13C ISOTOPIC FRACTIONATION OF HC3N IN STAR-FORMING REGIONS: LOW-MASS STAR-FORMING REGION L1527 AND HIGH-MASS STAR-FORMING REGION G28.28-0.36

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ABSTRACT

We observed the J = 9–8 and 10–9 rotational lines of three 13C isotopologues of HC3N in L1527 and G28.28-0.36, with the 45 m radio telescope of the Nobeyama Radio Observatory, in order to constrain the main formation mechanisms of HC3N in each source. The abundance ratios of the three 13C isotopologues of HC3N are found to be 0.9 (±0.2) : 1.00 : 1.29 (±0.19) (1σ), and 1.0 (±0.2) : 1.00 : 1.47 (±0.17) (1σ), for [H13CCCN : HC13CCN : HCC13CN] in L1527 and G28.28-0.36, respectively. We recognize, from a similar 13C isotopic fractionation pattern, that the abundances of H13CCCN and HC13CCN are comparable, and HCC13CN is more abundant than the others. Based on the results, we discuss the main formation pathway of HC3N. The 13C isotopic fractionation pattern derived from our observations can be explained by the neutral-neutral reaction between C2H2 and CN in both the low-mass (L1527) and high-mass (G28.28-0.36) star-forming regions.

Key words: astrochemistry – ISM: individual objects (L1527, G28.28-0.36) – ISM: molecules – stars: formation

1. INTRODUCTION

Almost 200 molecules have been detected in the interstellar medium (ISM) or circumstellar shells, so far. In dark clouds, unsaturated carbon-chain molecules such as CCS are abundant, whereas they decrease in star-forming cores (Suzuki et al. 1992). These carbon-chain molecules are formed from C or C+ in the gas phase, before carbon atoms are converted into CO. On the other hand, saturated complex organic molecules, such as CH3OH and CH3CN, increase in star-forming regions; these regions are called hot cores for high-mass star-forming regions, and hot corinos for low-mass star-forming regions. In hot cores and hot corinos, the combination between grain-surface reactions and gas-phase reactions produces various saturated complex organic molecules (e.g., Garrod & Herbst 2006).

Recently, in contrast to the above scenarios, several star-forming cores associated with carbon-chain molecules have been discovered. Sakai et al. (2008) showed that various carbon-chain molecules are abundant toward the low-mass star-forming region L1527. Several chemical model calculations showed that CH2 plays an essential role in efficient formation of carbon-chain molecules in the warm regions (≥25 K) (e.g., Aikawa et al. 2008; Hassel et al. 2008). Aikawa et al. (2008) indicated that carbon-chain molecules are formed by a combination of gas-phase reactions and grain-surface reactions, following the sublimation of CH4. These low-mass star-forming regions were named warm carbon chain chemistry (WCCC) sources.

Cyanopolyynes (HC2n+1N) are one of the representative carbon-chain-molecule series. Hassel et al. (2008) demonstrated that regeneration of carbon-chain molecules results from gas-phase chemistry, and showed the primary formation pathway of HC3N as follows:

\[ \text{CN} + \text{C}_2\text{H}_2 \to \text{HC}_3\text{N} + \text{H}. \]  

Chapman et al. (2009) presented their time-dependent gas-phase chemical model, and showed that cyanopolyynes (HC2n+1N; n = 1–4) can be formed under hot core conditions. They considered that C2H2 is released from the grain mantle inside hot cores, and the neutral-neutral reaction between C2H2 and CN (Reaction 1) proceeds relatively easily for the hot core temperature (100–300 K). Their chemical model calculation was supported by detections of HC3N toward 35 hot cores associated with 6.7 GHz methanol masers (Green et al. 2014). Therefore, the predicted main formation pathway of HC3N is Reaction (1) in both the low-mass star-forming region L1527 and the high-mass star-forming regions.

Deriving 13C isotopic fractionation of carbon-chain molecules by observations is one of the promising methods to constrain their main formation mechanism. For example, the dominant formation mechanisms of HC3N has been investigated, based on its 13C isotopic fractionation (Takano et al. 1998) toward the cyanopolyyne peak in Taurus Molecular Cloud-1 (TMC-1 CP; d = 140 pc). The derived abundance ratios of three 13C isotopologues of HC3N are [H13CCCN : HC13CCN : HCC13CN] = 1.0 : 1.0 : 1.4 (±0.2) (1σ), and it is suggested that its main formation pathway is the neutral-neutral reaction between C2H2 and CN (Takano et al. 1998). Thus investigation of formation mechanism of HC3N using its 13C isotopic fractionation has proved successful.

In the present paper, we observe the three 13C isotopologues of HC3N, the shortest cyanopolyyne, toward L1527 (d = 140 pc) and G28.28-0.36 (d = 3.0 kpc) (Green et al. 2014) with the 45 m radio telescope of the Nobeyama Radio Observatory (NRO), in order to compare 13C isotopic fractionation of HC3N and its main formation mechanisms in the two star-forming regions. G28.28-0.36 is one of the hot cores that Green et al. (2014) detected HC3N, and associates with an ultra compact HII region. Purcell et al. (2006) detected CH3CN, a hot core tracer, and H13CO+ toward the hot core.

2. OBSERVATIONS

We carried out observations of the three 13C isotopologues of HC3N (H13CCCN, HC13CCN, and HCC13CN) simultaneously with the NRO 45 m radio telescope in 2015 December, and 2016 February, March, and April (2015–2016 season). We
also observed the normal species of the \( J = 9 \rightarrow 8 \) rotational lines simultaneously, when we observed the \( J = 9 \rightarrow 8 \) lines of the three \(^{13}\mathrm{C}\) isotopologues. We used the TZ and the T70 receivers for the observations of the \( J = 9 \rightarrow 8 \) transition lines, and the TZ receiver for the observations of the \( J = 10 \rightarrow 9 \) transition lines. We used the TZ receiver for the observations of the \( J = 9 \rightarrow 8 \) lines, after we could not use the T70 receiver due to equipment troubles. The rest frequencies of the observed lines are in Table 2. Both receivers allow us to simultaneously obtain dual-polarization data. The beam sizes (HPBW) and main beam efficiencies (\( \eta_B \)) are 18° and 54% for the TZ receiver, and 20° and 56% for the T70 receiver at 86 GHz, respectively. The system temperatures were between 120 and 250 K, depending on the weather conditions and elevation. We employed the position-switching mode.

The observed position and off-source position for L1527 were \((\alpha_{2000}, \delta_{2000}) = (04^h39^m53^s18^f, 26^\circ03'11''0^f)\) and \((04^h42^m35^s9^f, 25^\circ53'23''3^f)\), respectively. The telescope pointing was checked, using the H40 receiver every 1 hr, by observing the SiO maser line (\( J = 1 \rightarrow 0 \)) from NML Tau; the pointing error was less than 3\(^{\prime}\). The observed position for G28.28-0.36 was \((\alpha_{2000}, \delta_{2000}) = (18^h44^m13^s3^f, -04^\circ18'03''3^f)\), and the off-source position was set to be +15" away in the declination. We checked the pointing accuracy by observing the SiO maser lines (\( J = 1 \rightarrow 0 \)) from OH39.7+1.5 every 1–1.5 hr, depending on wind conditions. The pointing error was within 3\(^{\prime}\). We used the SAM45FX-type digital correlator at frequency settings with bandwidths and resolutions of 125 MHz and 30.52 kHz for L1527, and 250 MHz and 61.04 kHz for G28.28-0.36. We applied two-channel binding, and velocity resolutions of final spectra are 0.25 and 0.5 km s\(^{-1}\) for L1527 and G28.28-0.36, respectively.

3. RESULTS AND ANALYSIS

3.1. Results

The spectra of the three \(^{13}\mathrm{C}\) isotopologues of HC\(_3\)N were taken with signal-to-noise ratios of 6.3–10.6 in L1527, except for the \( J = 10 \rightarrow 9 \) line of H\(^{13}\)CCCN, as shown in Figure 1. We also show the spectra of the \( J = 9 \rightarrow 8 \) rotational line of the normal species, observed with its \(^{13}\mathrm{C}\) isotopologues, simultaneously. The values of \( V_{\text{LSR}} \) are in good agreement with the \( V_{\text{LSR}} \) value reported for this source (5.9 km s\(^{-1}\)). We derived their integrated intensities with the same velocity range, and the results are summarized in Table 1. The ratios of the integrated intensities among the three \(^{13}\mathrm{C}\) isotopologues of the \( J = 10 \rightarrow 9 \) lines are consistent with those of the \( J = 9 \rightarrow 8 \) lines. However, we could not detect H\(^{13}\)CCCN using the \( J = 10 \rightarrow 9 \) line with a signal-to-noise ratio above 3, and we do not use the \( J = 10 \rightarrow 9 \) lines in the following analyses. We evaluated the error of the integrated intensities using the following formula:

\[
\Delta T_A^* (K) \times \sqrt{n (ch) \times v (km s^{-1})}. \tag{2}
\]

In Equation (2), \( \Delta T_A^* \) is the rms noise in the emission-free regions, \( n \) is the number of channels, and \( v \) is the velocity resolution per channel. The rms noises are summarized in Table 2. We used 4 ch and 0.25 km s\(^{-1}\) for \( n \) and \( v \), respectively, in L1527.

The three \(^{13}\mathrm{C}\) isotopologues of HC\(_3\)N were detected with signal-to-noise ratios of 5.1–10.7 in G28.28-0.36, as shown in Figure 2. The values of \( V_{\text{LSR}} \) agree with one another and the systematic velocity reported for the source (48.9 km s\(^{-1}\)) Purcell et al. 2006). We derived the integrated intensities of the three \(^{13}\mathrm{C}\) isotopologues of HC\(_3\)N in the same way as L1527, and their errors were calculated using Equation (2) with 7 ch and 0.5 km s\(^{-1}\) for \( n \) and \( v \), respectively. We summarize the results in Table 1.

3.2. Analysis

We fitted the spectra with a Gaussian profile and obtained the spectral line parameters, as summarized in Table 2. We calculated the column densities of the normal species and the three \(^{13}\mathrm{C}\) isotopologues of HC\(_3\)N using the local thermodynamic equilibrium (LTE) analysis, as shown in the following formulæ (Takano et al. 1998):

\[
\tau = -\ln \left( 1 - \frac{T_A^*}{f_{\text{bg}} (J(T_{\text{ex}}) - J(T_{\text{bg}}))} \right), \tag{3}
\]

where

\[
J(T) = \frac{h\nu}{k} \left\{ \exp \left( \frac{h\nu}{kT} \right) - 1 \right\}^{-1}, \tag{4}
\]

and

\[
N = \frac{3\hbar\Delta \nu}{8\pi^3} \sqrt{\frac{\pi}{4 \ln 2}} \frac{Q_1}{\mu^2 J_{\text{lower}} + 1} \times \exp \left( \frac{E_{\text{lower}}}{kT_{\text{ex}}} \right) \left[ 1 - \exp \left( -\frac{h\nu}{kT_{\text{ex}}} \right) \right]^{-1}. \tag{5}
\]

In Equation (3), \( T_A^* \) denotes the antenna temperature, \( f_{\text{bg}} \) the beam filling factor, \( \eta_B \) the main beam efficiency, and \( \tau \) the optical depth. We used 1 and 0.54 for \( f \) and \( \eta_B \) (Section 2), respectively. \( T_{\text{ex}} \) is the excitation temperature, and \( T_{\text{bg}} \) is the cosmic microwave background temperature (\( \approx 2.7 K \)). \( J(T) \) in Equation (4) is the Planck function. In Equation (5), \( N \) is the column density, \( \Delta \nu \) is the line width (FWHM), \( Q \) is the partition function, \( \mu \) is the permanent electric dipole moment of HC\(_3\)N (3.73172 \times 10^{-15} \text{ esu cm} \) as found in Deleón & Muenter (1985), and \( E_{\text{lower}} \) is the energy of the lower rotational energy level.

Sakai et al. (2009) derived the excitation temperatures and column densities of HC\(_3\)N, using LTE analysis. The determined excitation temperatures and column densities are 9.7 ± 0.2 K and (2.7 ± 0.2) \times 10^{13} \text{ cm}^{-2}, with the \( J = 5 \rightarrow 4 \) and \( J = 10 \rightarrow 9 \) data included, and 16.9 ± 0.5 K and (1.19 ± 0.03) \times 10^{13} \text{ cm}^{-2} using only the \( J = 10 \rightarrow 9 \) and \( J = 17 \rightarrow 16 \) lines. We then derived \( \tau \), assuming excitation temperatures of 9.7 K and 16.9 K, respectively, using Equation (3). The calculated column densities are summarized in Table 3. The column densities are determined to be (2.61 ± 0.03) \times 10^{13}, (2.8 ± 0.6) \times 10^{13}, (3.0 ± 0.5) \times 10^{11}, and (3.9 ± 0.6) \times 10^{11} \text{ cm}^{-2} using the excitation temperature of 9.7 K, and (7.87 ± 0.09) \times 10^{12}, (1.1 ± 0.2) \times 10^{11}, (1.2 ± 0.2) \times 10^{11}, and (1.5 ± 0.2) \times 10^{11} \text{ cm}^{-2} using the excitation temperature of 16.9K for HC\(_3\)N, H\(^{13}\)CCCN, HC\(^{13}\)CCN, and HCC\(^{13}\)CN, respectively. The two assumed excitation temperatures seem to be the lower and upper limits; the derived column densities are also the upper and lower limits. A change in the assumed excitation temperature by a factor of 2 does not affect the derived column densities of the three \(^{13}\mathrm{C}\) isotopologues within 3-sigma errors. The derived column density of the normal species, using the excitation temperature of 9.7 K, agrees with that derived by Sakai et al.
Using the column densities of the normal species of \((2.7 \pm 0.2) \times 10^{13} \text{ cm}^{-2}\) and \((1.19 \pm 0.03) \times 10^{13} \text{ cm}^{-2}\) for the excitation temperatures of 9.7 K and 16.9 K, respectively (Sakai et al. 2009), we also calculated the \(^{12}\text{C}/^{13}\text{C}\) ratios of \(\text{HC}_3\text{N}\), as summarized in Table 3. When the excitation temperature is 9.7 K, the \(^{12}\text{C}/^{13}\text{C}\) ratios are determined to be 97 ± 21, 90 ± 15, and 70 ± 10 (1σ) for \(^{13}\text{CCCN}\),

\(^{13}\text{CCCN}\), and \(^{13}\text{CCCN}\) by Sakai et al. (2009). The abundance ratios of the three \(^{13}\text{C}\) isotopologues are derived to be \(0.9 \pm 0.2 : 1.00 : 1.29 (1\sigma)\) for \([\text{H}^{13}\text{CCCN} : \text{HC}^{13}\text{CCN} : \text{HCC}^{13}\text{CN}]\).

### Table 3

|               | \(^{13}\text{CCCN}\) | \(^{13}\text{CCCN}\) | \(^{13}\text{CCCN}\) |
|---------------|----------------------|----------------------|----------------------|
| L1527         | 0.021 (3)            | 0.028 (3)            | 0.035 (3)            |
| \(J = 9\)     | 0.016 (4)            | 0.023 (3)            | 0.032 (3)            |
| \(J = 10\)    | 0.055 (9)            | 0.064 (7)            | 0.090 (7)            |
| G28.28-0.36   | 0.049 (5)            | 0.047 (4)            | 0.059 (4)            |

#### Note

The numbers in parenthesis represent the error values evaluated by Equation (2).

Figure 1. Spectra of the three \(^{13}\text{C}\) isotopologues of \(\text{HC}_3\text{N}\) of the \(J = 9\) \(-\) 8 and \(J = 10\) \(-\) 9 rotational transitions and the normal species of the \(J = 9\) \(-\) 8 rotational transition toward L1527. The gray vertical lines show \(V_{\text{LSR}} = 5.9 \text{ km s}^{-1}\). The red vertical lines show the range used for the integrated intensities.
The numbers in parentheses represent one standard deviation in the Gaussian fit, except for frequency.

4. DISCUSSION

4.1. $^{13}$C Isotopic Fractionation and Formation Mechanisms of HC$_3$N

The abundance ratios of the three $^{13}$C isotopologues are derived to be 0.9 ($\pm 0.2$) : 1.00 : 1.29 ($\pm 0.19$) (1$\sigma$) and 1.0 ($\pm 0.2$) : 1.00 : 1.47 ($\pm 0.17$) (1$\sigma$) for [H$^{13}$CCCN : HC$^{13}$CCN : HCC$^{13}$CN] in L1527 and G28.28-0.36, respectively. One possible mechanism producing $^{13}$C isotopic fractionation is isotope exchange reactions. As Takano et al. (1998) discussed, the isotope exchange reactions can be negligible in the case of HC$_3$N. Hence, the differences in abundances among the three $^{13}$C isotopologues should occur during their formation processes.

In both L1527 and G28.28-0.36, the abundance ratios of the three $^{13}$C isotopologues of HC$_3$N show the following two characteristics;

1. The abundances of H$^{13}$CCCN and HC$^{13}$CCN are comparable with each other, and
2. The abundance of HCC$^{13}$CN is higher than the previous two species.

These characteristics imply that the main formation pathway of HC$_3$N contains two equivalent carbon atoms, and the other carbon atom originates from different parent species. We investigate possible reactions leading to HC$_3$N, using the UMIST Database for Astrochemistry 2012 (McElroy et al. 2013). The four formation pathways are possible as follows.

Pathway 1: the neutral-neutral reaction between C$_2$H$_2$ and CN (Reaction (1)).

Pathway 2: the neutral-neutral reaction between C$_2$H and HCN.

Pathway 3: the ion-molecule reactions between C$_2$H$_3^+$ \((n = 3-5)\) and nitrogen atoms, followed by electron recombination reactions.

Pathway 4: the ion-molecule reactions between C$_2$H$_4^+$ and HCN, followed by electron recombination reactions.

If Pathway 1 is the main formation pathway of HC$_3$N, the abundance ratios of the three $^{13}$C isotopologues of HC$_3$N should be $1 : 1 : x$, where $x$ is an arbitrary value, for [H$^{13}$CCCN : HC$^{13}$CCN : HCC$^{13}$CN], because two carbon atoms in C$_2$H$_2$ are equivalent and the triple bond between C and N in a CN molecule is preserved during the reaction process (Fukuzawa & Osamura 1997). Our observational results show 0.9 ($\pm 0.2$) : 1.00 : 1.29 ($\pm 0.19$) (1$\sigma$) and 1.0 ($\pm 0.2$) : 1.00 : 1.47 ($\pm 0.17$) (1$\sigma$) for [H$^{13}$CCCN : HC$^{13}$CCN : HCC$^{13}$CN] in L1527 and G28.28-0.36, respectively. Therefore, our observational results are consistent with the ratios expected for Pathway 1.

In L1527, Hassel et al. (2008) showed the formation pathways leading to C$_2$H$_2$ from CH$_4$ as follows;

\[ C^+ + CH_4 \rightarrow C_2H_2^+ + H, \tag{6} \]

\[ C^+ + CH_4 \rightarrow C_2H_2^+ + H_2, \tag{7} \]
followed by
\[ \text{C}_2\text{H}_2 \xrightarrow{+} \text{H}_2 \rightarrow \text{C}_2\text{H}_2 \xrightarrow{+} \text{H}, \]  
\[ \text{C}_2\text{H}_2 \xrightarrow{+} \text{e} \rightarrow \text{C}_2\text{H}_2 + \text{H}, \]  
\[ \text{C}_2\text{H}_2 \xrightarrow{+} \text{e} \rightarrow \text{C}_2\text{H}_2 + 2\text{H}. \] 

C\text{H}_2 then can be efficiently formed from CH\text{H}_4, and the neutral-neutral reaction between C\text{H}_2 \text{H}_2 and CN (Reaction (1)) proceeds under the hot core condition, and C\text{H}_2 \text{H}_2 is released from the grain mantle inside hot cores. Our conclusion about G28.28-0.36 is consistent with their chemical model calculation. The validity of their model calculation seems to be supported by detections of HC\text{H}_5N (Green et al. 2014) and HC\text{H}_7N (K. Taniguchi et al. 2016, in preparation).

We next consider the possibility that Pathway 2 is the dominant formation reaction leading to HC\text{H}_3N. In this reaction, three carbon atoms are not equivalent, and the expected abundance ratios are \( x : y : z \) for [H\text{H}\text{H}_5CN : H\text{H}\text{H}_3\text{CCCN} : H\text{H}\text{H}_3\text{C}CN], where \( x, y, \) and \( z \) are arbitrary values. In fact, Sakai
and we conclude that the reaction between C2H and HNC is not 1.19 2.7 (et al. 2010) b. The ratios were derived using the column density of the normal species of Species T ex = 9.7 K T ex = 16.9 K H13CCCN 2.8 ± 0.6 97 ± 21 1.1 ± 0.2 108 ± 23 HC3CCN 3.0 ± 0.5 90 ± 15 1.2 ± 0.2 102 ± 18 HCC13CN 3.9 ± 0.6 70 ± 10 1.5 ± 0.2 79 ± 12

Note. The error corresponds to one standard deviation.

a. The ratios were derived using the column density of the normal species of 2.7 ± 0.2 × 1014 cm−2, which was derived by the LTE analysis using T ex = 9.7 K (Sakai et al. 2009).

b. The ratios were derived using the column density of the normal species of 1.19 ± 0.03 × 1013 cm−2, which was derived by the LTE analysis, using T ex = 16.9 K (Sakai et al. 2009).

Table 3

| Species      | Column Density (×1014 cm−2) | 12C/13C Ratio | Column Density (×1014 cm−2) | 12C/13C Ratio |
|--------------|----------------------------|---------------|----------------------------|---------------|
| H13CCCN      | 2.8 ± 0.6                  | 97 ± 21       | 1.1 ± 0.2                  | 108 ± 23      |
| HC3CCN       | 3.0 ± 0.5                  | 90 ± 15       | 1.2 ± 0.2                  | 102 ± 18      |
| HCC13CN      | 3.9 ± 0.6                  | 70 ± 10       | 1.5 ± 0.2                  | 79 ± 12       |

Table 4

| Species      | Column Density (×1014 cm−2) | 12C/13C Ratio | Column Density (×1018 cm−2) | 12C/13C Ratio |
|--------------|----------------------------|---------------|------------------------------|---------------|
| HC3N         | (4.97 ± 0.18) × 10          | ...           | ...                          | ...           |
| H13CCCN      | 1.0 ± 0.2                  | 50 ± 11       | 7.1 ± 1.0                   |               |
| HC3CCN       | 1.04 ± 0.17                | 48 ± 8        | 6.7 ± 0.8                   |               |
| HCC13CN      | 1.53 ± 0.17                | 32 ± 4        | 8.4 ± 0.9                   |               |

Notes. The error corresponds to one standard deviation. The assumed excitation temperature is 100 K.

et al. (2010) showed that the [C13CH]/[13CCH] abundance ratio is 1.6 ± 0.1 (3σ). Fukuzawa & Osamura (1997) also demonstrated their quantum chemical calculations, and their results show that a carbon atom in HNC and a carbon atom with an unpaired electron in CCH are connected. From the above two results, the abundance ratios of HC3N should be [H13CCCN : HC3CCN : HCC13CN] = 1.6 : 1.0 : x, where x is an arbitrary value, if Pathway 2 is the main formation pathway of HC3N. Pathway 2 cannot explain our observational results, and we conclude that the reaction between C2H and HNC is not the primary formation pathway of HC3N.

Pathways 3 and 4 include the ion-molecule reactions. There is a possibility that there are no significant differences in abundances among all of the 13C isotopologues, when the main formation mechanism is the ion-molecule reactions (Taniguchi et al. 2016). We also consider that scrambling may occur during the processes of these ion-molecule reactions. The clear differences in abundances among the three 13C isotopologues of HC3N should not be apparent, if scrambling occurs. Hence, these ion-molecule reactions are not the main formation mechanisms of HC3N in L1527 and G28.28-0.36.

In summary, the abundance ratios derived by our observations agree with the ratios of only Pathway 1. Thus, we propose that the neutral-neutral reaction between C2H2 and CN (Reaction (1)) dominates other formation pathways in both L1527 and G28.28-0.36. This proposal also agrees with the predicted primary formation pathway of HC3N by chemical model calculations (Hassel et al. 2008; Chapman et al. 2009), et al. 2016) that the [C13CH]/[13CCH] abundance ratio is 1.6 ± 0.1 (3σ). Fukuzawa & Osamura (1997) also demonstrated their quantum chemical calculations, and their results show that a carbon atom in HNC and a carbon atom with an unpaired electron in CCH are connected. From the above two results, the abundance ratios of HC3N should be [H13CCCN : HC3CCN : HCC13CN] = 1.6 : 1.0 : x, where x is an arbitrary value, if Pathway 2 is the main formation pathway of HC3N. Pathway 2 cannot explain our observational results, and we conclude that the reaction between C2H and HNC is not the primary formation pathway of HC3N.

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4.2. 12C/13C Ratios in L1527 and G28.28-0.36

The 12C/13C ratios of HC3N in L1527 are summarized in Table 3. When we assume that the excitation temperature is 9.7 K, the 12C/13C ratios are consistent with the elemental ratio of 60–70 in the local ISM (Langer & Penzias 1993; Savage et al. 2002; Milam et al. 2005), within 1-sigma errors. The derived 12C/13C ratios of H13CCCN and HC13CCN are slightly higher than the elemental ratio in the local ISM, using the excitation temperature of 16.9 K. However, the ratios of these two 13C isotopologues are consistent with the elemental ratio in the local ISM, within 2-sigma errors. The 12C/13C ratio of HCC13CN agrees with the elemental ratio of the local ISM, within 1-sigma error. Therefore, the 13C species of HC3N are not significantly diluted in L1527, as well as TMC-1 CP (Takano et al. 1998).

In Table 4, the 12C/13C ratios of the three 13C isotopologues in G28.28-0.36 are summarized. These 12C/13C values are lower than the elemental ratio of 60–70 in the local ISM, because G28.28-0.36 is located nearer the Galactic center than the Earth and L1527. The 12C/13C ratio shows a gradient with Galactic distance (D GC) (Savage et al. 2002; Milam et al. 2005). We estimated the D GC of G28.28-0.36 to be 5.4 kpc, using trigonometry. The 12C/13C ratios at D GC = 5.4 kpc are derived to be 39–65, using the results obtained by observations of CN, CO, and H2CO (12C/13C) = 6.21(1.00)(D GC + 18.71(7.57)) (Milam et al. 2005). The 12C/13C ratios of HC3N obtained by our observations are consistent with the estimated values at D GC = 5.4 kpc. These suggest that 13C isotopologues of HC3N are not heavily diluted, which is in good agreement with the local ISM.

The column densities derived by the J = 10–9 lines are lower than those derived by the J = 9–8 lines by a factor of 1.3–1.9. The explanation for the differences in the column densities between the J = 10–9 lines and J = 9–8 lines is that the spatial distribution of HC3N displays a ring-like structure with outer strong emission peaks, which is supported by our high spatial resolution map with the Karl G. Jansky Very Large Array (K. Taniguchi et al. 2016, in prepration).

4.3. Comparison of 13C Isotopic Fractionation in Various Sources

We summarize 13C isotopic fractionation of HC3N in the four sources, using HC13CCN as a reference, in Table 5. We also summarize the source types and their typical temperatures and densities in Table 5. We categorize these four sources into the star-forming cores (L1527 and G28.28-0.36) and the starless cores (TMC-1 CP and Serpens South 1A). We can also categorize these four sources into the low-mass star-forming regions (TMC-1 CP and L1527) and the high-mass star-forming regions (Serpens South 1A and G28.28-0.36). We then compare various environment in star-forming regions. Although there are wide ranges of temperatures (∼10 K–200 K) and densities (104 cm−3–106 cm−3), the 13C isotopic fractionation patterns in all four of the sources show the same tendency. The abundances of H13CCCN and HC13CCN are comparable with each other, and HCC13CN is more abundant than the others. In addition, the [HCC13CN]/[HC13CCN] ratios are in good agreement (∼1.3) among the four sources, within 1-sigma errors. These results may imply that the neutral-neutral reaction between C2H2 and CN (Reaction (1)) is the universal main formation mechanism of HC3N.
5. CONCLUSIONS

We carried out observations of the \( J = 9 \rightarrow 8 \) and \( 10 \rightarrow 9 \) rotational transitions of the three \(^{13}\)C isotopologues of HC\(_3\)N, toward the low-mass star-forming region L1527 and the high-mass star-forming region G28.28-0.36, with the NRO 45 m telescope. The abundance ratios are found to be 0.9 (±0.2) : 1.00 : 1.29 (±0.19) (1σ) and 1.0 (±0.2) : 1.47 (±0.17) (1σ) for \([^{13}\text{C}]\text{CCCN} : \text{HC}^{13}\text{CCN} : \text{HCC}^{13}\text{CN}\) in L1527 and G28.28-0.36, respectively. Our observational results suggest that the neutral-neutral reaction between C\(_2\)H\(_2\) and CN seems to overwhelm the other formation pathways in both L1527 and G28.28-0.36. In addition, the \(^{13}\)C isotopic fractionation pattern seen in the two star-forming regions is the same one observed in starless cores. The primary formation pathway of HC\(_3\)N may be common, from low-mass prestellar cores to high-mass star-forming cores.

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| Source        | \(^{13}\text{C}\text{CCCN}\) | \(^{13}\text{C}\text{CCN}\) | \(^{13}\text{C}\text{CN}\) | Source Type | Temperature (K) | Density (cm\(^{-3}\)) |
|---------------|-----------------|-----------------|-----------------|--------------|-----------------|---------------------|
| L1527         | 0.9 (±0.2)      | 1.00            | 1.29 (±0.19)    | WCCC        | 20–30           | \(\sim 10^5\)       |
| G28.28-0.36   | 1.0 (±0.2)      | 1.00            | 1.47 (±0.17)    | hot core    | 100–200         | \(\sim 10^6\)       |
| TMC-1 CP\(^a\)| 1.0             | 1.0             | 1.4 (±0.2)      | dark cloud  | \(\sim 10\)     | \(\sim 10^4\)       |
| Serpens South 1Ab\(^b\)| 0.91 (±0.09) | 1.00 | 1.32 (±0.09) | IRDC | \(\sim 15\) | \(\sim 10^5\) |

Notes. The error corresponds to one standard deviation.
\(^a\) The ratios were derived using the column densities (Takano et al. 1998).
\(^b\) The ratios were derived using the column densities (Li et al. 2016).
\(^c\) Takakuwa et al. (2001).