2.08 ± 0.01	3.01 ± 0.04	1.30
CCH	1-0 1/2-1/2 $F = 1-1$	87402.00	4.12 ± 0.05	-2.16 ± 0.01	2.98 ± 0.04	1.30
CCH	1-0 1/2-1/2 $F = 0-1$	87407.16	1.94 ± 0.04	-2.17 ± 0.03	2.94 ± 0.08	0.62
CCH	1-0 1/2-1/2 $F = 1-0$	87446.47	1.01 ± 0.04	-2.10 ± 0.05	2.75 ± 0.13	0.35
H β	H65 β	87615.00	2.29 ± 0.16	-0.14 ± 1.39	36.62 ± 3.22	0.02
HC ₅ N	33-32	87863.63	0.27 ± 0.04	-1.99 ± 0.15	2.13 ± 0.33	0.12
HNCO	4(0,4)-3(0,3)	87925.23	0.43 ± 0.05	-2.22 ± 0.14	2.54 ± 0.37	0.16
HCN	1-0 $F = 1-1$	88630.41	7.24 ± 0.18	-1.22 ± 0.04	3.95 ± 0.11	1.72
HCN	1-0 $F = 2-1$	88631.84	19.00 ± 0.41	-2.43 ± 0.03	4.66 ± 0.09	3.84
HCN	1-0 $F = 0-1$	88633.93	8.43 ± 0.61	-2.26 ± 0.66	5.00 ± 0.66	1.59
H ¹⁵ NC	1-0	88865.69	0.15 ± 0.04	-1.97 ± 0.22	1.65 ± 0.40	0.09
HCO ⁺	$v = 0, 1-0$	89188.52	28.74 ± 0.41	-3.08 ± 0.06	9.44 ± 0.18	2.87
HCCNC	9-8	89419.26	0.23 ± 0.05	-2.10 ± 0.30	3.00 ± 0.72	0.07
<i>l</i> -HCOOH	4(3,1)-3(3,0)	89950.33	0.29 ± 0.05	-1.31 ± 0.52	4.99 ± 1.04	0.05
<i>l</i> -HCOOH	4(2,2)-3(2,1)	90164.63	0.28 ± 0.07	-4.49 ± 0.78	8.02 ± 2.90	0.03
HC ₃ N	34-33	90525.89	0.25 ± 0.02	-2.20 ± 0.17	2.86 ± 0.38	0.08
HC ¹³ CCN	10-9	90593.05	0.27 ± 0.02	-1.75 ± 0.18	3.09 ± 0.46	0.08
HCC ¹³ CN	10-9	90601.79	0.19 ± 0.02	-2.08 ± 0.16	2.10 ± 0.35	0.09
HNC	$v = 0, 1-0$	90663.56	13.72 ± 0.06	-2.29 ± 0.00	3.82 ± 0.02	3.39
CCS	$N, J = 7, 7-6, 6$	90686.38	0.13 ± 0.04	-2.88 ± 0.61	3.80 ± 1.58	0.03
HCCCN	$v = 0$	90979.02	4.82 ± 0.04	-0.93 ± 0.00	2.44 ± 0.02	1.86
c-C ₃ H	2(1,2)-1(1,1) 5/2,3-3/2,2	91494.34	0.22 ± 0.04	-2.50 ± 0.22	2.76 ± 0.55	0.08
c-C ₃ H	2(1,2)-1(1,1) 5/2,2-3/2,1	91497.60	0.19 ± 0.04	-2.24 ± 0.27	2.86 ± 0.86	0.06
H β	H64 β	91663.13	1.87 ± 0.13	-0.87 ± 0.99	28.14 ± 2.11	0.05
CH ₃ CN	5(3)-4(3) $F = 4-3$	91971.46	0.45 ± 0.06	-1.67 ± 0.16	6.46 ± 1.15	0.06
CH ₃ CN	5(2)-4(2) $F = 6-5$	91979.99	0.14 ± 0.02	-2.71 ± 0.16	1.71 ± 0.32	0.08
CH ₃ CN	5(1)-4(1)	91985.31	0.43 ± 0.04	-2.32 ± 0.11	2.69 ± 0.29	0.16
CH ₃ CN	5(0)-4(0)	91987.08	0.63 ± 0.04	-2.13 ± 0.09	3.08 ± 0.28	0.19

Table B3 – *continued.*

Molecule	Transition	Frequency (MHz)	$\int T_{\text{mb}} dv$ (K km s ⁻¹)	v_{LSR} (km s ⁻¹)	FWHM (km s ⁻¹)	T_{mb} (K)
H α	H41 α	92034.43	23.86 $\pm$ 0.14	-0.95 $\pm$ 0.09	31.55 $\pm$ 0.21	0.32
DCO ⁺	2-1	144077.28	0.43 $\pm$ 0.04	-1.86 $\pm$ 0.10	2.24 $\pm$ 0.22	0.18
Unidentified		144199.70	0.49 $\pm$ 0.05	-2.26 $\pm$ 0.11	2.05 $\pm$ 0.27	0.23
CCD	$N = 2-1, J = 5/2-3/2, F = 7/2-5/2$	144241.93	0.32 $\pm$ 0.04	-3.12 $\pm$ 0.20	3.09 $\pm$ 0.42	0.10
CH ₃ OCHO	$v = 1$ 18(14,5)-19(13,6) A	144373.86	0.23 $\pm$ 0.04	-2.94 $\pm$ 0.68	3.49 $\pm$ 0.90	0.03
C ³⁴ S	3-2	144616.13	1.50 $\pm$ 0.04	-4.37 $\pm$ 0.03	2.59 $\pm$ 0.08	0.55
DCN	$J = 2-1, F = 2-1$	144828.00	0.97 $\pm$ 0.05	-1.76 $\pm$ 0.13	5.22 $\pm$ 0.45	0.17
<i>c</i> -C ₃ H ₂	3(1,2)-2(2,1)	145089.62	0.27 $\pm$ 0.09	-2.35 $\pm$ 0.37	2.06 $\pm$ 0.88	0.12
CH ₃ OH	3(-1,3)-2(-1,2) E	145097.44	0.80 $\pm$ 0.10	-2.29 $\pm$ 0.17	2.78 $\pm$ 0.45	0.27
CH ₃ OH	3(0,3)-2(0,2) A++	145103.19	1.08 $\pm$ 0.09	-2.19 $\pm$ 0.11	2.91 $\pm$ 0.32	0.35
CH ₃ OH	3(-2,2)-2(-2,1) E	145126.39	0.92 $\pm$ 0.06	-1.65 $\pm$ 0.25	6.26 $\pm$ 0.47	0.14
CH ₃ OH	3(1,2)-2(1,1) E	145131.87	0.46 $\pm$ 0.05	-2.84 $\pm$ 0.45	6.92 $\pm$ 1.09	0.06
(CH ₃) ₂ CO	23(11,13)-22(12,10) AE	145369.23	0.65 $\pm$ 0.04	-2.71 $\pm$ 0.09	3.01 $\pm$ 0.19	0.06
<i>l</i> -H ₂ CCC	7(2,5)-6(2,4)	145532.32	0.31 $\pm$ 0.06	-4.54 $\pm$ 0.41	3.99 $\pm$ 0.85	0.07
HCCCN	16-15	145560.95	1.95 $\pm$ 0.04	-2.21 $\pm$ 0.02	2.61 $\pm$ 0.06	0.70
H ₂ CO	(0,2)-1(0,1)	145602.95	4.32 $\pm$ 0.05	-2.42 $\pm$ 0.02	3.72 $\pm$ 0.05	1.09
C ³³ S	3-2 $F = 3/2-1/2$	145755.62	0.28 $\pm$ 0.04	-2.66 $\pm$ 0.20	3.05 $\pm$ 0.65	0.09
CH ₃ OH	3(1,2)-2(1,1) --	146368.34	2.60 $\pm$ 0.22	-3.76 $\pm$ 0.31	7.51 $\pm$ 0.80	0.33
SO ²	4(2,2)-4(1,3)	146605.51	2.48 $\pm$ 0.20	-4.84 $\pm$ 0.32	7.72 $\pm$ 0.73	0.30
CH ₃ OH	9(0,9)-8(1,8) A++	146618.83	0.33 $\pm$ 0.04	-2.64 $\pm$ 0.21	3.14 $\pm$ 0.49	0.10
H ₂ CN	2(0,2)-1(0,1), $F=5/2-5/2$	146660.74	0.43 $\pm$ 0.08	-1.83 $\pm$ 0.43	4.46 $\pm$ 0.76	0.09
CH ₃ OCHO	26(6,21)-25(7,18) A	146753.39	0.23 $\pm$ 0.05	-3.66 $\pm$ 0.31	2.86 $\pm$ 0.79	0.08
¹³ CH ₂ CHCN	13(1,13)-12(0,12)	146846.03	0.22 $\pm$ 0.05	-1.41 $\pm$ 0.55	3.84 $\pm$ 0.77	0.06
<i>c</i> -CH ₂ OHCHO	$v = 0$ 40(5,35)-41(4,38)	146916.98	0.48 $\pm$ 0.08	-3.96 $\pm$ 0.59	5.90 $\pm$ 1.08	0.08
CS	3-2	146969.02	12.52 $\pm$ 0.13	-2.44 $\pm$ 0.01	4.00 $\pm$ 0.05	2.94
H ₂ CCH ¹³ CN	18(0,18)-17(1,17)	147042.13	2.10 $\pm$ 0.14	-1.00 $\pm$ 0.23	7.07 $\pm$ 0.58	0.28

Table B4. G34.

Molecule	Transition	Frequency (MHz)	$\int T_{\text{mb}} dv$ (K km s ⁻¹)	v_{LSR} (km s ⁻¹)	FWHM (km s ⁻¹)	T_{mb} (K)
C ₆ H	23/2 $J = 61/2$ –59/2 f	84574.59	0.13 ± 0.04	60.97 ± 0.33	2.71 ± 0.91	0.05
<i>t</i> -CH ₃ CH ₂ OH	4(2,3)–4(1,4)	84595.78	0.27 ± 0.06	60.04 ± 0.65	6.26 ± 1.64	0.04
³⁰ SiO	2–1 $v = 0$	84745.99	0.43 ± 0.07	60.90 ± 0.96	11.14 ± 1.87	0.04
NH ₂ CHO	4(2,3)–3(2,2) n, t	84807.79	0.41 ± 0.05	58.08 ± 0.37	6.01 ± 0.83	0.07
O ¹³ CS	7–6	84865.15	0.22 ± 0.04	58.04 ± 0.50	4.69 ± 1.01	0.05
H α	H60 γ	84914.39	0.71 ± 0.09	55.64 ± 1.33	20.87 ± 2.49	0.03
¹³ CH ₃ OH	8(0,8)–7(1,7) A++	84970.23	0.63 ± 0.06	59.76 ± 0.37	7.42 ± 0.80	0.08
NH ₂ CHO	4(2,2)–3(2,1)	85093.26	0.13 ± 0.04	59.38 ± 0.42	3.29 ± 1.14	0.04
OCS	7–6	85139.10	1.02 ± 0.05	59.28 ± 0.12	5.39 ± 0.29	0.18
HC ¹⁸ O ⁺	1–0	85162.22	0.65 ± 0.04	59.02 ± 0.12	4.10 ± 0.32	0.15
C ¹³ CH	1–0 3/2–1/2 $F = 1, 0.5$ –0.5	85247.65	0.13 ± 0.04	59.61 ± 0.43	2.65 ± 0.74	0.04
C ¹³ CH	1–0 3/2–1/2 $F = 1, 1.5$ –0.5	85256.96	0.18 ± 0.05	58.90 ± 0.96	5.89 ± 2.11	0.03
<i>t</i> -CH ₃ CH ₂ OH	6(0,6)–5(1,5)	85265.50	0.32 ± 0.05	59.25 ± 0.40	5.52 ± 1.07	0.06
<i>c</i> -C ₃ H ₂	2(1,2)–1(0,1)	85338.90	1.74 ± 0.05	59.30 ± 0.07	5.41 ± 0.20	0.30
HCS ⁺	2–1	85347.86	0.84 ± 0.05	58.99 ± 0.13	5.15 ± 0.33	0.15
CH ₃ CCH	5(3)–4(3)	85442.60	0.23 ± 0.19	58.88 ± 1.58	3.65 ± 3.15	0.06
CH ₃ CCH	5(2)–4(2)	85450.76	0.62 ± 0.05	58.85 ± 0.16	4.44 ± 0.43	0.13
CH ₃ CCH	5(1)–4(1)	85455.66	1.40 ± 0.06	58.96 ± 0.08	4.35 ± 0.20	0.30
CH ₃ CCH	5(0)–4(0)	85457.29	1.64 ± 0.06	58.97 ± 0.07	4.24 ± 0.17	0.36
CH ₃ OH	6(–2,5)–7(–1,7) E	85568.07	0.16 ± 0.04	59.06 ± 0.37	3.68 ± 1.00	0.04
C ₄ H	9(10,10)–8(9,9)	85634.02	0.26 ± 0.05	60.08 ± 0.54	6.19 ± 1.48	0.04
CH ₃ OCHO	4(2,3)–3(1,2) A	85655.80	0.16 ± 0.04	58.71 ± 0.71	6.01 ± 1.91	0.03
H α	H42 α	85688.39	3.38 ± 0.09	54.48 ± 0.39	27.11 ± 0.98	0.12
²⁹ SiO	2–1 $v = 0$	85759.18	0.19 ± 0.04	58.71 ± 0.33	3.48 ± 0.72	0.05
CH ₃ OCHO	7(6,2)–6(6,1) A+E	85926.50	0.47 ± 0.06	59.52 ± 0.45	7.85 ± 1.36	0.06
CH ₃ OCHO	7(5,2)–6(5,1) E	86021.00	0.26 ± 0.04	59.27 ± 0.44	5.68 ± 1.05	0.04
CH ₃ OCHO	7(5,3)–6(5,2) E	86027.67	0.06 ± 0.02	60.30 ± 0.38	1.82 ± 0.64	0.04
CH ₃ OCHO	7(5,2)–6(5,1) A	86030.21	0.77 ± 0.11	60.56 ± 1.08	16.09 ± 3.14	0.05
HC ¹⁵ N	1–0	86054.96	1.08 ± 0.04	58.96 ± 0.07	4.00 ± 0.19	0.25
SO	$N, J = 2, 2$ –1,1	86093.98	1.54 ± 0.05	59.39 ± 0.07	5.23 ± 0.20	0.28
CCS	$N, J = 7, 6$ –6,5	86181.41	0.21 ± 0.04	59.52 ± 0.39	4.58 ± 1.19	0.05
CH ₃ OCHO	7(4,4)–6(4,3) A	86210.07	0.41 ± 0.07	59.24 ± 0.60	6.98 ± 1.25	0.06
CH ₃ OCH ₃	7(4,3)–6(4,2) E	86223.54	0.66 ± 0.05	58.04 ± 0.29	7.37 ± 0.69	0.08
CH ₃ OCHO	7(4,3)–6(4,2) A	86250.57	0.26 ± 0.04	59.33 ± 0.50	5.42 ± 0.91	0.04
CH ₃ OCHO	7(3,5)–6(3,4) A	86265.82	0.36 ± 0.06	60.28 ± 0.38	5.36 ± 1.16	0.06
CH ₃ OCHO	7(3,5)–6(3,4) E	86268.65	0.54 ± 0.06	58.58 ± 0.38	7.55 ± 1.06	0.07
H ¹³ CN	1–0 $F = 1$ –1	86338.73	2.46 ± 0.08	59.20 ± 0.06	4.18 ± 0.14	0.55
H ¹³ CN	1–0 $F = 2$ –1	86340.17	4.45 ± 0.14	58.95 ± 0.67	4.40 ± 0.67	0.95
H ¹³ CN	1–0 $F = 0$ –1	86342.25	1.51 ± 0.11	59.69 ± 0.22	6.49 ± 0.54	0.22
<i>t</i> -HCOOH	4(1,4)–3(1,3)	86546.19	0.08 ± 0.02	58.68 ± 0.26	1.56 ± 0.60	0.05
CH ₃ OH	7(2,6)–6(3,3) A---	86615.60	0.36 ± 0.06	58.66 ± 0.87	10.42 ± 1.81	0.03
SO ₂	8(3,5)–9(2,8)	86639.09	0.42 ± 0.04	58.03 ± 0.24	4.80 ± 0.59	0.08
HCO	(0,1)–0(0,0) 3/2–1/2 $F = 2$ –1	86670.82	0.25 ± 0.04	60.01 ± 0.32	3.98 ± 0.77	0.06
CCCS	15–14	86708.37	0.16 ± 0.04	59.08 ± 0.42	3.74 ± 1.05	0.04
H ¹³ CO ⁺	1–0	86754.28	4.57 ± 0.04	58.73 ± 0.01	4.49 ± 0.04	0.98
CH ₃ CH ₂ CN	10(1,10)–9(1,9)	86819.84	0.45 ± 0.05	57.84 ± 0.32	5.59 ± 0.92	0.08
SiO	2–1 $v = 0$	86846.99	2.96 ± 0.07	59.55 ± 0.07	7.21 ± 0.23	0.38
<i>t</i> -HCOOD	4(2,3)–3(2,2)	86895.46	0.14 ± 0.04	59.03 ± 0.71	4.60 ± 1.30	0.03
CH ₃ OH	7(2,5)–6(3,4) A++	86902.94	0.40 ± 0.05	57.96 ± 0.66	9.45 ± 1.25	0.04
HC ¹⁷ O ⁺	1–0 $F = 7/2$ –5/2	87057.25	0.30 ± 0.05	56.89 ± 0.52	6.91 ± 1.27	0.04
HN ¹³ C	1–0 $F = 2$ –1	87090.85	2.15 ± 0.04	59.08 ± 0.03	4.03 ± 0.09	0.50
C ₄ H	23/2 $J = 19/2$ –17/2 1 v 7 e	87142.30	0.50 ± 0.06	56.51 ± 0.54	8.91 ± 1.65	0.05
Unidentified		87161.31	1.06 ± 0.02	59.19 ± 0.21	1.81 ± 0.52	0.05
C ₂ H	1–0 3/2–1/2 $F = 1$ –1	87284.15	1.04 ± 0.05	59.08 ± 0.09	4.50 ± 0.25	0.22
C ₂ H	1–0 3/2–1/2 $F = 2$ –1	87316.92	7.03 ± 0.05	58.71 ± 0.01	4.36 ± 0.03	1.51
C ₂ H	1–0 3/2–1/2 $F = 1$ –0	87328.62	4.01 ± 0.05	58.91 ± 0.02	4.37 ± 0.06	0.86
C ₂ H	1–0 1/2–1/2 $F = 1$ –1	87402.00	4.01 ± 0.04	58.80 ± 0.02	4.34 ± 0.06	0.87
C ₂ H	1–0 1/2–1/2 $F = 0$ –1	87407.16	1.87 ± 0.04	58.89 ± 0.04	4.21 ± 0.11	0.42
C ₂ H	1–0 1/2–1/2 $F = 1$ –0	87446.51	1.17 ± 0.04	58.94 ± 0.08	4.76 ± 0.20	0.23
HNCO	4(1,4)–3(1,3)	87597.33	0.47 ± 0.05	57.60 ± 0.34	6.21 ± 0.94	0.07
<i>t</i> -CH ₃ CH ₂ OH	5(2,4)–5(1,5)	87716.02	0.22 ± 0.04	57.30 ± 0.55	5.41 ± 1.04	0.04
NH ₂ CHO	4(1,3)–3(1,2)	87848.87	0.40 ± 0.05	58.11 ± 0.58	8.27 ± 1.12	0.05

Table B4 – *continued.*

Molecule	Transition	Frequency (MHz)	$\int T_{\text{mb}} dv$ (K km s ⁻¹)	v_{LSR} (km s ⁻¹)	FWHM (km s ⁻¹)	T_{mb} (K)
HC ₅ N	33–32	87863.63	0.22 ± 0.04	58.64 ± 0.34	4.07 ± 1.20	0.05
H ₂ CCCHCN	17(4,14)–16(4,13)	87894.36	0.22 ± 0.04	55.45 ± 0.56	5.23 ± 1.03	0.04
HNCO	4(2,2)–3(2,1)	87898.62	0.25 ± 0.05	47.34 ± 0.65	6.19 ± 1.15	0.04
Unidentified		87911.49	0.15 ± 0.05	57.73 ± 0.43	2.87 ± 1.26	0.05
HNCO	4(0,4)–3(0,3)	87925.23	1.62 ± 0.04	58.84 ± 0.06	4.91 ± 0.15	0.31
CH ₃ OCH ₃	2(2,0)–2(1,1) EE	88226.72	0.15 ± 0.05	58.86 ± 0.65	3.93 ± 1.36	0.04
CH ₃ CH ₂ CHO	30(6,24)–30(6,25)	88628.80	2.23 ± 0.16	59.44 ± 0.16	4.53 ± 0.44	0.46
HCN	1–0 $F = 1-1$	88630.41	0.80 ± 0.08	58.49 ± 0.07	1.43 ± 0.17	0.53
HCN	1–0 $F = 2-1$	88631.84	6.02 ± 0.11	56.92 ± 0.03	3.39 ± 0.06	1.67
HCN	1–0 $F = 0-1$	88633.93	5.18 ± 0.11	57.15 ± 0.03	3.06 ± 0.08	1.59
H ¹⁵ NC	1–0	88865.69	0.21 ± 0.05	58.87 ± 0.35	2.81 ± 0.95	0.07
CH ₃ OH	15(3,12)–14(4,11) A–	88939.99	0.46 ± 0.05	58.59 ± 0.36	5.74 ± 0.82	0.08
HSCH ₂ CN	15(6,10)–14(6,9)	88966.54	0.30 ± 0.06	57.93 ± 0.54	5.37 ± 0.94	0.05
HSCH ₂ CN	15(4,11)–14(4,10)	88990.96	0.16 ± 0.04	57.87 ± 0.68	5.14 ± 1.39	0.03
Unidentified		88999.14	0.18 ± 0.04	58.77 ± 0.94	6.49 ± 2.15	0.26
Unidentified		89007.42	0.07 ± 0.02	57.29 ± 0.35	1.87 ± 0.99	0.04
HSCH ₂ CN	15(10,6)–14(10,5)	89026.90	0.18 ± 0.40	56.48 ± 0.58	4.66 ± 0.88	0.04
C ₃ N	9(10,9)–8(9,9)	89048.27	0.13 ± 0.03	55.92 ± 0.80	5.24 ± 1.36	0.03
C ₃ N	9(9,8)–8(8,8)	89065.02	0.13 ± 0.03	56.01 ± 0.42	3.61 ± 1.25	0.03
HSCH ₂ CN	15(12,3)–14(12,2)	89080.78	0.21 ± 0.04	60.25 ± 0.70	6.24 ± 1.39	0.03
<i>c</i> -C ₃ D ₂	5(4,2)–5(3,3)	89316.91	0.62 ± 0.07	59.85 ± 0.88	12.00 ± 1.75	0.04
CH ₃ CH ₂ CN	10(5)–9(5)	89568.10	0.45 ± 0.06	56.97 ± 0.37	5.64 ± 0.87	0.08
CH ₃ CH ₂ CN	10(8)–9(8)	89573.05	0.26 ± 0.04	57.73 ± 0.36	4.04 ± 0.73	0.06
CH ₃ CH ₂ CN	10(4,6)–9(4,5)	89591.01	0.79 ± 0.06	59.28 ± 0.27	6.58 ± 0.69	0.11
CH ₃ CH ₂ CN	10(3,8)–9(3,7)	89628.44	0.45 ± 0.05	57.15 ± 0.31	5.39 ± 0.67	0.08
CH ₃ CH ₂ CN	10(3,7)–9(3,6)	89684.71	0.18 ± 0.04	57.22 ± 0.50	3.79 ± 1.01	0.05
(CH ₃) ₂ CO	9(7,3)–8(8,0) AE	89684.71	0.12 ± 0.04	67.65 ± 0.83	4.18 ± 1.59	0.03
Unidentified		89970.13	0.18 ± 0.04	60.42 ± 0.42	4.02 ± 0.93	0.04
<i>t</i> -CH ₃ CH ₂ OH	4(1,4)–3(0,3)	90117.59	0.19 ± 0.02	58.53 ± 0.31	3.82 ± 0.66	0.05
CH ₃ OCHO	7(2,5)–6(2,4) E	90145.63	0.28 ± 0.04	58.16 ± 0.47	6.46 ± 0.92	0.04
CH ₃ OCHO	7(2,5)–6(2,4) A	90156.51	0.25 ± 0.04	58.60 ± 0.37	4.92 ± 0.90	0.05
CH ₃ OCHO	$v = 0$ 8(0,8)–7(0,7) E	90227.66	0.56 ± 0.05	56.35 ± 0.45	10.49 ± 0.91	0.05
¹⁵ NNH ⁺	1–0	90263.83	0.19 ± 0.02	60.06 ± 0.33	4.47 ± 0.68	0.04
CH ₃ CH ₂ CN	10(2,8)–9(2,7)	90453.35	0.26 ± 0.05	55.83 ± 0.78	8.29 ± 2.12	0.03
HC ₅ N	34–33	90525.89	0.14 ± 0.02	58.40 ± 0.42	3.71 ± 0.87	0.04
SO ₂	25(3,23)–24(4,20)	90548.16	0.13 ± 0.04	57.83 ± 0.90	6.22 ± 1.77	0.02
HC ¹³ CCN	10–9	90593.05	0.23 ± 0.04	58.75 ± 0.41	4.98 ± 0.82	0.05
HCC ¹³ CN	10–9	90601.79	0.13 ± 0.02	54.65 ± 0.61	4.25 ± 1.37	0.02
HNC	1–0 $F = 0-1$	90663.45	1.54 ± 0.04	62.69 ± 0.03	3.37 ± 0.08	0.44
HNC	1–0 $F = 2-1$	90663.57	15.39 ± 0.04	56.83 ± 0.00	3.85 ± 0.01	3.72
CCS	$N, J = 7, 7-6, 6$	90686.38	0.23 ± 0.05	58.68 ± 0.54	6.01 ± 1.75	0.04
CH ₃ OH	20(–3,17)–19(–2,17) Et	90812.39	0.09 ± 0.02	54.72 ± 0.64	3.97 ± 1.33	0.02
CH ₂ CH ¹³ CN	79(4,75)–78(6,72)	90920.15	0.07 ± 0.02	56.59 ± 0.34	2.04 ± 0.94	0.04
¹³ C ³⁴ S	2–1	90925.99	0.21 ± 0.05	57.90 ± 0.57	5.85 ± 1.60	0.04
CH ₃ OCH ₃	6(0,6)–5(1,5) AA	90937.50	0.27 ± 0.06	54.87 ± 0.93	8.41 ± 2.62	0.03
HCCCN	10–9	90978.98	6.19 ± 0.04	58.30 ± 0.01	4.14 ± 0.03	1.40
HDCS	3(1,3)–2(1,2)	91171.03	0.08 ± 0.01	58.23 ± 0.19	1.55 ± 0.50	0.05
H ₂ CN	13(2,11)–13(2,12), $F=27/2-27/2$, ($n=11-11$)	91201.96	0.09 ± 0.02	62.19 ± 0.42	2.67 ± 0.79	0.03
H ₂ CN	13(2,11)–13(2,12), $F=21/2-21/2$, ($n=23-23$)	91203.59	0.59 ± 0.07	59.35 ± 0.36	6.54 ± 0.94	0.09
H ₂ CN	13(2,11)–13(2,12), $F=23/2-23/2$, ($n=22-22$)	91209.19	0.23 ± 0.11	68.64 ± 1.12	7.30 ± 3.87	0.03
HCCCN	10–9 $1v7e = 1f$	91333.37	0.07 ± 0.02	58.08 ± 0.52	2.69 ± 0.95	0.03
SO ₂	18(5,13)–19(4,16)	91550.44	0.08 ± 0.02	58.16 ± 0.54	3.31 ± 1.09	0.03
CH ¹³ CN	5(0)–4(0)	91941.60	0.38 ± 0.07	59.28 ± 1.40	16.66 ± 4.80	0.02
CH ₃ CN	5(4)–4(4) $F = 6-5$	91959.02	0.19 ± 0.05	59.69 ± 0.74	5.17 ± 1.67	0.03
CH ₃ CN	5(3)–4(3) $F = 4-3$	91971.46	0.72 ± 0.05	59.45 ± 0.22	6.73 ± 0.50	0.10
CH ₃ CN	5(2)–4(2) $F = 6-5$	91979.99	0.73 ± 0.05	58.18 ± 0.18	4.84 ± 0.44	0.14
CH ₃ CN	5(1)–4(1)	91985.31	1.34 ± 0.07	58.39 ± 0.10	4.47 ± 0.26	0.28
CH ₃ CN	5(0)–4(0)	91987.08	1.57 ± 0.06	58.10 ± 0.08	4.80 ± 0.22	0.31
H α	H41 α	92034.43	2.98 ± 0.08	54.40 ± 0.37	27.66 ± 0.90	0.10

Table B4 – *continued.*

Molecule	Transition	Frequency (MHz)	$\int T_{\text{mb}} dv$ (K km s ⁻¹)	v_{LSR} (km s ⁻¹)	FWHM (km s ⁻¹)	T_{mb} (K)
Unidentified		143778.87	0.27 ± 0.03	56.92 ± 0.24	3.68 ± 0.55	0.07
CH ₃ OCHO	$v = 1$ 46(15,32)–67(16,29)A	143833.84	0.22 ± 0.04	56.23 ± 0.45	4.00 ± 0.86	0.05
Unidentified		143858.80	0.59 ± 0.06	57.72 ± 0.27	5.81 ± 0.67	0.10
CH ₃ OH	3(1,3)–2(1,2) A++	143865.79	1.27 ± 0.05	58.82 ± 0.09	4.90 ± 0.23	0.25
DCO ⁺	2–1	144077.28	0.22 ± 0.04	58.40 ± 0.26	3.14 ± 0.75	0.07
c-C ₃ H ₄	8(3,6)–8(1,7)	144178.68	0.38 ± 0.05	59.53 ± 0.32	4.48 ± 0.82	0.08
CCD	2–1 $J = 5/2$ –3/2 $F = 5/2$ –3/2	144243.05	0.20 ± 0.04	58.67 ± 0.65	5.38 ± 0.97	0.04
H ₂ NCH ₂ CN	33(4,29)–33(3,30)	144258.27	1.76 ± 0.06	61.25 ± 0.07	4.39 ± 0.18	0.38
CH ₃ OH	3(0,3)–2(0,2) A++ Vt=2	144571.97	0.70 ± 0.06	60.71 ± 0.50	8.99 ± 0.97	0.07
CH ₃ OH	3(–1,2)–2(–1,1) Et=2	144583.91	0.83 ± 0.08	61.16 ± 0.46	8.85 ± 1.00	0.09
CH ₃ OH	3(1,3)–2(1,2) A++ t=1	144589.85	0.83 ± 0.10	58.00 ± 0.42	6.83 ± 0.99	0.12
C ¹³ ₃ CCH	30–29	144524.63	0.22 ± 0.04	58.44 ± 0.33	3.94 ± 0.56	0.05
CH ₃ OH	3(0,3)–2(0,2) A++ Vt=2	144571.97	0.16 ± 0.04	61.39 ± 1.41	6.67 ± 2.22	0.03
C ³⁴ S	3–2	144617.10	3.63 ± 0.04	58.43 ± 0.02	4.26 ± 0.06	0.80
CH ₃ C ₅ N	93(6)–92(6),F=93–92	144657.80	0.73 ± 0.05	57.03 ± 0.24	6.08 ± 0.49	0.11
CH ₃ OH	3(–2,1)–2(–2,0) Et=1	144728.77	1.20 ± 0.08	59.52 ± 0.20	6.68 ± 0.56	0.17
CH ₃ OH	3(2,2)–2(2,1) Et=1	144733.24	2.03 ± 0.05	55.54 ± 0.12	8.26 ± 0.29	0.23
CH ₃ OH	3(–1,2)–2(–1,1) Et=1	144750.24	0.47 ± 0.05	58.84 ± 0.33	5.99 ± 0.72	0.08
CH ₃ OH	3(0,3)–2(0,2) A++ t=1	144768.17	0.37 ± 0.05	58.39 ± 0.34	4.33 ± 0.82	0.08
DCN	2–1 $F1 = 2$ –2	144826.57	0.96 ± 0.05	55.80 ± 0.14	5.48 ± 0.44	0.17
CH ₃ OH	6(3,3)–6(2,4) EE	144858.98	0.73 ± 0.08	57.45 ± 0.55	10.55 ± 1.37	0.06
CH ₃ OH	3(1,2)–2(1,1) A–t=1	144878.57	0.61 ± 0.06	58.28 ± 0.51	8.57 ± 0.99	0.07
c-C ₃ H ₂	3(1,2)–2(2,1)	145089.62	1.36 ± 0.29	58.49 ± 0.40	5.59 ± 0.40	0.22
CH ₃ OH	3(0,3)–2(0,2) E	145093.76	2.54 ± 0.05	58.58 ± 0.04	4.69 ± 0.13	0.51
CH ₃ OH	3(–1,3)–2(–1,2) E	145097.44	6.28 ± 0.05	58.49 ± 0.00	4.50 ± 0.04	1.31
CH ₃ OH	3(0,3)–2(0,2) A++	145103.19	7.19 ± 0.04	58.55 ± 0.01	4.44 ± 0.03	1.52
CH ₃ OH	3(2,2)–2(2,1) A–	145124.33	1.49 ± 0.90	54.76 ± 1.55	5.82 ± 5.02	0.24
CH ₃ OH	3(1,2)–2(1,1) E	145131.87	1.50 ± 0.83	58.36 ± 1.44	5.76 ± 4.09	0.25
SiC ₂	6(2,4)–5(2,3)	145325.84	0.59 ± 0.05	61.83 ± 0.29	6.20 ± 0.59	0.09
c-C ₃ H ₃ CN	19(3,16)19–19(2,17)19	145373.47	0.13 ± 0.03	57.05 ± 0.50	3.56 ± 1.01	0.03
¹³ CH ₂ (OH)CHO	12(3,9)–11(3,8)	145362.26	0.13 ± 0.03	58.84 ± 0.37	3.23 ± 0.75	0.04
ONCN	14(0,14)–13(0,13)	145397.59	0.88 ± 0.03	55.84 ± 0.06	2.95 ± 0.12	0.28
CH ₃ CH ₂ CN	16(1,15)–15(1,14)	145418.03	0.31 ± 0.10	58.01 ± 0.78	4.62 ± 1.58	0.06
NCCONH ₂	21(4,17)–20(5,16)	145550.10	0.43 ± 0.06	57.75 ± 0.39	5.95 ± 0.96	0.07
HCCCN	16–15 $1v7 = 1e$	145560.95	1.75 ± 0.04	58.60 ± 0.05	4.80 ± 0.14	0.34
n-C ₃ H ₇ CN	9(7,3)–8(6,3)	145700.18	0.21 ± 0.03	56.81 ± 0.33	4.16 ± 0.79	0.05
Unidentified		145723.50	0.32 ± 0.04	57.49 ± 0.50	7.68 ± 1.15	0.04
Unidentified		145745.70	0.11 ± 0.03	57.29 ± 0.78	3.86 ± 1.42	0.03
OCS	12–11	145946.81	0.66 ± 0.05	58.69 ± 0.20	5.50 ± 0.50	0.11
CH ₃ CH ₂ CN	16(2,14)–15(2,13)	146120.04	0.37 ± 0.05	56.98 ± 0.34	4.89 ± 0.73	0.07
HCCCN	$J = 16$ –15, $l = 1f$	146127.53	0.66 ± 0.06	58.00 ± 0.38	7.13 ± 0.90	0.09
CH ₃ OH	20(6,15)–21(5,16) –	146286.58	1.04 ± 0.08	59.60 ± 0.55	12.92 ± 1.16	0.08
CH ₃ OH	3(1,2)–2(1,1) A–	146368.34	1.78 ± 0.05	58.28 ± 0.07	5.23 ± 0.22	0.32
SO ₂	4(2,2)–4(1,3)	146605.51	0.41 ± 0.05	57.87 ± 0.29	4.78 ± 0.60	0.08
CH ₃ OH	14(1,14)–13(2,11) A++	146617.41	1.21 ± 0.08	56.09 ± 0.19	6.10 ± 0.49	0.19
H ¹³ ₂ CO	2(1,1)–1(1,0)	146635.67	0.50 ± 0.06	58.82 ± 0.33	5.80 ± 0.99	0.08
CH ₂ N	2(0,2)–1(0,1) 7/2–5/2 9/2–7/2	146675.06	0.20 ± 0.04	52.20 ± 0.56	4.48 ± 0.94	0.25
CS	3–2	146969.02	19.62 ± 0.05	57.63 ± 0.00	5.55 ± 0.02	3.32

Table B5. S76E.

Molecule	Transition	Frequency (MHz)	$\int T_{\text{mb}} dv$ (K km s ⁻¹)	v_{LSR} (km s ⁻¹)	FWHM (km s ⁻¹)	T_{mb} (K)
OCS	7–6	85139.10	0.15 ± 0.01	33.69 ± 0.13	2.40 ± 0.33	0.06
HC ¹⁸ O ⁺	1–0	85162.22	0.14 ± 0.01	33.83 ± 0.14	2.43 ± 0.30	0.06
HC ₅ N	32–31	85201.34	0.11 ± 0.01	33.58 ± 0.31	2.81 ± 0.71	0.04
c–C ₃ H ₂	2(1,2)–1(0,1)	85338.89	0.79 ± 0.01	34.11 ± 0.03	2.66 ± 0.08	0.28
HCS ⁺	2–1	85347.89	0.32 ± 0.01	33.93 ± 0.08	2.67 ± 0.22	0.11
CH ₃ CCH	5(3)–4(3)	85442.60	0.14 ± 0.02	32.92 ± 0.27	3.35 ± 0.60	0.04
CH ₃ CCH	5(2)–4(2)	85450.76	0.16 ± 0.01	33.66 ± 0.11	2.50 ± 0.26	0.07
CH ₃ CCH	5(1)–4(1)	85455.66	0.43 ± 0.01	33.47 ± 0.04	2.42 ± 0.09	0.17
CH ₃ CCH	5(0)–4(0)	85457.30	0.55 ± 0.01	33.53 ± 0.04	2.65 ± 0.10	0.20
C ₄ H	9–8 $J = 19/2$ –17/2	85634.01	0.09 ± 0.01	34.48 ± 0.27	2.83 ± 0.59	0.03
NH ₂ D	1(1,1)0+–1(0,1)0–	85926.27	0.27 ± 0.02	33.18 ± 0.22	4.64 ± 0.66	0.06
HC ¹⁵ N	1–0	86054.96	0.45 ± 0.02	33.74 ± 0.07	2.86 ± 0.17	0.15
SO	$N, J = 2, 2$ –1, 1	86093.95	0.36 ± 0.01	33.43 ± 0.07	2.74 ± 0.18	0.13
H ¹³ CN	1–0 $F = 1$ –1	86338.73	0.88 ± 0.01	33.60 ± 0.03	2.62 ± 0.07	0.32
H ¹³ CN	1–0 $F = 2$ –1	86340.17	1.62 ± 0.02	33.64 ± 0.01	2.82 ± 0.05	0.54
H ¹³ CN	1–0 $F = 0$ –1	86342.25	0.36 ± 0.02	33.63 ± 0.10	3.07 ± 0.28	0.11
HC13O ⁺	1–0	86754.28	1.38 ± 0.01	33.36 ± 0.02	2.77 ± 0.04	0.47
C ₃ S	15–14	86708.38	0.19 ± 0.03	34.32 ± 0.15	2.59 ± 0.55	0.07
Unidentified		86777.10	0.18 ± 0.03	32.87 ± 0.18	2.93 ± 0.51	0.06
SiO	2–1 $v = 0$	86846.96	0.72 ± 0.04	33.50 ± 0.13	5.15 ± 0.40	0.13
HN ¹³ C	1–0 $F = 2$ –1	87090.85	0.81 ± 0.01	33.38 ± 0.03	2.81 ± 0.07	0.27
CCH	1–0 3/2–1/2 $F = 1$ –1	87284.10	0.57 ± 0.01	33.51 ± 0.04	2.58 ± 0.10	0.21
CCH	1–0 3/2–1/2 $F = 2$ –1	87316.89	4.08 ± 0.02	33.64 ± 0.00	2.50 ± 0.01	1.53
CCH	1–0 3/2–1/2 $F = 1$ –0	87328.58	2.26 ± 0.01	33.58 ± 0.01	2.53 ± 0.02	0.84
CCH	1–0 1/2–1/2 $F = 1$ –1	87401.98	2.26 ± 0.01	33.60 ± 0.01	2.51 ± 0.02	0.85
CCH	1–0 1/2–1/2 $F = 0$ –1	87407.16	1.09 ± 0.01	33.55 ± 0.02	2.59 ± 0.05	0.40
CCH	1–0 1/2–1/2 $F = 1$ –0	87446.47	0.59 ± 0.01	33.52 ± 0.03	2.39 ± 0.09	0.23
HC ₅ N	33–32	87863.63	0.25 ± 0.04	33.29 ± 0.35	3.02 ± 0.60	0.03
HNCO	4(0,4)–3(0,3)	87925.23	0.35 ± 0.02	33.04 ± 0.11	3.42 ± 0.27	0.10
HCN	1–0 $F = 1$ –1	88630.41	6.03 ± 0.12	33.78 ± 0.02	3.02 ± 0.07	1.87
HCN	1–0 $F = 2$ –1	88631.84	1.24 ± 0.08	34.55 ± 0.06	1.71 ± 0.15	0.68
HCN	1–0 $F = 0$ –1	88633.93	1.08 ± 0.08	32.08 ± 0.06	1.73 ± 0.17	0.59
HCO ⁺	1–0	89188.52	4.29 ± 0.07	34.05 ± 0.02	3.09 ± 0.06	1.31
<i>l</i> -C ¹³ CC ₂ H ₂	10(2,8)–9(2,7)	88865.38	0.23 ± 0.03	31.87 ± 0.14	2.58 ± 0.31	0.09
c–C ₃ D ₂	5(4,2)–5(3,3)	89316.91	0.15 ± 0.03	33.31 ± 0.91	7.21 ± 1.58	0.02
Unidentified		89441.30	0.20 ± 0.04	32.65 ± 0.70	6.70 ± 1.54	0.03
Unidentified		89449.50	0.20 ± 0.04	32.53 ± 0.87	8.47 ± 1.62	0.02
HOCHCHCHO	6(4,3)–5(3,2)	89458.20	0.16 ± 0.04	33.94 ± 0.71	6.18 ± 1.34	0.03
HC ₅ N	34–33	90525.88	0.25 ± 0.02	32.96 ± 0.18	2.83 ± 0.41	0.03
HC ¹³ CCN	10–9	90593.05	0.16 ± 0.02	32.81 ± 0.33	3.88 ± 0.64	0.04
HCC ¹³ CN	10–9	90601.77	0.12 ± 0.01	32.70 ± 0.20	2.25 ± 0.45	0.05
HNC	1–0 $F = 2$ –1	90663.56	9.70 ± 0.04	33.05 ± 0.00	2.69 ± 0.01	3.39
HCCCN	10–9	90979.02	3.13 ± 0.01	32.81 ± 0.01	2.62 ± 0.01	1.12
HDCS	3(1,3)–2(1,2)	91171.03	0.13 ± 0.04	32.09 ± 0.38	2.85 ± 0.89	0.03
H ₂ CCCHCN	4(2,2)–2(1,3)	91494.56	0.13 ± 0.03	33.66 ± 0.29	3.25 ± 0.99	0.04
CH ₃ CN	5(3)–4(3)	91971.13	0.32 ± 0.04	32.33 ± 0.29	6.03 ± 0.92	0.05
CH ₃ CN	5(2)–4(2)	91979.99	0.38 ± 0.03	32.42 ± 0.16	4.40 ± 0.41	0.08
CH ₃ CN	5(1)–4(1)	91985.31	0.30 ± 0.02	32.66 ± 0.09	2.37 ± 0.22	0.12
CH ₃ CN	5(0)–4(0)	91987.08	0.43 ± 0.02	32.66 ± 0.09	3.22 ± 0.21	0.13
H α	H41 α	92034.43	0.90 ± 0.04	21.00 ± 0.70	28.40 ± 1.75	0.03
CH ₃ COOH	$v = 0$ 18(13,6)–18(–10,8) $v = 0$	143755.42	0.04 ± 0.00	32.60 ± 0.10	1.10 ± 0.25	0.04
CH ₃ OH	3(1,3)–2(1,2) A++	143865.79	0.34 ± 0.01	32.58 ± 0.08	3.32 ± 0.24	0.10
DCO ⁺	2–1	144077.28	0.24 ± 0.03	32.09 ± 0.34	6.64 ± 1.05	0.03
CH ₃ C ₃ N	35(16)–34(16)	144231.92	0.36 ± 0.01	30.70 ± 0.07	2.61 ± 0.17	0.13
CCD	2–1 $J = 5/2$ –3/2 $F = 7/2$ –5/2	144241.96	0.06 ± 0.01	32.38 ± 0.37	3.08 ± 0.66	0.02
Unidentified		144609.02	0.10 ± 0.03	40.55 ± 0.27	2.00 ± 0.58	0.05
C ³⁴ S	3–2	144617.10	0.93 ± 0.01	33.20 ± 0.02	2.57 ± 0.05	0.34
DCN	2–1 $F1 = 2$ –1	144828.00	0.31 ± 0.03	33.32 ± 0.16	4.35 ± 0.51	0.07
c–C ₃ H ₂	3(1,2)–2(2,1)	145089.62	0.61 ± 0.07	32.25 ± 0.15	6.17 ± 0.77	0.09
CH ₃ OH	3(0,3)–2(0,2) E	145093.76	0.80 ± 0.05	32.41 ± 0.10	3.45 ± 0.28	0.22
CH ₃ OH	3(–1,3)–2(–1,2) E	145097.44	2.33 ± 0.05	32.76 ± 0.03	3.05 ± 0.08	0.72
CH ₃ OH	3(0,3)–2(0,2) A++	145103.19	2.64 ± 0.03	32.81 ± 0.02	3.01 ± 0.05	0.82

Table B5 – *continued*.

Molecule	Transition	Frequency (MHz)	$\int T_{\text{mb}} dv$ (K km s ⁻¹)	v_{LSR} (km s ⁻¹)	FWHM (km s ⁻¹)	T_{mb} (K)
CH ₃ OH	3(-2,2)-2(-2,1) E	145126.39	0.36 ± 0.01	32.97 ± 0.10	3.30 ± 0.27	0.10
CH ₃ OH	3(1,2)-2(1,1) E	145131.87	0.37 ± 0.03	32.49 ± 0.11	3.82 ± 0.33	0.09
CH ₃ SH	$v = 0$ 12(-3)-13(-2) E	145386.10	0.78 ± 0.01	31.98 ± 0.02	2.67 ± 0.06	0.28
HCCCN	16-15	145560.95	0.80 ± 0.01	32.98 ± 0.03	2.53 ± 0.07	0.30
H ₂ CO	2(0,2)-1(0,1)	145602.95	4.00 ± 0.03	33.12 ± 0.01	2.86 ± 0.02	1.31
Unidentified		145677.00	0.13 ± 0.02	32.88 ± 0.31	3.38 ± 1.04	0.04
Unidentified		145692.20	0.06 ± 0.01	32.88 ± 0.28	1.77 ± 0.43	0.03
<i>n</i> -C ₃ H ₇ CN	9(7,3)-8(6,2)	145700.18	0.14 ± 0.02	31.39 ± 0.44	5.70 ± 1.02	0.03
<i>t</i> -HC(O)SH	15(2,13)-15(1,14)	145746.31	0.18 ± 0.02	34.70 ± 0.18	3.23 ± 0.46	0.05
C ³³ S	3-2 $F = 9/2-7/2$	145755.62	0.18 ± 0.01	32.51 ± 0.17	3.24 ± 0.48	0.05
OCS	12-11	145946.81	0.10 ± 0.01	32.46 ± 0.20	2.23 ± 0.54	0.04
CH ₃ OH	3(1,2)-2(1,1)A-	146368.34	0.41 ± 0.01	32.53 ± 0.09	3.32 ± 0.24	0.12
CH ₃ OH	9(0,9)-8(1,8)A++	146618.83	0.50 ± 0.03	32.42 ± 0.07	3.13 ± 0.20	0.15
H ₂ ¹³ CO	2(1,1)-1(1,0)	146635.67	0.14 ± 0.03	32.56 ± 0.33	3.02 ± 0.70	0.05
H ₂ CN	2(0,2)-1(0,1) $F = 3/2-5/2$	146640.12	0.41 ± 0.03	32.30 ± 0.09	3.07 ± 0.24	0.13
CS	3-2	146969.02	9.68 ± 0.03	33.01 ± 0.00	2.90 ± 0.01	3.13

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