Interferometric Observations of Cyanopolyynes toward the G28.28–0.36
High-mass Star-forming Region

Kotomi Taniguchi1,5,6,7,†, Yusuke Miyamoto1,†, Masao Saito1,2,†, Patricio Sanhueza1,†, Tomomi Shimoikura3,†, Kazuhiro Dobashi3,†, Fumitaka Nakamura1,2,†, and Hiroyuki Ozeki4,†

1 Department of Astronomical Science, School of Physical Science, SOKENDAI (The Graduate University for Advanced Studies), Osawa, Mitaka, Tokyo 181-8588, Japan
2 National Astronomical Observatory of Japan, Osawa, Mitaka, Tokyo 181-8588, Japan
3 Department of Astronomy and Earth Sciences, Tokyo Gakugei University, Nukuikitamachi, Koganei, Tokyo 184-8501, Japan
4 Department of Environmental Science, Faculty of Science, Toho University, Miyama, Funabashi, Chiba 274-8510, Japan
5 Current Virginia Initiative on Cosmic Origins Fellow.
6 Research Fellow of Japan Society for the Promotion of Science.
7 Currently at Department of Astronomy, University of Virginia, Charlottesville, VA, 22904, USA; k8pm@virginia.edu.

Abstract
We have carried out interferometric observations of cyanopolyynes, HC3N, HC5N, and HC7N, in the 36 GHz band toward the G28.28–0.36 high-mass star-forming region using the Ka-band receiver of the Karl G. Jansky Very Large Array. The spatial distributions of HC3N and HC5N are obtained. HC3N emission is coincident with a 450 μm dust continuum emission, and this clump with a diameter of ~0.2 pc is located at a position ~0.15 pc east of the 6.7 GHz methanol maser. HC7N is tentatively detected toward the clump. The HC3N:HC5N:HC7N column density ratios are estimated to be 1.0:~0.3:~0.2 at an HC3N peak position. We discuss possible natures of the 450 μm continuum clump associated with the cyanopolyynes. This clump seems to contain deeply embedded low- or intermediate-mass protostellar cores, and the most likely formation mechanism of the cyanopolyynes is the mechanism of warm carbon-chain chemistry. In addition, HC3N and compact HC5N emission is detected at the edge of the 4.5 μm emission, which possibly implies that such emission has a shock origin.

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

1. Introduction
Cyanopolyynes (HC2+n−1N, n = 1, 2, 3, ...) are a representative carbon-chain species. In low-mass star-forming regions, carbon-chain molecules are known to be early-type species; they are abundant in young starless cores and deficient in star-forming cores (e.g., Suzuki et al. 1992; Hirota et al. 2009). In contrast to the general picture, cyanoacetylene (HC3N), the shortest member of the cyanopolyynes, is detected from various regions such as infrared dark clouds (e.g., Sanhueza et al. 2012), molecular outflows (Bachiller & Pérez Gutiérrez 1997), protoplanetary disks (Öberg et al. 2015; Bergner et al. 2018), and comets (e.g., Mumma & Charnley 2011), and it is interesting to trace cyanopolyyne chemistry to better understand the evolution of molecules during the star/planet formation process. Cyanopolyynes attract astrobiological as well as astrochemical interest. Since they contain the nitrile bond (–C≡N), cyanopolyynes have been suggested as possible intermediates in the synthesis of simple amino acids (e.g., Fontani et al. 2017; Calcutt et al. 2018).

Saturated complex organic molecules (COMs), consisting of more than six atoms with rich hydrogen atoms, are abundant around protostars. Such chemistry is known as “hot core” in high-mass star-forming regions and “hot corino” in low-mass star-forming regions. In addition to hot corino, around a few low-mass protostars, carbon-chain molecules are formed from CH4 evaporated from dust grains, which is known as warm carbon-chain chemistry (WCCC; e.g., Sakai & Yamamoto 2013).

Progress in observational studies of carbon-chain molecules has been slower in high-mass star-forming regions than in low-mass star-forming regions. Regarding hot cores, HC3N has been detected in chemically rich sources, such as Orion KL (Esplugues et al. 2013) and Sgr B2 (Belloche et al. 2013), while only a tentative detection of HC3N in Orion KL was reported (Feng et al. 2015). Chapman et al. (2009) performed a chemical network simulation and suggested that cyanopolyynes could be formed in a hot core from C2H2 evaporated from grain mantles. Motivated by the chemical network simulation, Green et al. (2014) carried out survey observations of HC3N toward 79 hot cores associated with the 6.7 GHz methanol masers and reported its detection in 35 sources. However, the association with the maser is questionable, because they used a large beam (0.95) and a line of low excitation energy (J = 12−11; E_u/k = 10.0 K), which can be excited even in dark clouds.

Taniguchi et al. (2017) carried out observations of long cyanopolyynes (HC2N and HC3N) toward four massive young stellar objects (MYSOs), where Green et al. (2014) had reported the detection of HC3N, using the Green Bank 100 m and the Nobeyama 45 m radio telescopes, and detected lines of high excitation energy (E_u/k ≈ 100 K) from HC3N. The detection of such lines means that HC3N exists at least in the warm gas, not in cold molecular clouds (T_kin ≈ 10 K). Taniguchi et al. (2018) found that the G28.28−0.36 high-mass star-forming region is a particular cyanopolyyne-rich source with fewer COMs than other sources. Hence, G28.28−0.36 is considered to be a good target region to study the cyanopolyyne chemistry around MYSOs. Using the Nobeyama 45 m radio telescope, Taniguchi et al. (2016) investigated the main formation mechanism of HC3N in G28.28−0.36 from its 13C isotopic fractionation. The reaction “C2H2 + CN” was proposed as the main formation pathway of HC3N, which is consistent with the chemical network simulation conducted by Chapman et al. (2009) and the WCCC model (Hassel et al. 2008).

In this paper, we carried out interferometric observations of cyanopolyynes (HC3N, HC5N, and HC7N) toward the
The Karl G. Jansky Very Large Array

Figure 1. Spitzer’s IRAC 3.6 μm image toward G28.28−0.36. The open circle and cross indicate the 6.7 GHz methanol maser (Cyganowski et al. 2009) and ultracompact H II (UCH II) region (Urquhart et al. 2009), respectively.

G28.28−0.36 high-mass star-forming region (d = 3 kpc) with the Karl G. Jansky Very Large Array (VLA). Figure 1 shows the Spitzer IRAC 3.6 μm image from the Spitzer Galactic Legacy Infrared Mid-Plane Survey Extraordinaire (Benjamin et al. 2003). In Figure 1, the open circle and cross indicate the 6.7 GHz methanol maser (Cyganowski et al. 2009) and the ultracompact H II (UCH II) region (Urquhart et al. 2009), respectively. The 6.7 GHz maser is considered to give us the exact position of MYSOs (Urquhart et al. 2013). A UCH II region seems to heat the environment. As shown in Figure 1, the ring structure around the UCH II region is suggestive of expanding motion and on-going massive star formation. We describe the observational details and data analyses in Section 2. The resultant images and spectra of cyanopolyyenes are presented in Section 3. We compare the spatial distributions of cyanopolyyenes with the infrared images and discuss possible formation mechanisms in Section 4.

2. Observations

The observations of G28.28−0.36 using the VLA Ka-band receiver were carried out in the C configuration with the 27 × 25 m antennas on 2016 March 20 (Proposal ID = 16A-084, PI: Kotomi Taniguchi). The field of view is ~60″4. Four spectral windows of the correlator were set at our target lines summarized in Table 1. All of these target lines were observed simultaneously. The channel separation of the correlator is 0.5 km s⁻¹. The angular resolutions and position angles for each line are summarized in Table 1.

The phase reference center was set at (α2000, δ2000) = (18h44m16s, −04°18′03″), the position of the 6.7 GHz methanol maser. The pointing source is J1832−1035 at (α2000, δ2000) = (18h32m20s, −10°35′11″). Calibrations of the absolute flux density and the bandpass were conducted by observing 3C 286 at (α2000, δ2000) = (13h31m08s, +30°30′ 32″9589′). The gain/phase calibration was conducted by observing J1851+0035 at (α2000, δ2000) = (18h51m46″7217, +00°35′32″414).

We conducted data reduction using the Common Astronomy Software Application (CASA; McMullin et al. 2007). We used the VLA calibration pipeline provided by the National Radio Astronomical Observatory to perform basic flagging and calibration.

The data cubes were imaged using the CLEAN task. Natural weighting was applied. The pixel size and image size are 0″2 and 1000 × 1000 pixels. After the CLEAN, we smoothed the cube using the “imsmooth” command, applying 1″ × 1″ and the position angle of 0° with the Gaussian kernel. The spatial resolution of 1″ of the resultant images corresponds to ~0.015 pc. The 1σ values are approximately 0.6, 0.7, 0.7, and 0.6 mK for HC3N, HC5N, HC7N, and CH3CN, respectively. We made the moment-zero images of HC3N and HC5N using the “immoments” task in CASA.

3. Results

Figure 2 shows the moment-zero images of (a) HC3N and (b) HC5N in G28.28−0.36. The velocity components in the range VLSR = 47.5−51.5 km s⁻¹ were integrated in these moment-zero images. The spatial distribution of HC3N is more extended than that of HC5N, because of their excitation energies of the observed lines (Table 1). The observed HC3N line has lower excitation energy (E_u/k = 4.4 K) than that of HC5N (E_u/k = 13.4 K), and colder envelopes could be traced by HC3N.

The signal-to-noise ratio of HC3N is low, which precludes determination of its spatial distribution. Figure 3 shows HC3N spectra, as well as HC5N and HC7N spectra, observed toward its four peak positions A−D indicated in Figure 4(b). In order to improve the signal-to-noise ratio, we applied the 1″ uv taper of CLEAN for HC3N data. The intensities of these spectra are estimated within 1σ regions, which corresponds to the spatial resolution of HC3N with the uv taper. HC3N is detected around the regions where CH3CN is detected as shown in Figure 2(b). CH3CN emission is undetected at the rms noise level of 0.6 mK.

4. Discussion

4.1. Comparisons of Cyanopolyyne Ratios

We derived the column densities of HC3N, HC5N, and HC7N at Position A (Figure 3) assuming the local thermodynamic equilibrium. We use the following formulae (Goldsmith & Langer 1999):

\[
\tau = -\ln \left[ 1 - \frac{T_b}{J(T_a) - J(T_b)} \right]
\]

5 http://sha.ipac.caltech.edu/applications/Spitzer/SHA/

6 https://science.nrao.edu/facilities/vla/data-processing/pipeline
temperature ($\sim 2.73$ K), respectively. $J(T)$ in Equation (2) is the effective temperature equivalent to that in the Rayleigh–Jeans law. In Equation (3), $N$, $\Delta v$, $Q$, $\mu$, and $E_{\text{lower}}$ denote the column density, line width (FWHM), partition function, permanent electric dipole moment, and energy of the lower rotational energy level, respectively. The brightness temperatures and line widths are obtained by the Gaussian fitting of spectra. Figure 7 in the Appendix shows the fitting results for each spectrum, and the obtained spectral line parameters and permanent electric dipole moments of each species are summarized in Table 4.

We derived the column densities assuming excitation temperatures of 15, 20, 30, and 50 K. The column densities of cyanopolyyynes and the HC$_3$N:HC$_5$N:HC$_7$N ratios at each excitation temperature are summarized in Table 2. The uncertainties in the excitation temperatures do not significantly affect the derived column densities of HC$_3$N and HC$_5$N, and these derived column densities agree with each other within their standard deviation errors. On the other hand, the uncertainties in the excitation temperatures introduce larger differences in the HC$_3$N column density.

The HC$_3$N:HC$_5$N:HC$_7$N ratios at Position A are derived to be 1.0:0.3:0.2. The ratios in L1527, which is one of the WCCC sources, are 1.0:0.3−0.6:0.1 (Sakai et al. 2008, 2009). The ratios at Position A seem to be similar to those in L1527.

### Table 1

Summary of Target Lines

| Species | Transition | Rest Frequency (GHz) | $E_{\text{v}}/k$ (K) | Angular Resolution | PA (deg) |
|---------|------------|----------------------|----------------------|--------------------|----------|
| HC$_3$N | $J = 4$–$3$ | 36.39232             | 4.4                  | 0.84$\times 0.63$  | −9.92    |
| HC$_3$N | $J = 14$–$13$ | 37.27694             | 13.4                 | 0.81$\times 0.63$  | −11.04   |
| HC$_3$N | $J = 33$–32 | 37.22349             | 30.4                 | 0.82$\times 0.63$  | −10.20   |
| CH$_3$CN | $I = 2$–1 | 36.795477            | 2.6                  | 0.83$\times 0.64$  | −11.22   |

**Note.** Rest frequencies are taken from the Cologne Database for Molecular Spectroscopy (CDMS; Müller et al. 2005) and the Jet Propulsion Laboratory catalog (JPL catalog; Pickett et al. 1998).

Figure 2. Moment-zero images of (a) HC$_3$N and (b) HC$_5$N obtained with the VLA, including the data above 2$\sigma$. The contour levels are 0.2, 0.4, 0.6, and 0.8 of their peak levels, where the peak intensities are 27.9 and 13.5 mK km s$^{-1}$ for (a) HC$_3$N and (b) HC$_5$N, respectively. The rms noise levels are 1.8 and 1.3 mK km s$^{-1}$ in the images of HC$_3$N and HC$_5$N, respectively. The open circle and magenta cross indicate the 6.7 GHz methanol maser. The spatial distribution of HC$_5$N is consistent with the cyanopolyyne-rich clump, Figure 4(b). The HC$_3$N seems to be distributed around the cyanopolyyne-rich clump (Figure 4(a)), not just at it. HC$_3$N emission is also located at the position west of the 6.7 GHz methanol maser, or the edge of the 450 $\mu$m continuum. A small region of the UCH II region in Section 4.3.

#### 4.2. Comparison of Spatial Distributions between Cyanopolyyynes and 450 $\mu$m Dust Continuum

Figure 4 shows 450 $\mu$m dust continuum images overlaid by the black contours of moment-zero images of (a) HC$_3$N and (b) HC$_5$N. The 450 $\mu$m data, which are available from the James Clerk Maxwell Telescope (JCMT) Science Archive, were obtained with the SCUBA installed on the JCMT. The main beam size of the SCUBA is 7$''$ at 450 $\mu$m, corresponding to $\sim 0.11$ pc.

Three strong peaks in the 450 $\mu$m continuum emission can be recognized: the UCH II position, the position northwest of the UCH II, and the position east of the 6.7 GHz methanol maser. The spatial distribution of HC$_3$N is consistent with the 450 $\mu$m continuum peak of the position east of the 6.7 GHz methanol maser (hereafter cyanopolyyne-rich clump, Figure 4(b)). The HC$_3$N seems to be distributed around the cyanopolyyne-rich clump (Figure 4(a)), not just at it. HC$_3$N emission is also located at the position west of the 6.7 GHz methanol maser, or the edge of the 450 $\mu$m continuum. A small region of HC$_3$N emission is seen at the same edge of the 450 $\mu$m continuum. We will briefly discuss a possible origin of this emission region in Section 4.3.

---

http://www.cadc-ccda.hia-iha.nrc-cnrc.gc.ca/en/jcmt/index.html
4.3. Possible Nature of the 450 μm Continuum Peak Position Associated with Cyanopolyynes

We examine four possible types of object for the cyanopolyyne-rich clump (Section 4.2): a hot core, a starless clump, low- or intermediate-mass protostellar core(s), and a photon-dominated region (PDR) driven by the associated UCH II region.

Figure 5 shows the Spitzer three-color (3.6 μm, 4.5 μm, 8.0 μm) image in panel (a), overlaid by yellow contours showing (b) the 450 μm continuum, (c) the HC$_3$N moment-zero image, and (d) the HC$_5$N moment-zero image. In panel (b), the green contours show the 8.3 mm continuum emission obtained simultaneously with cyanopolyynes by the VLA. The 8.3 mm continuum peak is compact and consistent with the UCH II region. In the cyanopolyyne-rich clump, no point source can be recognized from the Spitzer image, which suggests that no massive young protostar is currently present at the clump position. Therefore, the possibility of a hot core is unrealistic.

We derived the average column density of H$_2$, $N$(H$_2$), of the cyanopolyyne-rich clump from the 450 μm continuum data using the following formula (Shirley et al. 2005):

$$N(H_2) = 2.02 \times 10^{20} \text{ cm}^{-2} (e^{1.439(\lambda/\text{mm})^{-3}}(T/10 \text{ K}^{-1}) - 1)$$

$$\times \left(\frac{\kappa_{\nu}}{0.01 \text{ cm}^2 \text{ g}^{-1}}\right)^{-1} \left(\frac{S_{\text{beam}}}{\text{mJy beam}^{-1}}\right)$$

$$\times \left(\frac{\theta_{\text{HPBW}}}{10 \text{ arcsec}}\right)^{-2} \left(\frac{\lambda}{\text{mm}}\right)^3.$$
We estimated the continuum flux ($S_{\nu}^{\text{beam}}$) toward the cyanopolyynes-rich clump within a size of 14″, and the flux intensity is $9.7 \times 10^3 \text{ mJy beam}^{-1}$. We assumed that $\kappa_{\nu}$ is 0.0619 cm$^2$ g$^{-1}$ at $\lambda = 450 \mu m$. $T$ is the dust temperature, and we assumed it to be 30 ± 15 K. The derived $N(H_2)$ value is $2.8^{+8.1}_{-1.3} \times 10^{22}$ cm$^{-2}$, which is similar to the typical value of massive clumps forming young star clusters (e.g., Shimoyama et al. 2018). The value is an average for the clump, and it can be considered as a lower limit for cores. The derived $N(H_2)$ value for the cyanopolyynes-rich clump is higher than the threshold value for star formation cores, $N(H_2) \approx 9 \times 10^{21}$ cm$^{-2}$ (e.g., Tachihara et al. 2002). Hence, the cyanopolyynes-rich clump is considered to contain deeply embedded low- or intermediate-mass protostellar core(s), and is not a starless clump.

In a case where a low- or intermediate-mass protostar has been born, the WCCC mechanism is likely to work; cyanopolyynes are formed from CH$_4$ evaporated from grain mantles in the lukewarm gas ($T = 20$–$30$ K). This may be supported by the similar HC$_3$N:HC$_5$N:HC$_7$N ratios in this clump and in L1527 (Section 4.1).

In order to investigate the possibility of a PDR, we compare the fractional abundances of cyanopolyynes in the cyanopolyynes-rich clump with those derived from a simulation of a PDR chemical network (Le Gal et al. 2017). We derived the fractional abundances, $X(a) = N(a)/N(H_2)$, of cyanopolyynes at Position A as summarized in Table 3. A recent simulation of the chemical network in the Horsehead nebula, which is one of the most studied PDRs, estimated the HC$_3$N and HC$_5$N abundances (Le Gal et al. 2017). The PDR and core positions are positions with visual extinctions ($A_v$) of $\sim 2$ mag and $\sim 10$–$20$ mag, respectively. We summarize the fractional abundances of these two positions in Table 3. The $X(\text{HC}_3\text{N})$ and $X(\text{HC}_5\text{N})$ values in the cyanopolyynes-rich clump are significantly higher than those at the PDR position by three orders of magnitude and by more than four orders of magnitude, respectively. Moreover, the HC$_3$N and HC$_5$N fractional abundances in the cyanopolyynes-rich clump are still higher than those at the core position in the PDR model by factors of $\sim 55$ and $\sim 80$, respectively. Therefore, cyanopolyynes in the cyanopolyynes-rich clump in the G28.28–0.36 high-mass star-forming region are not formed by the PDR chemistry. If we take large uncertainties in deriving $N(H_2)$ values into consideration, the differences between the cyanopolyynes-rich clump and the PDR models are plausible. However, we cannot completely exclude any effects from the UCH II region, such as UV radiation.

We also compare the fractional abundances of HC$_3$N, HC$_5$N, and HC$_7$N in the cyanopolyynes-rich clump to those in L1527. These fractional abundances in the cyanopolyynes-rich clump are higher than those in L1527 by factors of 7–15, 7–37, and 18–17, respectively. Hence, the cyanopolyynes in the cyanopolyynes-rich clump seem to be more abundant than in L1527, even if we take uncertainties in fractional abundances into account. It cannot be excluded that several low-mass protostars are concentrated within a small region (e.g., $\sim 0.02$ pc, corresponding to 1″5 at the distance of 3 kpc). In another interpretation, these results may imply that there is an intermediate-mass protostar because an intermediate-mass protostar heats its surroundings more widely than a low-mass protostar; the size of lukewarm envelopes will be larger and the column densities of carbon-chain species in such lukewarm envelopes will increase. This could explain the result that the cyanopolyynes in the cyanopolyynes-rich clump are more abundant than those in L1527.

In Figure 5(d), compact HC$_3$N emission region is located at the position west of the 6.7 GHz methanol maser position. This position corresponds to the edge of the 4.5 μm emission, which seems to trace shock regions (Cyganowski et al. 2008). Figure 6 shows spectra of HC$_3$N and HC$_5$N in the shock region. The line widths (FWHM) derived from the Gaussian fit are $2.7 \pm 0.2$ and $2.6 \pm 0.2$ km s$^{-1}$ for HC$_3$N and HC$_5$N, respectively. These line widths in the shock region are wider than those in the cyanopolyynes-rich clump, $2.05 \pm 0.16$ and $1.4 \pm 0.2$ km s$^{-1}$ for HC$_3$N and HC$_5$N, respectively. These
results probably support the idea that the cyanopolyynes have a shock origin. Molecules such as C$_2$H$_2$ evaporated from grain mantles may be parent species of the cyanopolyynes. It is still unclear whether HC$_5$N is formed and can survive in shock regions, but this may be the first observational result showing that HC$_5$N can be enhanced in shock regions.

Figure 5. (a) Spitzer three-color image (red: 8.0 μm, green: 4.5 μm, blue: 3.6 μm), overlaid by yellow contours showing (b) the 450 μm continuum, (c) the HC$_3$N moment-zero image, and (d) the HC$_5$N moment-zero image. The green contour in panel (b) is the 8.3 mm continuum emission obtained with the VLA. The contour levels are 90%, 80%, 70%, 60%, and 50% of their peak levels. The blue open circle and diamond indicate the 6.7 GHz methanol maser and the UCH II region, respectively.

Figure 6. Spectra of HC$_3$N and HC$_5$N in the shock region. The red lines show the Gaussian fitting results.
4.4. Comparison with Previous Single-dish Telescope Observations

Taniguchi et al. (2017) reported the detection of lines of high excitation energy ($E_u/k \simeq 100$ K) from HC$_5$N with the Nobeyama 45 m radio telescope (half-power beam width = 18") toward the methanol maser position, which is considered to be an MYSO position (Urquhart et al. 2013). The significant HC$_5$N peak is not seen at the methanol maser position in the VLA map. This is probably caused by the different excitation energies of the observed lines. The lines observed with the VLA have low excitation energies (Table 1), and preferably trace lower-temperature regions such as low- or intermediate-mass protostellar cores or envelopes. On the other hand, HC$_3$N emission observed with the Nobeyama 45 m telescope seems to come from higher-temperature regions closer to the methanol maser or the MYSO. In these higher-temperature regions, HC$_3$N should be highly excited and lines of low excitation energy observed with the VLA should be weak. In contrast, the hotter components detected with the Nobeyama 45 m telescope were not detected with the VLA, because the lines of low excitation energy are not suitable tracers of the hot components. Combining the results from the VLA and the Nobeyama 45 m telescope, both the MYSO associated with the methanol maser and low- or intermediate-mass protostellar core(s) in the cyanopolyne-rich clump appear to be rich in cyanopolyynes.

It is still unclear why the G28.28–0.36 high-mass star-forming region is a cyanopolyne-rich/COMs-poor source (Taniguchi et al. 2018). Studies of chemical diversity among high-mass star-forming regions will become a key to our understanding of the processes of massive star formation. We need the observations at high spatial resolution and in higher frequency bands in order to investigate the spatial resolution of higher-temperature components of cyanopolyynes to confirm that cyanopolyynes exist at the hot-core position.

5. Conclusions

We have carried out interferometric observations of cyanopolyynes (HC$_3$N, HC$_5$N, and HC$_7$N) toward the G28.28–0.36 high-mass star-forming region with the VLA Ka-band receiver. We obtained the moment-zero images of HC$_3$N and HC$_5$N and tentatively detected HC$_7$N. The spatial distributions of HC$_3$N and HC$_5$N are consistent with the 450 $\mu$m dust continuum clump, i.e., the cyanopolyne-rich clump. The HC$_3$N:HC$_5$N:HC$_7$N column density ratios are estimated to be 1.0:0.3:0.2 at Position A. The cyanopolyne-rich clump seems to contain deeply embedded low- or intermediate-mass protostellar core(s). The most probable formation mechanism of the cyanopolyynes in the cyanopolyne-rich clump is the WCCC mechanism. We possibly found HC$_3$N and HC$_5$N emission in the shock region.

We express our sincere thanks and appreciation to the staff of the National Radio Astronomy Observatory. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. K.T. appreciates support from a Granting-Aid for Science Research of Japan (17J03516).

Facility: Karl G. Jansky Very Large Array (VLA).

Common Astronomy Software Applications (CASA).

Appendix

Gaussian Fitting Results and Spectral Line Parameters

We show the Gaussian fitting results for the spectra of HC$_3$N, HC$_5$N, and HC$_7$N at Position A in Figure 7. The obtained spectral line parameters are summarized in Table 4.
The Astrophysical Journal, 866:32 (8pp), 2018 October 10

Taniguchi et al.

Figure 7. Spectra of HC$_3$N, HC$_5$N, and HC$_7$N at Position A obtained with the VLA. The best Gaussian fits are shown overlaid in red.

Table 4

| Species | $\mu$ (Debye) | $T_b$ (K) | FWHM (km s$^{-1}$) | $\int T_b dv$ (K km s$^{-1}$) |
|---------|--------------|------------|------------------|-------------------------------|
| HC$_3$N | 3.73         | 5.4 ± 0.4  | 2.05 ± 0.16      | 11.7 ± 1.2                    |
| HC$_5$N | 4.33         | 2.3 ± 0.3  | 1.4 ± 0.2        | 3.5 ± 0.8                     |
| HC$_7$N | 4.82         | 1.0 ± 0.2  | 1.3 ± 0.3        | 1.3 ± 0.4                     |

Note. The errors represent the standard deviation. Values of their permanent electric dipole moments are taken from the Cologne Database for Molecular Spectroscopy (CDMS; Müller et al. 2005).

ORCID iDs

Kotomi Taniguchi https://orcid.org/0000-0003-4402-6475
Yusuke Miyamoto https://orcid.org/0000-0002-7616-7427
Masao Saito https://orcid.org/0000-0003-0769-8627
Patricio Sanhueza https://orcid.org/0000-0002-7125-7685
Tomomi Shimoikura https://orcid.org/0000-0002-1054-3004
Kazuhiro Dobashi https://orcid.org/0000-0001-8058-8577
Fumitaka Nakamura https://orcid.org/0000-0001-5431-2294

References

Bachiller, R., & Pérez Gutiérrez, M. 1997, ApJ., 487, L93
Belloche, A., Müller, H. S. P., Menten, K. M., Schilke, P., & Comito, C. 2013, A&A, 559, A47
Benjamin, R. A., Churchwell, E., Babler, B. L., et al. 2003, PASP, 115, 953
Bergner, J. B., Guzmán, V. G., Öberg, K. I., Loomis, R. A., & Pegues, J. 2018, ApJ., 857, 69
Calcutt, H., Jørgensen, J. K., Müller, H. S. P., et al. 2018, arXiv:1804.09210
Chapman, J. F., Millar, T. J., Wardle, M., Burton, M. G., & Walsh, A. J. 2009, MNRAS, 394, 221

Cyganowski, C. J., Brogan, C. L., Hunter, T. R., & Churchwell, E. 2009, ApJ, 702, 1615
Cyganowski, C. J., Whitney, B. A., Holden, E., et al. 2008, AJ, 136, 2391
Esplugues, G. B., Cernicharo, J., Viti, S., et al. 2013, A&A, 559, A51
Feng, S., Beuther, H., Henning, T., et al. 2015, A&A, 581, A71
Fontani, F., Ceccarelli, C., Favre, C., et al. 2017, A&A, 605, A57
Goldsmith, P. F., & Langer, W. D. 1999, ApJ, 517, 209
Green, C.-E., Green, J. A., Burton, M. G., et al. 2014, MNRAS, 443, 2252
Hassel, G. E., Herbst, E., & Garrod, R. T. 2008, ApJ, 681, 1385
Hirota, T., Ohishi, M., & Yamamoto, S. 2019, ApJ, 699, 585
Jaber Al-Edhari, A., Ceccarelli, C., Kahane, C., et al. 2017, A&A, 597, A40
Jørgensen, J. K., Schöier, F. L., & van Dishoeck, E. F. 2002, A&A, 389, 908
Le Gal, R., Herbst, E., Dufour, G., et al. 2017, A&A, 605, A88
Lee, K. I., Dunham, M. M., Myers, P. C., et al. 2015, ApJ, 814, 114
McMullin, J. P., Waters, B., Schiebel, D., Young, W., & Golap, K. 2007, in ASP Conf. Ser. 376, Astronomical Data Analysis Software and Systems XVI, ed. R. A. Shaw, F. Hill, & D. J. Bell (San Francisco, CA: ASP), 127
Müller, H. S. P., Schlöder, F., Stutzki, J., & Winnewisser, G. 2005, JMoSt, 742, 215
Mumma, M. J., & Charnley, S. B. 2011, ARA&A, 49, 471
Obert, K. J., Guzmán, V. V., Furuya, K., et al. 2015, Natur, 520, 198
Pickett, H. M., Poynter, R. L., Cohen, E. A., et al. 1998, JQSRT, 60, 883
Sakai, N., Sakai, T., Hirota, T., & Yamamoto, S. 2008, ApJ, 672, 371
Sakai, N., Sakai, T., Hirota, T., & Yamamoto, S. 2009, ApJ, 702, 1025
Sakai, N., & Yamamoto, S. 2013, ChRv, 113, 8961
Sanhueza, P., Jackson, J. M., Foster, J. B., et al. 2012, ApJ, 756, 60
Shimoikura, T., Dobashi, K., Nakamura, F., Matsumoto, T., & Hirota, T. 2018, ApJ, 855, 45
Shirley, Y. L., Nordhaus, M. K., Grcevich, J. M., et al. 2005, ApJ, 632, 982
Suzuki, H., Yamamoto, S., Ohishi, M., et al. 1992, ApJ, 392, 551
Tachihara, K., Onishi, T., Mizuno, A., & Fukui, Y. 2002, A&A, 385, 909
Taniguchi, K., Saito, M., Hirota, T., & Yamamoto, S. 2017, ApJ, 844, 68
Taniguchi, K., Saito, M., Majumdar, L., et al. 2018, ApJ, in press (arXiv:1804.05205)
Taniguchi, K., Saito, M., & Ozeki, H. 2016, ApJ, 830, 106
Urquhart, J. S., Hoare, M. G., Purcell, C. R., et al. 2009, A&A, 501, 539
Urquhart, J. S., Moore, T. J. T., Schuller, F., et al. 2013, MNRAS, 431, 1752