DISTRIBUTION OF CCS AND HC₃N IN L1147, AN EARLY PHASE DARK CLOUD

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Received 2013 September 14; accepted 2014 April 28; published 2014 May 28

ABSTRACT

We used the Nobeyama 45 m radio telescope to reveal spatial distributions of CCS and HC₃N in L1147, one of the carbon-chain producing region (CCPR) candidates, where carbon-chain molecules are dominant rather than NH₃. We found that three cores (two CCS cores and one HC₃N core), which are away from a very low luminosity object (a source that may turn into a sub-stellar mass brown dwarf), exist along the NE–SW filament traced by the 850 μm dust continuum. The column densities of CCS are 3–7 × 10¹² cm⁻² and those of HC₃N are 2–6 × 10¹² cm⁻², respectively, much lower than those previously reported toward other CCPRs. We also found that two CCS peaks are displaced from the peaks of HC₃N. In order to interpret such interleaved distributions, we conducted chemical reaction network simulations and found that slightly different gas densities could lead to large variation of the CCS-to-HC₃N ratio in the early phase of dark cloud evolution. Such a chemical “variation” may be seen in other CCPRs. Finally, we were able to confirm that the L1147 filament can be regarded as a CCPR.

Key words: ISM: individual objects (L1147) – ISM: molecules – radio lines: ISM

Online-only material: color figure

1. INTRODUCTION

It is well known that dark cloud cores, where low mass stars are formed, can be traced by abundant carbon-chain molecules. Suzuki et al. (1992) conducted survey observations of CCS, HC₃N, HC₅N, and NH₃ toward 49 molecular clouds, and pointed out that CCS is observed in the early phase of cloud evolution, while the abundance of NH₃ gradually increases in the later phase. The column density ratio of NH₃ to CCS (hereafter we call it the NH₃/CCS ratio) is a good indicator of cloud age, and clouds with low NH₃/CCS ratio are called carbon-chain producing regions (CCPRs). Such characteristics indicate that the chemical and the physical evolution of a molecular cloud are well-connected, providing useful information for the investigation of the cloud’s evolution. Since then, CCS observations have been carried out to study the early phase of cloud evolution (e.g., Hirahara et al. 1992; Velusamy et al. 1995; Ohashi et al. 1999; Hirota et al. 2002, 2004, 2009, 2011; Hirota & Yamamoto 2006; Tafalla & Santiago 2004).

Hirota et al. (2009) carried out survey observations in order to find CCPRs outside of the Taurus region, and suggested that five molecular clouds showed lower NH₃/CCS ratios of less than 10, which were consistent with the known features of CCPRs. Four clouds, L1517D, L530D, L1147, and L1172B, specifically showed the notable feature that their CCS column densities are lower than other CCPRs.

L1147 is a dark cloud in the Cepheus region at a distance of 325 pc (Straizys et al. 1992). Since the original Lynds’ catalog gave the same center positions for both L1147 and L1148 (Lynds 1962), some literatures call this dark cloud L1148 (e.g., Kirk et al. 2009). Such a situation is confusing, so we call this source L1147 throughout this paper since we have already adopted this source name in our past papers. Kirk et al. (2005) obtained a dust continuum map toward L1147 taken by SCUBA at 850 μm, and reported that the dust continuum emission is weak in this cloud, which may represent a physically young evolutionary phase. Kirk et al. (2009) also reported the dust continuum map of the entire region including L1147. They mentioned that L1147 has a very low luminosity object (VeLLO), which is defined as a source whose luminosity is lower than 0.1 L☉, and that it may form sub-stellar mass brown dwarfs (Kaufmann et al. 2011; Di Francesco et al. 2007). This VeLLO source was discovered by the Spitzer mission as the Spitzer Multiband Imaging Photometer for Spitzer source SSTc2d J204056.66+672304.9.

Among the CCPR candidates L1147 has the lowest NH₃/CCS ratio of 1.5; however, Hirota et al. (2009) observed a position away from the VeLLO source. Thus further observation was needed to confirm that this dark cloud is certainly chemically young, since Hirota et al. (2009) made single point observations of the CCPR candidate sources and did not exclude the possibility that these candidate sources are located at the edge of a dense core.

In this paper, we report mapping results toward L1147 in the 45 GHz CCS and HC₃N lines, and discuss its evolutionary phase using a chemical reaction network. The observational method is described in Section 2 (Observations). The intensity distributions of CCS and HC₃N, their velocity structure as well as their column density distributions are shown in Section 3 (Results). In Section 4 (Discussion) we compare the CCS and HC₃N abundances with our unpublished NH₃ data and chemical reaction simulation results to determine whether L1147 is a chemically young CCPR. Finally we summarize the results of our study in Section 5.

2. OBSERVATIONS

We conducted mapping observations with the 45 m radio telescope of the Nobeyama Radio Observatory, National Astronomical Observatory of Japan, in 2012 April. The CCS (J = 4−3), and the HC₃N (J = 5−4) lines in the 45 GHz region were observed simultaneously with a superconductor–insulator–superconductor mixer receiver, whose system temperature was 200–300 K during our observations. The main beam efficiency (η_m) was 0.72, and the beam size (FWHM)
was 38\arcsec. The pointing accuracy was checked about every two hours by observing the SiO masers ($v = 1$ and 2, $J = 1\rightarrow0$) toward T Cep. The pointing error was estimated to be within 5\arcsec.

The rest frequencies, the intrinsic line strengths, and the permanent dipole moments for CCS and HC$_3$N are $\nu =$ 45379.033 and 45490.316 MHz, $S_{\text{int}} =$ 3.97 and 5.00, and $\mu =$ 2.81 and 3.72 D (Murakami 1990; Lafferty & Lovas 1978), respectively. Acousto-optical radio spectrometers with the frequency resolution of 37 kHz, corresponding to the velocity resolution of 0.24 km s$^{-1}$, were used for the backend. The mapping center was set to $x_{\text{C2000}} = 20^h40^m32^s0$, $\delta_{\text{C2000}} = 67^\circ21\arcmin45\arcsec$. In the mapping observations of HC$_3$N and CCS, the spectra were observed with a grid spacing of 40\arcsec in the position-switching mode, in which the offset position was 10\arcsec away from each source position. We observed at 39 positions along the L1147 filament (for the mapping area, see, e.g., Figure 3). The integration time per position was 200 s.

3. RESULTS
3.1. Molecular Distributions

Figure 1 shows examples of the observed spectra for the individual molecules. The top panel shows the CCS spectrum at its peak ($\Delta \alpha, \Delta \delta = (-40^\circ, -120^\circ)$), and the bottom corresponds to the HC$_3$N spectrum at its peak ($\Delta \alpha, \Delta \delta = (0^\circ, -40^\circ)$), respectively. The highest antenna temperatures were 0.89 K for CCS and 0.95 K for HC$_3$N, respectively, in our mapping region. In Figure 1(b), we could not observe the hyperfine structure ($\Delta F = 0$) lines of HC$_3$N, suggesting that the HC$_3$N lines are optically thin.

Figures 2(a) and (b) show integrated intensity maps in the CCS $J_N = 4_3\rightarrow3_2$ line and HC$_3$N $J = 5\rightarrow4$ line, respectively. The velocity range of integration is from 2.3 to 3.3 km s$^{-1}$. We found that the CCS and HC$_3$N emissions are elongated in the NE–SW direction, which is consistent with the 850 $\mu$m map obtained by Kirk et al. (2005) (see Figure 3 and the 850 $\mu$m map from the SCUBA Legacy Catalogues; Di Francesco et al. 2008). There are two CCS peaks and one HC$_3$N peak on the same filament: the two CCS peaks are located at ($80^\circ, 0^\circ$) and ($-40^\circ, -120^\circ$), and one HC$_3$N peak is found at ($0^\circ, -40^\circ$). Such a CCS distribution agrees well with the CCS $J_N = 2_1\rightarrow1_0$ map obtained by Kauffmann et al. (2005). Hereafter we call these three cores A, B, and C from east to west, respectively. The line parameters in these cores are summarized in Table 1. The HC$_3$N emission lines toward cores A and B show slightly broader linewidths due to blended hyperfine structure lines (see Figure 1(b)).

The dust continuum distribution, which would trace the H$_2$ density, is strongest toward core B, followed by cores A and C. H$_2$ column densities were derived from the dust continuum map using the methodology described in Kauffmann.
Table 1

| Core | $T_B$ (rms) (K) | $V_{LSR}$ (km s$^{-1}$) | $\Delta v$ (km s$^{-1}$) | $\int T_B dv$ (3$\sigma$) (K km s$^{-1}$) | $T_B$ (rms) (K) | $V_{LSR}$ (km s$^{-1}$) | $\Delta v$ (km s$^{-1}$) | $\int T_B dv$ (3$\sigma$) (K km s$^{-1}$) |
|------|----------------|-------------------------|--------------------------|------------------------------------------|----------------|-------------------------|--------------------------|------------------------------------------|
| A    | 0.72 (0.10)    | 2.6                     | 0.5                      | 0.38 (0.16)                              | 0.49 (0.09)   | 2.4                     | 0.5                      | 0.26 (0.14)                              |
| B    | 0.63 (0.10)    | 2.8                     | 0.6                      | 0.40 (0.19)                              | 0.95 (0.08)   | 2.7                     | 0.7                      | 0.71 (0.18)                              |
| C    | 0.89 (0.10)    | 2.7                     | 0.5                      | 0.47 (0.16)                              | $<0.21$ (0.07)| ...                    | ...                      | $<0.13$                                  |

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cores A and C; however, we see that HC3N emission exists around the two CCS peaks. Detailed descriptions for individual cores are summarized in Table 1.

In our mapping observations, we found that the three peaks are clearly interleaved to each other, contrary to the past observation results where CCS and HC3N show similar spatial distributions (Hirahara et al. 1992; Tafalla et al. 2006; Hirota et al. 2002, 2004). For example, Figure 4 in Hirota et al. (2009) showed the integrated intensity maps of CCS and HC3N toward seven dark clouds. The spatial distributions of CCS and HC3N in six dark clouds are very similar, including their peak positions, even if there is a slight difference in the distributions. The only exception is L1172D: there are two CCS peaks and HC3N is located between the CCS peaks. It is well known that carbon-chain molecules are sometimes depleted in the central part of an infrared source and that their distributions show a central hole (Velusamy et al. 1995; Kuiper et al. 1996; Ohashi et al. 1999; Lai & Crutcher 2000; Lai et al. 2003). The observed characteristics of the interleaved peaks seem to have different spatial distributions from the central-hole case mentioned above, and we will discuss later how such an interleaved distribution could be explained.

3.2. Position–Velocity Maps

Figure 5 shows position–velocity maps in L1147. For CCS, we put a cutting line (a–a′) along the edge passing through cores A and C. Additionally, we have set two cutting lines perpendicular to the line a–a′, passing through these cores. We drew four lines in Figures 5(a) and (b), including three cores (b–b′ and c–c′). Similarly, for HC3N, we set a cutting line (d–d′) perpendicular to the line (a–a′) and passing through core B. The position–velocity maps along the ridge (bottom left in Figure 5) and perpendicular to the cores (bottom right in Figure 5) do not show any sign of rotation. This fact is consistent with the three cores being in a very early phase in their physical evolution.

3.3. Molecular Column Densities

We derived the column densities of CCS and HC3N. For the calculations, we used the following equations, assuming local thermal equilibrium (LTE) condition and both lines are optically thin:

\[ T_A^* = \eta_{\text{mb}} [J(T_{\text{ex}}) - J(T_{\text{BB}})] [1 - \exp(-\tau)]. \]  

\[ \text{(1)} \]
Figure 6. (a) and (b) We have chosen eight points along the ridge with different declination offsets; (c) distribution of column densities of CCS and HC$_3$N along the ridge. The abscissa denotes the declination offset, whose positions are shown in (a) and (b). The position of the VeLLO source is shown by the black star. (A color version of this figure is available in the online journal.)

where

\[ J(T) = \left( \frac{\nu}{k} \right) \left[ \exp\left( \frac{\nu}{kT} \right) - 1 \right]^{-1}, \]  

(2)

\[ N = \frac{3h}{8\pi^3} \frac{Q}{\mu^2 S_{ij}} \frac{\Delta v}{\exp(\nu/kT_{ex})} \exp(\nu/kT_{ex}) - 1 \tau. \]  

(3)

In these equations, $\eta_{mb}$ denotes the main beam efficiency, $\nu$ the rest frequency of the line, $N$ the column density, $\Delta v$ the line width (FWHM), $Q$ the rotational partition function, $S_{ij}$ the intrinsic line strength of the transition, $\mu$ the permanent dipole moment, and $E_u$ the upper state energy from the ground state rotational level. Since we observed a single line for each molecule, the excitation temperatures were fixed to 5 K for CCS and 6.5 K for HC$_3$N, which are consistent with our previous studies (e.g., Suzuki et al. 1992; Hirota et al. 2009). A change of excitation temperature by 1 K changes their column densities by about 30%.

Figure 6 shows the derived column density distributions along the prominent NE–SW ridge seen in the integrated intensity maps (Figure 2). The column densities of both molecules resulted in a range of $2-7 \times 10^{12}$ cm$^{-2}$, which is consistent with the values reported by Hirota et al. (2009). We found that the derived column densities of CCS ($3-7 \times 10^{12}$ cm$^{-2}$) are about one order of magnitude less than those in other known CCPRs, e.g., $66 \times 10^{12}$ cm$^{-2}$ for TMC1(CP) (Suzuki et al. 1992) and $53 \times 10^{12}$ cm$^{-2}$ for L492 (Hirota et al. 2009).

The three peaks (cores A, B, and C) are also seen in the column density distributions along the NE–SW ridge; however, we have found that the column density ratio between CCS and HC$_3$N (hereafter the CCS/HC$_3$N ratio) varies dramatically.

We summarized in Table 2 their column densities, fractional abundances relative to H$_2$, and CCS/HC$_3$N ratios. The errors of the column densities are calculated using the rms noise in each observation. The upper limit to the column density of HC$_3$N in core C was calculated using the $3\sigma$ rms noise at this position. We took the estimated error of H$_2$ into account when calculating the fractional abundance values. Note that the dust emission in core C is weaker than the noise level. Therefore we used the $3\sigma$ level of the rms noise for the H$_2$ density to calculate the upper limit of the fractional abundances of CCS. In core A, CCS has a higher abundance than HC$_3$N. On the other hand,
Figure 7. CCS/HC3N ratio as a function of NH3/CCS ratio in various clouds. The data points were taken from Suzuki et al. (1992) and Hirota et al. (2009) where the CCS, HC3N, and NH3 data are available. The arrows indicate upper or lower limits to the ratios. The data point corresponding to L1147 is shown by the open square.

Table 2: Column Densities, Fractional Abundances, and CCS/HC3N Ratios toward Cores A, B, and C

| Core | N[CCS] \(10^{12}\) cm\(^{-2}\) | N[HC3N] \(10^{12}\) cm\(^{-2}\) | N[H2] \(10^{21}\) cm\(^{-2}\) | X[CCS] \(10^{-10}\) | X[HC3N] \(10^{-10}\) | N[CCS]/N[HC3N] |
|------|-----------------|-----------------|-----------------|-----------------|-----------------|----------------|
| A    | 5.8 (±3.9)      | 1.8 (±0.9)      | 6.2 (±1.9)      | 9.5 (±7.1)      | 3.0 (±1.7)      | 3.2 (±2.6)     |
| B    | 3.5 (±2.5)      | 6.1 (±4.3)      | 11 (±1.9)       | 3.3 (±2.4)      | 5.7 (±4.1)      | 0.6 (±0.6)     |
| C    | 7.4 (±4.3)      | <0.8            | <5.7            | >13             | ---             | >9             |

In this section we will discuss whether L1147 can be regarded as a CCPR, and how we could reconcile the displacement of the emission peaks and the variation in the CCS-to-HC3N ratio among the prominent cores.

4. DISCUSSION

In this section we will discuss whether L1147 can be regarded as a CCPR, and how we could reconcile the displacement of the emission peaks and the variation in the CCS-to-HC3N ratio among the prominent cores.

4.1. NH3 Data in the L1147 Filament

The first issue that we want to clarify is whether L1147 is a CCPR as a whole. In this regard, it would be important to know how strong or weak the NH3 line is. Hirota et al. (2009) reported the NH3 (1,1) data only toward the \((0'',-80'')\) position by using the Nobeyama 45 m radio telescope, which shows very weak emission (the antenna temperature of 80 mK). T. Hirota et al. (2013, unpublished) observed the NH3 (1,1) line toward the IRS position (the VeLLO source); however, the line was too faint to detect with an rms noise level of 30 mK. Therefore it is possible to calculate an upper limit to the column density of NH3 toward the VeLLO source, which is \(9 \times 10^{12} \text{ cm}^{-2}\), using the same method as Hirota et al. (2009). This value is comparable with that reported by Hirota et al. (2009) \(8 \times 10^{12} \text{ cm}^{-2}\). Since the beam size is large \(\sim 80\) arcsec, the two beams covered most of the mapping area in the CCS and the HC3N lines. Thus we may conclude that the column density of NH3 in the L1147 filament is less than \(9 \times 10^{12} \text{ cm}^{-2}\) as a whole. When we use this upper limit to the NH3 column density together with the column densities of CCS tabulated in Table 2, the NH3/CCS ratio is found in a range between 0.95 and 4.3. This leads us to confirm that the entire L1147 filament is a CCPR.

4.2. Variation of CCS/HC3N Ratios

It is well known that abundances of carbon-chain molecules increase rapidly then decrease as the cloud evolves (Suzuki et al. 1992). Although Suzuki et al. (1992) reported observation results for CCS, HC3N, HC5N, and NH3, they did not compare abundances of CCS and HC3N based on their gas-phase chemical evolution model. Further, to the best of our knowledge, no one has conducted such comparisons, especially in the early phase of cloud evolution. The CCS/HC3N ratio is expected to be uniform since cores formed in a single filament would have similar evolutionary phase. However, we have found that the three cores in the L1147 filament show the different variations of the CCS/HC3N ratios. This would suggest that the three cores are in different evolutionary phases.

Can we then see such variations of the CCS/HC3N ratio for other dark clouds? Figure 7 shows a cloud-to-cloud variation of the CCS/HC3N ratio as a function of the NH3/CCS ratio. The data were taken from Suzuki et al. (1992) and Hirota et al. (2009) where the CCS, HC3N, and NH3 data are available. Since it is well known that the NH3/CCS ratio is a good indicator
of the chemical evolution of a cloud, this plot represents a
time evolution of the CCS/HCN ratio along with the
global evolution. A weak trend where a majority of cores in the CCPRs
and their candidates (the NH$_3$/CCS ratio is less than 10) have
higher CCS/HCN ratios, whereas a majority of evolved cores have lower CCS/HCN ratios, can be seen from this figure.

In order to understand the difference among the three cores
in L1147 as well as the trend of the CCS/HCN ratios, we
utilize chemical reaction network simulations to understand
the chemical evolution of early phase molecular clouds.

4.3. Chemical Evolution Model

We have conducted chemical evolution simulations based on
the latest theoretical model that incorporates surface reactions
on the dust particles.

For chemical reactions and their rate coefficients, we used the
KIDA (KInetic Database for Astrochemistry) data set (Wakelam
et al. 2012), which is a collection of measured and theoretical
values published in literatures. The simulation code was also
provided by Wakelam et al. (2012), and includes 684 molecules
and 8317 reactions. The simulation code numerically solves the
chemical kinetics equations, shown below, that describes the
formation and destruction of molecules.

$$\frac{dn_i}{dt} = \sum_{l,m} k_{il} n_l n_m - n_i \sum_{l \neq i} k_{li} n_l + k_{des_i} n_i - k_{acc_i} n_i$$ (4)

$$\frac{dn_i^s}{dt} = \sum_{l,m} k_{il}^s n_l^s n_m^s - n_i^s \sum_{l \neq i} k_{li}^s n_l^s + k_{des_i}^s n_i^s - k_{acc_i}^s n_i^s$$, (5)

where $n_i$ and $n_i^s$ are the gas-phase and surface concentrations of
the $i$th species (cm$^{-3}$), $k_{il}$ and $k_l$ are the gas-phase reaction rates
(in units of s$^{-1}$ for the first-order kinetics and cm$^3$ s$^{-1}$ for the
second-order kinetics), $k_{acc}$ and $k_{des}$ denote the accretion and
desorption rates (s$^{-1}$), and $k_{il}^s$ and $k_{il}^s$ are the surface reaction rates (cm$^3$ s$^{-1}$). It should be noted that this model assumes
a constant number density of the hydrogen atom and other
physical parameters throughout a simulation. The gas kinetic
temperature was fixed to 10 K, a typical value for a dark cloud,
and the visual extinction, $A_v$, was fixed to 10 mag. For the initial
elemental abundances (see Table 3, we adopted the EA2 set used
by Wakelam & Herbst 2008).

Table 3

| Element | Abundance  | Element | Abundance  |
|---------|-----------|---------|-----------|
| He      | 9.00(−2)  | Fe*     | 2.00(−7)  |
| N       | 7.60(−5)  | Na*     | 2.00(−7)  |
| O       | 2.56(−4)  | Mg*     | 2.40(−6)  |
| C*      | 1.20(−4)  | Cl*     | 1.8(−7)   |
| S*      | 1.50(−5)  | P*      | 1.17(−7)  |
| Si*     | 1.70(−6)  | F*      | 1.8(−8)   |

Notes. Elemental abundance used in our chemical reaction model.
This table is taken from Wakelam & Herbst (2008).

N + CRP → N$^+$ + e$^−$ ($k = 2.9 \times 10^{-17}$ cm$^3$ s$^{-1}$) (1)

N$^+$ + H$_2$ → NH$^+_2$ + H ($k = 6.3 \times 10^{-12}$ cm$^3$ s$^{-1}$) (2)

NH$^+$ + H$_2$ → NH$_2^+$ + H ($k = 1.0 \times 10^{-9}$ cm$^3$ s$^{-1}$) (3)

NH$_2^+$ + H$_2$ → NH$_3^+$ + H ($k = 1.2 \times 10^{-10}$ cm$^3$ s$^{-1}$) (4)

NH$_3^+$ + H$_2$ → NH$_4^+$ + H ($k = 1.2 \times 10^{-12}$ cm$^3$ s$^{-1}$) (5)

NH$_4^+$ + e$^−$ → NH$_3$ + H ($k = 5.8 \times 10^{-6}$ cm$^3$ s$^{-1}$) (6)

Reaction (2) has a small rate coefficient since it has an activation
energy of about 42 K. Although reaction (5) has a negative
activation energy of about −36 K, the prefactor is so small
(3.36 × 10$^{-14}$ cm$^3$ s$^{-1}$). Such small rate coefficients, including
the ionization of the N atom by a cosmic ray, would result in
a long time to form NH$_3$. We drew a vertical line at 10$^3$ yr
in Figure 8, corresponding to a typical age for dark clouds. The
observed column densities of CCS and HCN agree with the
simulation results within a factor of 10 ($X_{obs}/10 \leq X_{model} \leq
10X_{obs}$), where $X_{obs}$ is the observed abundance and $X_{model}$ is the
Figure 8. Examples of simulation results for different hydrogen number densities: (a) \(1 \times 10^4 \text{ cm}^{-3}\), (b) \(2 \times 10^4 \text{ cm}^{-3}\), and (c) \(6 \times 10^4 \text{ cm}^{-3}\). The vertical line denotes \(1 \times 10^5 \text{ yr}\), a typical age of a dark cloud core. The column density range for CCS and HC$_3$N derived in our observation is shown in the gray region.

We simulated chemical evolution under different densities from \(10^4\) to \(10^6 \text{ cm}^{-3}\), and compared the CCS/HC$_3$N ratio with our observation between \(3.16 \times 10^4\) and \(1.0 \times 10^5 \text{ yr}\). Some examples of simulation under different densities are shown in Figures 8(b) and (c). It is seen that chemical evolution would be accelerated in physically evolved denser cores due to a larger number of reactants per unit volume.

Figures 9(a)–(c) show the simulated CCS/HC$_3$N ratios derived in different densities and ages. Each figure has the same ratio value for the same age and the density, but we prepared three to compare the simulation with the individual three cores since they have different fractional abundances of CCS and HC$_3$N, and the CCS/HC$_3$N ratio. We compared Figure 9 with (a) core A, (b) core B, and (c) core C. Now we classify them in terms of the observed ratios. As we expected, NH$_3$ becomes dominant in the later phase compared with the carbon-chain molecules. Since NH$_3$ is so weak in L1147, such an evolutionary stage would not be appropriate for L1147. Thus we excluded them from our comparison (in Figure 9 the regions are shown in gray). Some regions shown in white are not suitable in terms of the CCS/HC$_3$N ratios. We also excluded regions where observed fractional abundances of CCS and HC$_3$N are not within a factor of 10 (the regions are shown in purple and blue). For core C, we did not use the fractional abundance of HC$_3$N as criteria for comparison since we were only able to set upper limits to the column density of HC$_3$N and H$_2$. We then found that the observed CCS/HC$_3$N ratios in cores A, B, and C can be reproduced in the orange regions between \(6 \times 10^4–1 \times 10^5 \text{ yr}\), typical for dark clouds in Figures 9(a)–(c). All appropriate regions are those just before NH$_3$ becomes dominant. In realistic dark clouds, physical evolution would be accelerated along with the increase of gas density.
4.5. Evolutionary Phases in the Cores

In this last subsection we discuss whether the three cores were formed and evolved in a similar way.

Figures 9(a)–(c) were made assuming a visual extinction of 10 mag. Core C is located at the edge of the L1147 filament where the gas density could be lower than in cores A and B, and could have lower visual extinction. Figure 9(d) represents the result of a simulation with the visual extinction of 7.5 mag. Our simulations suggested that carbon-chain molecules tend to decrease more slowly in the later phase. This trend would conflict with the fact that HC$_3$N was not observed in the core C. As shown in Figure 9(d), we could not find the appropriate region that explains the observed column density with this parameter.

On the other hand, we were able to reproduce the chemical properties in cores A and B in the appropriate evolutionary phase for dark clouds (around 1 × 10$^5$ yr). Our results suggest that these cores may have slightly different densities, which might have led to slightly different evolutionary phases and subsequently slightly different chemical properties. Such a slight density difference might be achievable by enhancing a very small density fluctuation through gravitational instabilities even if the L1147 filament was formed at the given time.

While the chemical properties in core C were reproduced in a lower density using the same visual extinction as cores A and B, we could not find the suitable region, assuming lower visual extinction. This would mean that an improvement of the model is required to better explain the chemical properties in core C. In any case it was found that a combination of observational studies and chemical reaction network simulations can provide a powerful means of investigating the chemical evolution of molecular clouds. We would like to stress that the simulation code as well as the reaction databases are available online, and any researchers are able to utilize this powerful tool.

Finally, although there should be a density profile in the core and the density will increase in the actual cloud evolution, our model assumed constant hydrogen density. Thus to develop the chemical reaction network simulation code, a more realistic physical evolution of a cloud must be incorporated in order to better understand the chemical evolution of a molecular cloud.

In the present study, we had to assume the excitation temperatures because we conducted single line observations.
Such an observational constraint could introduce some uncertainties to our results. Future multi-line observations would be needed to discuss the chemical differences in the early phase of cloud evolution in more detail.

5. CONCLUSIONS

The main results of this paper can be summarized as follows.

1. It was confirmed that the L1147 cloud is a CCPR by combining the new CCS mapping result and past NH3 observational results by Hirota et al. (2009).

2. Two CCS cores and a HC3N core were found in the L1147. Three peaks are away from the Spitzer source (VeLLO source) and are located interleaved to each other. Such different spatial distributions between CCS and HC3N are not known, except for only one dark cloud (1172D).

3. The column densities of CCS are $3–7 \times 10^{12}$ cm$^{-2}$ and those of HC3N are $2–6 \times 10^{12}$ cm$^{-2}$, respectively, which are much lower than those reported in other CCPRs. In the three cores detected in L1147, the column densities are different within a factor of a few. We found that the CCS/HC3N ratios in the three cores are different despite forming in the same filament.

4. We used the chemical reaction network model to see whether we can reproduce the CCS/HC3N ratios derived in our observations assuming different densities, from $10^4$ cm$^{-3}$ to $10^6$ cm$^{-3}$. We found that our results can be reproduced for $6 \times 10^4$–$6 \times 10^5$ yr; such a time range is typical for dark cloud cores and would be appropriate for CCPRs. It would be likely that the difference of the CCS/HC3N ratios in L1147 is explained by a slightly different H$_2$ density. L1147 would be in a physically and chemically early phase of cloud evolution, and our result suggests the possibility that chemical features in the early phase may change among cores with different physical conditions. On the other hand, core C is not reproduced in our simulation under realistic visual extinction. Further development of the chemical model would be required.

We are grateful to all the staff members of the Nobeyama Radio Observatory, the National Astronomical Observatory of Japan (NAOJ), for their support throughout our observations. We thank Dr. J. M. Kirk for answering our questions regarding the SCUBA map, Dr. V. Wakelam and Dr. Y. Aikawa for providing us with the KIDA data and the chemical reaction simulation code, and to the anonymous referee who provided us with many valuable comments. Part of the data analysis was made at the Astronomy Data Center, NAOJ. We utilized the Japanese Virtual Observatory (http://jvo.nao.ac.jp/) in finding the SCUBA 850 $\mu$m data.

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