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# Vibrationally Excited Lines of HC<sub>3</sub>N Associated with the Molecular Disk around the G24.78+0.08 A1 Hypercompact H II Region

Kotomi Taniguchi<sup>1</sup>, Kei E. I. Tanaka<sup>1,2</sup>, Yichen Zhang<sup>3</sup>, Rubén Fedriani<sup>4</sup>, Jonathan C. Tan<sup>3,4</sup>, Shigehisa Takakuwa<sup>5,6</sup>, Fumitaka Nakamura<sup>1,7,8</sup>, Masao Saito<sup>1,7</sup>, Liton Majumdar<sup>9,10</sup>, and Eric Herbst<sup>3,11</sup>

<sup>1</sup> National Astronomical Observatory of Japan, National Institutes of Natural Sciences, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan; [kotomi.taniguchi@nao.ac.jp](mailto:kotomi.taniguchi@nao.ac.jp), [kei.tanaka@colorado.edu](mailto:kei.tanaka@colorado.edu)

<sup>2</sup> Center for Astrophysics and Space Astronomy, University of Colorado Boulder, Boulder, CO 80309, USA

<sup>3</sup> Department of Astronomy, University of Virginia, Charlottesville, VA 22904, USA

<sup>4</sup> Department of Space, Earth & Environment, Chalmers University of Technology, SE-412 93 Gothenburg, Sweden

<sup>5</sup> Department of Physics and Astronomy, Graduate School of Science and Engineering, Kagoshima University, 1-21-35 Korimoto, Kagoshima, Kagoshima 890-0065, Japan

<sup>6</sup> Academia Sinica Institute of Astronomy and Astrophysics, 11F of Astro-Math Bldg., 1, Section 4 Roosevelt Road, Taipei 10617, Taiwan

<sup>7</sup> Department of Astronomical Science, School of Physical Science, SOKENDAI (The Graduate University for Advanced Studies), Osawa, Mitaka, Tokyo 181-8588, Japan

<sup>8</sup> Department of Astronomy, Graduate School of Science, The University of Tokyo, Hongo, Bunkyo, Tokyo 113-0033, Japan

<sup>9</sup> School of Earth and Planetary Sciences, National Institute of Science Education and Research, Jatni 752050, Odisha, India

<sup>10</sup> Homi Bhabha National Institute, Training School Complex, Anushaktinagar, Mumbai 400094, India

<sup>11</sup> Department of Chemistry, University of Virginia, Charlottesville, VA 22904, USA

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## Abstract

We have analyzed Atacama Large Millimeter/submillimeter Array Band 6 data of the hypercompact H II region G24.78+0.08 A1 (G24 HC H II) and report the detection of vibrationally excited lines of HC<sub>3</sub>N ( $v_7 = 2$ ,  $J = 24 - 23$ ). The spatial distribution and kinematics of a vibrationally excited line of HC<sub>3</sub>N ( $v_7 = 2$ ,  $J = 24 - 23$ ,  $l = 2e$ ) are found to be similar to the CH<sub>3</sub>CN vibrationally excited line ( $v_8 = 1$ ), which indicates that the HC<sub>3</sub>N emission is tracing the disk around the G24 HC H II region previously identified by the CH<sub>3</sub>CN lines. We derive the <sup>13</sup>CH<sub>3</sub>CN/HC<sup>13</sup>CCN abundance ratios around G24 and compare them to the CH<sub>3</sub>CN/HC<sub>3</sub>N abundance ratios in disks around Herbig Ae and T Tauri stars. The <sup>13</sup>CH<sub>3</sub>CN/HC<sup>13</sup>CCN ratios around G24 ( $\sim 3.0$ – $3.5$ ) are higher than the CH<sub>3</sub>CN/HC<sub>3</sub>N ratios in the other disks ( $\sim 0.03$ – $0.11$ ) by more than 1 order of magnitude. The higher CH<sub>3</sub>CN/HC<sub>3</sub>N ratios around G24 suggest that the thermal desorption of CH<sub>3</sub>CN in the hot dense gas and efficient destruction of HC<sub>3</sub>N in the region irradiated by the strong UV radiation are occurring. Our results indicate that the vibrationally excited HC<sub>3</sub>N lines can be used as a disk tracer of massive protostars at the HC H II region stage, and the combination of these nitrile species will provide information of not only chemistry but also physical conditions of the disk structures.

*Unified Astronomy Thesaurus concepts:* [Astrochemistry](#) (75)

## 1. Introduction

Massive stars ( $>8 M_{\odot}$ ) play essential roles in the evolution and characterization of galaxies, because they produce and disperse large amounts of energy and heavy elements. However, the formation processes of massive stars remain uncertain (see, e.g., Tan et al. 2014, for a review). One formation scenario is the competitive accretion model, in which massive stars need to form in clustered environments (Bonnell et al. 2001; Wang et al. 2010). Another is the turbulent core accretion model, a scaled-up version of the formation process of low-mass stars (e.g., McKee & Tan 2002, 2003), and which can be applied to both clustered and isolated environments. Theoretical models further investigated stellar feedback from forming massive stars (e.g., disk wind, radiation pressure, photoevaporation, and stellar winds) in the core accretion model (e.g., Tanaka et al. 2016, 2017). In order to reveal the formation process of massive stars and test the theoretical models, high-angular-resolution and high-sensitivity observations are important (Zhang et al. 2019b, 2019c). In particular,

observations of molecular lines are essential, because they provide information about not only gas kinematics but also chemical composition, which is an important tracer of physical conditions and evolutionary stage (e.g., Caselli & Ceccarelli 2012; Taniguchi et al. 2019b, 2021b; Jørgensen et al. 2020).

Recent high-angular-resolution observations with interferometers such as the Atacama Large Millimeter/submillimeter Array (ALMA) have revealed the presence of disk structures around O-type and B-type massive protostars (Cesaroni et al. 2017; Maud et al. 2018; Zhang et al. 2019a). Tanaka et al. (2020) detected the high-temperature components of disks, which are located at very close distances to massive protostars ( $\sim 100$  au scale), using several molecular lines such as H<sub>2</sub>O ( $v_2 = 1$ ), NaCl, SiO, and SiS toward the O-type-binary system IRAS 16547–4247 with ALMA. However, the detailed physical and chemical properties of such disk structures around massive protostars are still unclear. The CH<sub>3</sub>CN lines are typically used as a disk tracer (Sánchez-Monge et al. 2013; Johnston et al. 2015; Ilee et al. 2016), and sometimes the SiO lines have been used (e.g., Maud et al. 2018; Zhang et al. 2019a).

Nitrile species, CH<sub>3</sub>CN and HC<sub>3</sub>N, have been frequently detected in disks around Herbig Ae and T Tauri stars (Bergner et al. 2018; Loomis et al. 2018). The Molecules with ALMA at Planet-forming Scale (MAPS; Öberg et al. 2021) Large Program



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reveals that these nitrile species trace different layers of these disks;  $\text{HC}_3\text{N}$  traces upper and warmer layers compared to  $\text{CH}_3\text{CN}$  (Ilee et al. 2021). In disks around Herbig Ae and T Tauri stars,  $\text{CH}_3\text{CN}$  is considered to mainly form on dust surfaces followed by the photodesorption or the thermal desorption, while  $\text{HC}_3\text{N}$  forms in the gas phase (Loomis et al. 2018; Le Gal et al. 2019). Based on the rotational temperatures of  $\text{CH}_3\text{CN}$ , the photodesorption is suggested to be more important than the thermal desorption in these disks (Loomis et al. 2018). Hence, it is useful for investigating physical conditions of disks to observe various nitrile species.

In the case of more massive stars, the  $\text{CH}_3\text{CN}$  lines have been frequently used for searching for disks around massive stars (e.g., Johnston et al. 2015; Cesaroni et al. 2017; Sanna et al. 2021), whereas fewer studies about the  $\text{HC}_3\text{N}$  lines have been conducted. The vibrationally excited lines of  $\text{HC}_3\text{N}$  have been detected in compact hot cores around massive protostars (e.g., Wyrowski et al. 1999; Taniguchi et al. 2020), but it was still unclear whether these lines trace massive protostellar disks due to the insufficient angular resolutions of those observations. Other higher-angular-resolution ALMA data ( $\sim 400$  au) show that an  $\text{HC}_3\text{N}$  vibrationally excited line ( $\nu_7 = 1e$ ,  $J = 38 - 37$ ;  $E_{\text{up}}/k = 645$  K) traces an accretion disk around the massive protostar in G328.2551-0.5321 (Csengeri et al. 2018). Their result suggests that the vibrationally excited lines of  $\text{HC}_3\text{N}$  could be a tracer of disks around massive young protostars. In order to confirm this hypothesis, it is essential to investigate massive protostars in various evolutionary stages (e.g., hypercompact H II regions). In addition, the  $\text{HC}_3\text{N}$  chemistry in disk structures around massive protostars has not been discussed yet.

In this paper, we present results of two vibrationally excited  $\text{HC}_3\text{N}$  ( $\nu_7 = 2$ ,  $J = 24 - 23$ ,  $l = 0$ , and  $l = 2e$ ) lines detected from the G24.78+0.08 A1 hypercompact H II (hereafter G24 HC H II) region obtained in an ALMA Cycle 6 program. The bolometric luminosity and distance of this source are  $\sim 2 \times 10^5 L_\odot$  and  $6.7 \pm 0.7$  kpc, respectively (Moscadelli et al. 2021). We adopt a distance of 6.7 kpc to the G24 HC H II region (Moscadelli et al. 2021). This source contains a thin shell ionized by an O9.5 star, which was suggested based on studies of the continuum emission and the hydrogen recombination lines (Cesaroni et al. 2019). Moscadelli et al. (2021) found that  $\text{CH}_3\text{CN}$  lines are consistent with a Keplerian rotation around a  $20 M_\odot$  star along the axis  $\text{PA} = 133^\circ$  (disk major axis), while an ionized jet has been identified along the axis at  $\text{PA} = 39^\circ$  at the G24 HC H II region.

The structure of this paper is as follows. We describe the archival data set and reduction procedure in Section 2. The resultant moment 0 maps of the molecular lines are presented in Section 3.1. The position–velocity ( $P$ – $V$ ) diagrams are constructed and the kinematics of  $\text{HC}_3\text{N}$  and  $\text{CH}_3\text{CN}$  are investigated in Section 3.2. We describe spectral analyses of the  $^{13}\text{CH}_3\text{CN}$  and  $\text{HC}^{13}\text{CCN}$  lines and derive the  $\text{CH}_3\text{CN}/\text{HC}_3\text{N}$  abundance ratios around the G24 HC H II region in Sections 3.3.1 and 3.3.2, respectively. The  $\text{CH}_3\text{CN}/\text{HC}_3\text{N}$  ratios in G24 are compared to those in disks around Herbig Ae and T Tauri stars in Section 3.3.3. We will discuss the possibility of a binary system in this source in Section 3.4. In Section 4, the main conclusions of this paper are summarized.

## 2. ALMA Archival Data and Reduction Procedure

We have analyzed the ALMA Band 6 archival data toward the G24 HC H II region.<sup>12</sup> The observations were conducted

**Table 1**  
Summary of Molecular Lines and a Recombination Line Presented in this Paper

Species	Transition	Frequency (GHz)	$E_{\text{up}}/k$ (K)
$\text{HC}_3\text{N}$ ( $\nu_7 = 2$ ) <sup>a</sup>	$J = 24 - 23$ , $l = 0$	219.6751141	773.5
	$J = 24 - 23$ , $l = 2e$	219.7073487	776.8
$\text{HC}^{13}\text{CCN}$ ( $\nu = 0$ ) <sup>a</sup>	$J = 26 - 25$	235.5094856	152.6
$\text{CH}_3\text{CN}$ ( $\nu_8 = 1$ ) <sup>b</sup>	$J_{K,l} = 12_{6,1} - 11_{6,1}$	221.3118349	771.1
$^{13}\text{CH}_3\text{CN}$ ( $\nu = 0$ ) <sup>a</sup>	$J_K = 13_6 - 12_6$	232.0772032	335.5
	$J_K = 13_5 - 12_5$	232.1251297	256.9
	$J_K = 13_4 - 12_4$	232.1643692	192.5
	$J_K = 13_3 - 12_3$	232.1949056	142.4
	$J_K = 13_2 - 12_2$	232.2167263	106.7
	$J_K = 13_1 - 12_1$	232.2298223	85.2
	$J_K = 13_0 - 12_0$	232.2341883	78.0
$\text{CH}_3\text{CN}$ ( $\nu = 0$ ) <sup>b</sup>	$J_K = 12_4 - 11_4$	220.6792869	183.1
H30 $\alpha$	...	231.900928	...

### Notes.

<sup>a</sup> The rest frequencies were taken from the Cologne Database for Molecular Spectroscopy (CDMS; Müller et al. 2005).

<sup>b</sup> The rest frequency was taken from the JPL database (Pickett et al. 1998).

using the 12 m array on 2019 July 29 during Cycle 6. Details of the observations are described in Moscadelli et al. (2021).

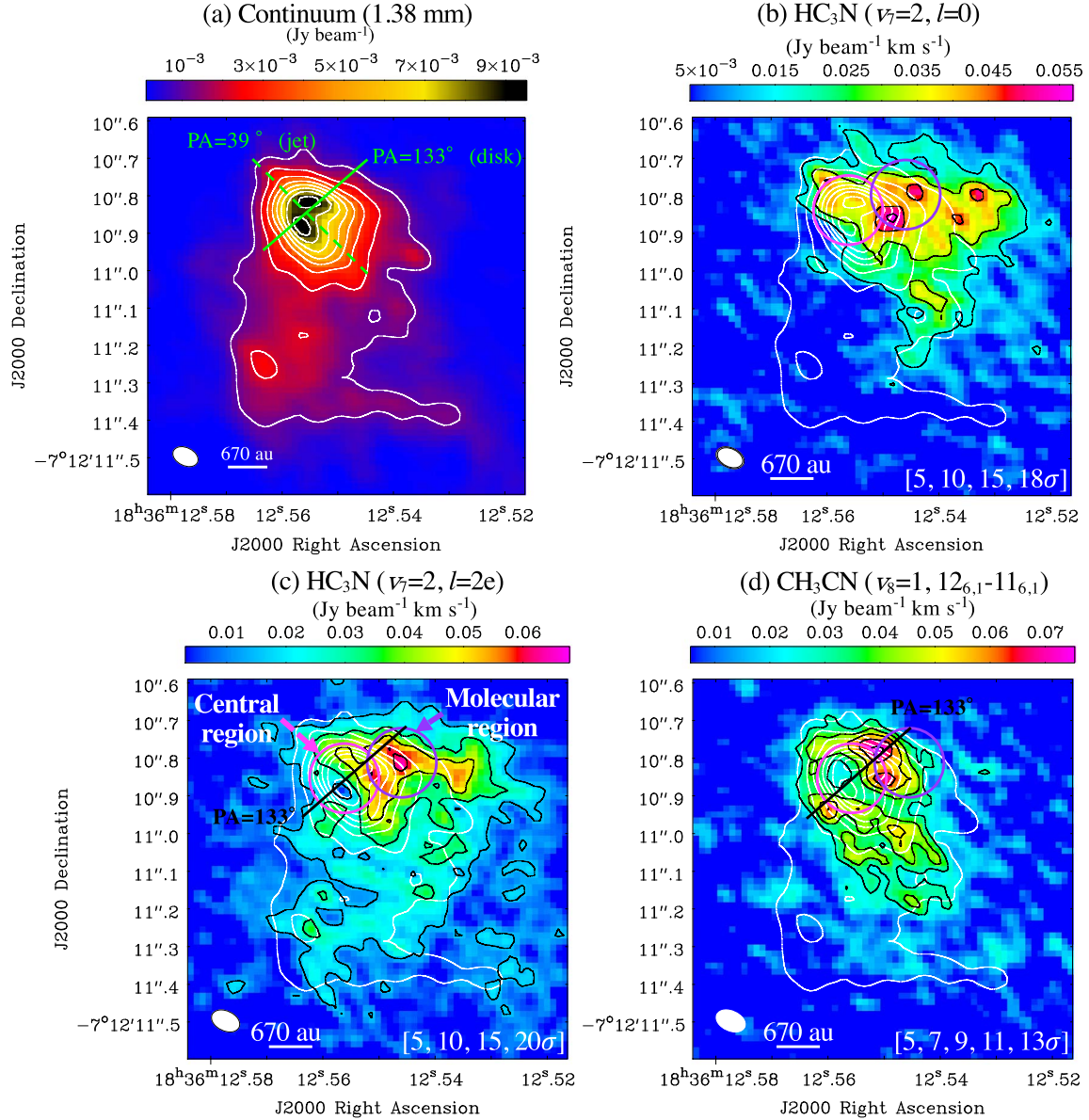
We conducted data reduction and imaging using the Common Astronomy Software Application (CASA; McMullin et al. 2007) on the pipeline-calibrated visibilities. We ran the calibration script using CASA version 5.6.1. The data cubes were created by the `tclean` task in CASA. Briggs weighting with a robust parameter of 0.5 was applied. The pixel size and image size are  $0''.016$  and  $3500 \times 3500$  pixels, respectively. The coordinate of the phase center is  $(\alpha_{\text{J2000}}, \delta_{\text{J2000}}) = (18^{\text{h}}36^{\text{m}}12^{\text{s}}.661, -07^\circ12'10''.15)$ . The maximum baseline length is 8547.6 m. The field of view (FoV) and maximum recoverable scale (MRS) are approximately  $26''$  and  $0''.8$ , respectively.

Molecular lines and a recombination line presented in this paper are summarized in Table 1. Two vibrationally excited lines of  $\text{HC}_3\text{N}$  ( $\nu_7 = 2$ ,  $J = 24 - 23$ ,  $l = 0$  and  $l = 2e$ ), which are of our main interest, were observed in the same spectral window. These vibrationally excited  $\text{HC}_3\text{N}$  lines have a high upper-state energy of  $E_{\text{up}}/k \approx 774\text{--}777$  K, which makes them suitable for tracing inner hot gas near the central star, i.e., the disk. In addition to the  $\text{HC}_3\text{N}$  lines, we present the data of the  $\text{CH}_3\text{CN}$  ( $\nu_8 = 1$ ,  $J_{K,l} = 12_{6,1} - 11_{6,1}$ ) line<sup>13</sup> that has a similar upper-state energy to the  $\text{HC}_3\text{N}$  ( $\nu_7 = 2$ ,  $J = 24 - 23$ ) lines. We will compare their spatial distributions and  $P$ – $V$  diagrams in order to confirm that the  $\text{HC}_3\text{N}$  lines trace the disk structure around the G24 HC H II region. We also made data cubes of vibrationally ground-state lines of  $^{13}\text{CH}_3\text{CN}$  ( $J_K = 13_K - 12_K$ ,  $K = 0 - 6$ ) and  $\text{HC}^{13}\text{CCN}$  ( $\nu = 0$ ,  $J = 26 - 25$ ), which are expected to be optically thin, in order to derive their column densities (Section 3.3.1). The data cube of the H30 $\alpha$  line is presented in Section 3.4 to discuss a possibility of the binary system. The velocity resolution of these data is  $0.63 \text{ km s}^{-1}$ .

A continuum image ( $\lambda = 1.38$  mm) was created from the broadest spectral window (1.9 GHz bandwidth, center frequency of 217.8 GHz) using the `imcontsub` task in CASA. As some lines have been detected at the HC H II region position in this spectral window, we determined line-free channels in the `tclean` image for

<sup>12</sup> Project ID; 2018.1.00745.S, PI; Luca Moscadelli.

<sup>13</sup> The detail studies of this line are summarized in Moscadelli et al. (2021).



**Figure 1.** Panel (a) shows the continuum image ( $\lambda = 1.38$  mm) toward the G24 HC H II region, which was first reported by Moscadelli et al. (2021). The rms noise level of the image is  $0.1 \text{ mJy beam}^{-1}$ . The contour levels are 10, 20, 30, 40, 50, 60, 70,  $80\sigma$ . The filled white ellipse indicates the angular resolution of  $0''.071 \times 0''.048$  and  $\text{PA} = 63^\circ.9$ . The linear scale is given for  $0''.1$  corresponding to 670 au. The green solid and dashed lines indicate  $\text{PA} = 133^\circ$  and  $\text{PA} = 39^\circ$ , corresponding to the disk major axis and jet directions, respectively (Moscadelli et al. 2021). Panels (b)–(d) show moment 0 images of  $\text{HC}_3\text{N}$  ( $v_7 = 2, J = 24 - 23, l = 0$ ),  $\text{HC}_3\text{N}$  ( $v_7 = 2, J = 24 - 23, l = 2e$ ), and  $\text{CH}_3\text{CN}$  ( $v_8 = 1, J_{K_A, K_C} = 12_{6,1} - 11_{6,1}$ ), respectively, toward the G24 HC H II region. The rms noise levels are  $3 \text{ mJy beam}^{-1} \text{ km s}^{-1}$  for panels (b) and (c), and  $5.6 \text{ mJy beam}^{-1} \text{ km s}^{-1}$  for panel (d), respectively. The black contour levels are indicated at the right bottom in each panel. The white contours indicate the continuum, which is the same one as panel (a). The filled white ellipses indicate the angular resolutions of  $0''.079 \times 0''.053$  for panels (b) and (c), and  $0''.082 \times 0''.053$  for panel (d), respectively. The linear scale is given for  $0''.1$  corresponding to 670 au. The magenta and purple circles ( $0''.1$  radius) indicate the “central region” and “molecular region,” respectively. The black lines in panels (c) and (d) indicate the disk major axis ( $\text{PA} = 133^\circ$ ) for the cutting position in the  $P$ - $V$  diagrams (Figure 3).

the imcontsub task. The polynomial order of 0 was adopted for the continuum estimation. The rms noise level of the continuum image is  $0.1 \text{ mJy beam}^{-1}$ .

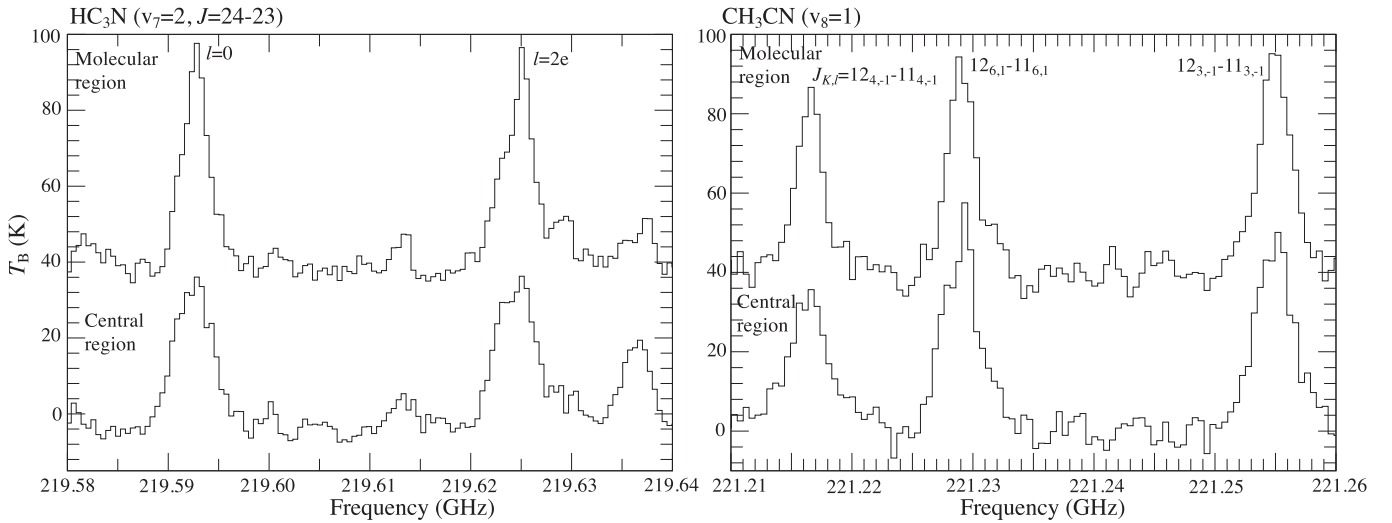
### 3. Results and Discussion

#### 3.1. Spatial Distributions of Molecular Lines

We show the continuum image ( $\lambda = 1.38$  mm) toward the G24 HC H II region in panel (a) of Figure 1, which was first reported by Moscadelli et al. (2021). The angular resolution is  $0''.071 \times 0''.048$ , corresponding to  $\sim 476 \text{ au} \times 322 \text{ au}$  at the

source distance of 6.7 kpc. The beam position angle (PA) is  $63^\circ.9$ . Two peaks are located at the center, and the spatial distribution of the continuum emission is slightly elongated along the northeast to southwest direction ( $\text{PA} = 39^\circ$ ). We will discuss a possible reason for the two peaks in the continuum emission in Section 3.4. Another continuum core is located  $\sim 0''.4$  (2680 au) south of the strongest continuum core. This position is consistent with A1M (a molecular emission peak position) named by Moscadelli et al. (2018), and they found that column densities of several complex organic molecules (COMs) are abundant here.





**Figure 2.** Spectra of the vibrationally excited lines of  $\text{HC}_3\text{N}$  (left panel) and  $\text{CH}_3\text{CN}$  (right panel) at the central and molecular regions obtained by averaging over a  $0''.1$  radius.

Panels (b)–(d) of Figure 1 show the moment 0 maps of three vibrationally excited molecular lines; (b)  $\text{HC}_3\text{N}$  ( $v_7 = 2$ ,  $J = 24 - 23$ ,  $l = 0$ ), (c)  $\text{HC}_3\text{N}$  ( $v_7 = 2$ ,  $J = 24 - 23$ ,  $l = 2e$ ), and (d)  $\text{CH}_3\text{CN}$  ( $v_8 = 1$ ,  $J_{K,l} = 12_{6,1} - 11_{6,1}$ ); toward the G24 HC H II region. We select two areas for our analysis, namely “central region” and “molecular region” (panel (c) of Figure 1). The central position of the central region corresponds to the middle of the two continuum peaks, and that of the molecular region is at the peak position of the  $\text{HC}_3\text{N}$  ( $v_7 = 2$ ,  $J = 24 - 23$ ,  $l = 2e$ ) line, respectively. Their coordinates are  $(\alpha_{J2000}, \delta_{J2000}) = (18^{\text{h}}36^{\text{m}}12^{\text{s}}.556, -07^{\circ}12'10''.85)$ , and  $(18^{\text{h}}36^{\text{m}}12^{\text{s}}.546, -07^{\circ}12'10''.80)$ , respectively. The other molecular lines also have peaks within the molecular region. We selected the two regions to investigate the potential chemical variation induced by different UV fluxes, which is expected to be higher in the central region. The central region is the same position that Moscadelli et al. (2021) analyzed. Following their work, we adopt the radii of  $0''.1$  for the two regions, which allows us to check the consistency between their and our analyses (see Section 3.3.1).

Figure 2 shows the spectra of the  $\text{HC}_3\text{N}$  and  $\text{CH}_3\text{CN}$  lines at the central and molecular regions. Other two  $\text{CH}_3\text{CN}$  lines ( $v_8 = 1$ ,  $J_{K,l} = 12_{4,-1} - 11_{4,-1}$  and  $12_{3,-1} - 11_{3,-1}$ ) are also detected near the  $\text{CH}_3\text{CN}$  ( $v_8 = 1$ ,  $J_{K,l} = 12_{6,1} - 11_{6,1}$ ) line. We checked the molecular lines in the Splatalogue database<sup>14</sup> and found that no other lines are likely to contaminate the spectra. In addition, the two vibrationally excited lines of  $\text{HC}_3\text{N}$  show similar intensities and spatial distributions as expected. We thus concluded that line contamination does not occur.

In the moment 0 maps (panels (b)–(d) of Figure 1), we can recognize the overall similarities in the spatial distributions of the  $\text{HC}_3\text{N}$  and  $\text{CH}_3\text{CN}$  emissions. Their emission regions have similar extents of  $\sim 1000$  au, because they have almost the same upper-state energies of 771–777 K (Table 1; see also Figure 6 of Moscadelli et al. 2021). Also, all three emissions are dimmer in the central region, probably due to photo-dissociation by intense UV flux (see also Section 3.3.2). These similarities suggest that the vibrationally excited  $\text{HC}_3\text{N}$  and  $\text{CH}_3\text{CN}$  lines trace the same hot, dense region surrounding the central ionized region, i.e., the molecular disk reported by Moscadelli et al. (2021). We note, despite these similarities, the

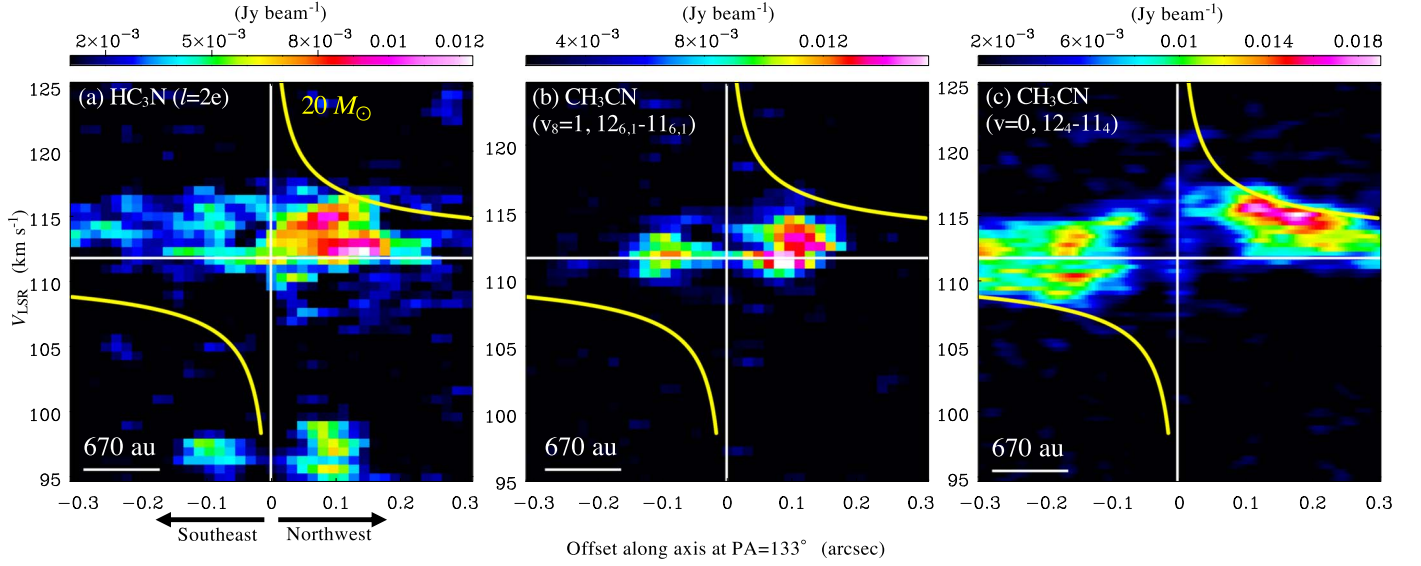
$\text{HC}_3\text{N}$  and  $\text{CH}_3\text{CN}$  lines also show a difference in their emission morphology. The  $\text{CH}_3\text{CN}$  emission surrounds the central region, while the two  $\text{HC}_3\text{N}$  lines are mainly located in the northwest. We can explain this spatial difference if the UV flux from the central region is stronger toward the south direction, because  $\text{HC}_3\text{N}$  would be more efficiently photo-dissociated than  $\text{CH}_3\text{CN}$  (Section 3.3.2). Unresolved asymmetric innermost structures, e.g., clumpy density structure and a presence of a binary system (Section 3.4), could be at the origin of such an anisotropic UV radiation field.

### 3.2. Kinematics of $\text{HC}_3\text{N}$ and $\text{CH}_3\text{CN}$

Having confirmed the similarity of the spatial distributions, we next investigate the kinematical similarity of the vibrationally excited  $\text{HC}_3\text{N}$  and  $\text{CH}_3\text{CN}$  lines. Moscadelli et al. (2021) reported the Keplerian disk of G24 using the  $P$ – $V$  diagrams of the  $\text{CH}_3\text{CN}$  lines, including its vibrationally excited line and  $^{13}\text{C}$  isotopologue line. In order to confirm that the vibrationally excited  $\text{HC}_3\text{N}$  line also traces the same molecular disk, we constructed  $P$ – $V$  diagrams of  $\text{HC}_3\text{N}$  ( $v_7 = 2$ ,  $J = 24 - 23$ ,  $l = 2e$ ) and  $\text{CH}_3\text{CN}$  ( $v_8 = 1$ ,  $J_{K,l} = 12_{6,1} - 11_{6,1}$ ) along the disk major axis of  $\text{PA} = 133^\circ$  (shown in Figure 1). We used “imprv” task in CASA and averaged the emission over three pixels across the positional cut. The center position (offset =  $0''$ ) is set at the coordinate of the central region. Panels (a) and (b) of Figure 3 show the  $P$ – $V$  diagrams of the vibrationally excited  $\text{HC}_3\text{N}$  and  $\text{CH}_3\text{CN}$  lines, respectively. Their channel maps are shown in Figures 11 and 12 in Appendix B. For comparison, we also provide the  $P$ – $V$  diagram of the vibrational ground-state line of  $\text{CH}_3\text{CN}$  ( $J_K = 12_4 - 11_4$ ), which clearly shows the Keplerian feature with  $20 M_\odot$ , but becomes dimmer in the innermost region (panel (c) of Figure 3).

In the  $P$ – $V$  diagrams, we could confirm that the  $\text{HC}_3\text{N}$  emission has kinematic similarities with the vibrationally excited and ground-state  $\text{CH}_3\text{CN}$  lines, but the resemblance is stronger to the vibrationally excited line of  $\text{CH}_3\text{CN}$ . The brightest features appear in the northwest and redshifted side, and the dimmest features are in the northwest and blueshifted side in all three panels of Figure 3. On the brightest side, the  $\text{HC}_3\text{N}$  emission covers the innermost region of  $+0''.0$  to  $+0''.1$  like the vibrationally excited  $\text{CH}_3\text{CN}$  line, which has almost the

<sup>14</sup> <https://splatalogue.online/advanced1.php>



**Figure 3.**  $P$ - $V$  diagrams of (a)  $\text{HC}_3\text{N}$  ( $v_7 = 2, J = 24 - 23, l = 2e$ ), (b)  $\text{CH}_3\text{CN}$  ( $v_8 = 1, J_{K,l} = 12_{6,1} - 11_{6,1}$ ), and (c)  $\text{CH}_3\text{CN}$  ( $v = 0, J_K = 12_4 - 11_4$ ) along the cut at  $\text{PA} = 133^\circ$  (the disk major axis). The horizontal white lines indicate  $V_{\text{LSR}} = 112 \text{ km s}^{-1}$ , which is the systemic velocity of the G24 HC H II region (Moscadelli et al. 2021). The offset center (offset =  $0''$ ) corresponds to the center of the HC H II region. The positive and negative offsets correspond to northwest and southeast directions, respectively. The yellow lines indicate the Keplerian velocity profile for a central mass of  $20 M_\odot$  (the disk inclination is not taken into account).

same upper-state energy (panels (a) and (b)). Moreover, on the same side, the  $\text{HC}_3\text{N}$  emission shows the consistent profile as the Keplerian rotation seen in the ground-state  $\text{CH}_3\text{CN}$  emission (panels (a) and (c)). Hence, we conclude that the vibrationally excited  $\text{HC}_3\text{N}$  line is associated with the same Keplerian disk reported by Moscadelli et al. (2021). Although the  $\text{HC}_3\text{N}$  emission shows some resemblance to that of  $\text{CH}_3\text{CN}$  in the  $P$ - $V$  diagrams (Figure 3), the degree of this resemblance is still debatable. Future higher-angular-resolution observations including other transitions are necessary for further discussions.

The other similarity is that these  $\text{HC}_3\text{N}$  and  $\text{CH}_3\text{CN}$  lines show emission features on the southeast and redshifted side of the  $P$ - $V$  diagrams (see also Figure 4 of Moscadelli et al. 2021). The distribution of the  $\text{HC}_3\text{N}$  emission lines is intermediate between those of the vibrationally excited and ground-state  $\text{CH}_3\text{CN}$  lines. This again supports that the  $\text{HC}_3\text{N}$  line traces the same gas as  $\text{CH}_3\text{CN}$ . We note that such a kinematical feature cannot be reproduced by a pure Keplerian disk (Sakai et al. 2014; Zhang et al. 2019a). Contamination from an infalling, rotating envelope is able to create this feature, even though we used the lines with the high upper-state energies, which can be excited only in hot dense gas (see  $E_{\text{up}}/k = 777 \text{ K}$  and the critical density of  $\gtrsim 4 \times 10^8 \text{ cm}^{-3}$  for the  $\text{HC}_3\text{N}$  line; Wyrowski et al. 1999). One difference between the  $\text{HC}_3\text{N}$  and ground-state  $\text{CH}_3\text{CN}$  lines appears on the southeast and blueshifted sides in their  $P$ - $V$  diagrams (panels (a) and (c)). The  $\text{HC}_3\text{N}$  emission is darker on the southeast side, making it difficult to trace that side of the Keplerian feature (see also Figure 1). An anisotropic UV radiation field could create this  $\text{HC}_3\text{N}$  depletion, which we also mentioned in Section 3.1. This would imply that fast chemical processes change the chemical composition of the molecular disk with a shorter timescale than the rotational timescale for the disk (e.g., Cleeves et al. 2017).

### 3.3. The Abundances of $\text{HC}_3\text{N}$ and $\text{CH}_3\text{CN}$

As mentioned in Section 1,  $\text{HC}_3\text{N}$  and  $\text{CH}_3\text{CN}$  trace different layers of disks around Herbig Ae and T Tauri stars (Ilee et al. 2021), suggesting that these species trace different

physical conditions in disk structures. In order to investigate the physical and chemical conditions of the molecular disk around the G24 HC H II region, we will evaluate the  $\text{CH}_3\text{CN}/\text{HC}_3\text{N}$  abundance ratios.

#### 3.3.1. Spectral Line Analyses of $^{13}\text{CH}_3\text{CN}$ and $\text{HC}^{13}\text{CCN}$

We derive column densities of  $\text{HC}^{13}\text{CCN}$  and  $^{13}\text{CH}_3\text{CN}$  using their vibrational ground-state lines. Figure 10 in Appendix A shows the moment 0 maps of the vibrational ground-state lines of their  $^{13}\text{C}$  isotopologues. These lines are usually optically thin, and we can derive their column densities more accurately than the case with the main species.

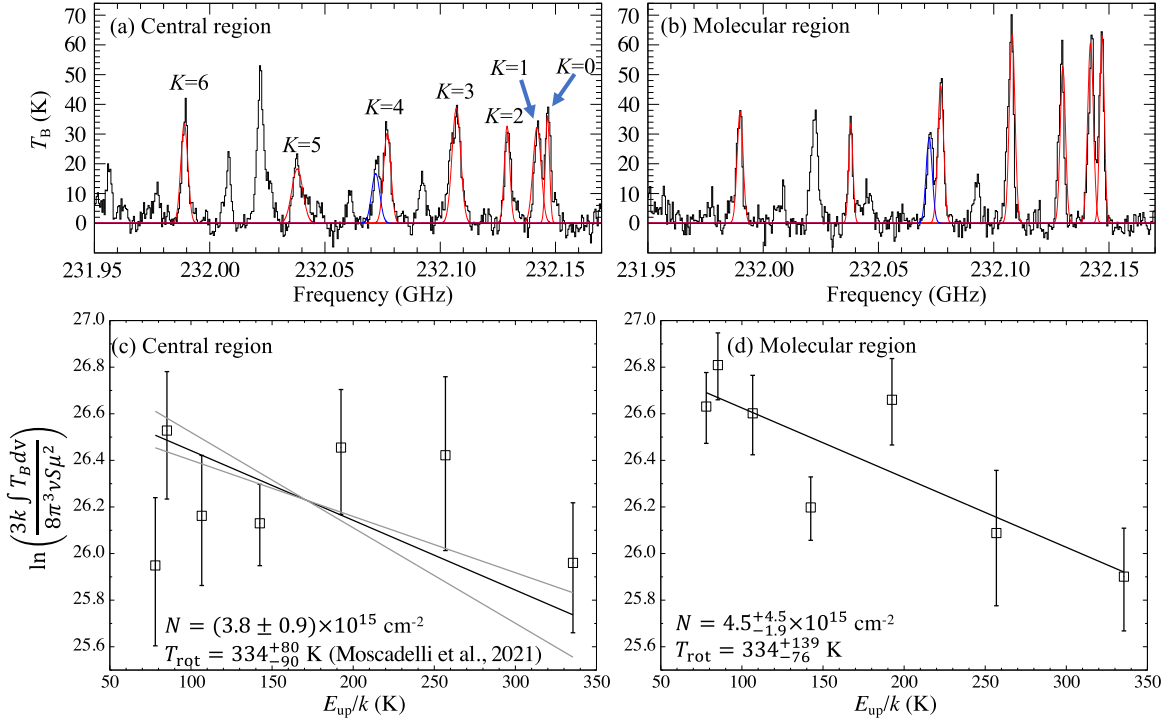
We obtained the spectra of  $^{13}\text{CH}_3\text{CN}$  and  $\text{HC}^{13}\text{CCN}$  at the central and molecular regions over the  $0''.1$  radius. As described in Section 3.1, the central region is the same region where Moscadelli et al. (2021) analyzed. The derived column densities and rotational temperatures in this section are the beam-averaged values, as Moscadelli et al. (2021) derived.

Panels (a) and (b) of Figure 4 show the spectra of  $^{13}\text{CH}_3\text{CN}$  ( $J = 13 - 12$ ) at the central and molecular regions, respectively. We fitted the spectra with a Gaussian profile and summarized the obtained parameters in Table 2. We analyzed the  $^{13}\text{CH}_3\text{CN}$  spectra with the rotational diagram method using the following formula (Goldsmith & Langer 1999);

$$\ln \frac{3k \int T_B dv}{8\pi^3 \nu S \mu^2} = \ln \frac{N}{Q(T_{\text{rot}})} - \frac{E_{\text{up}}}{kT_{\text{rot}}}, \quad (1)$$

where  $k$  is the Boltzmann constant,  $S$  is the line strength,  $\mu$  is the permanent electric dipole moment,  $N$  is the column density,  $T_{\text{rot}}$  is the rotational temperature,  $E_{\text{up}}$  is the upper-state energy, and  $Q(T_{\text{rot}})$  is the partition function. The permanent electric dipole moment of  $^{13}\text{CH}_3\text{CN}$  is 3.92197 Debye (Gadhi et al. 1995).

Panels (c) and (d) of Figure 4 show results of the rotational diagram analysis at the central and molecular regions, respectively. At the central region, we could not obtain the rotational temperature by the fitting, partly because some lines do not show a Gaussian profile, and then we applied a



**Figure 4.** Spectra of  $^{13}\text{CH}_3\text{CN}$  obtained by averaging over a  $0''.1$  radius at the center of the central and molecular regions in panels (a) and (b), respectively. Red curves show the Gaussian fitting results for the  $^{13}\text{CH}_3\text{CN}$  lines, and blue curves indicate the fit results for a line from another molecule (we could not clearly identify a molecule and its transition because of a possibility of line contamination). Panels (c) and (d) show results of the rotational diagram fit at the central and molecular regions, respectively. The error bars for each data point are derived from the standard deviation of the line fitting with a Gaussian profile summarized in Table 2. In panel (c), the black line shows the fitting result to our data using  $T_{\text{rot}} = 334$  K, and the gray lines indicate the fitting results to our data using  $T_{\text{rot}} = (334 + 80)$  K and  $T_{\text{rot}} = (334 - 90)$  K.

**Table 2**  
Gaussian Fitting Results of the  $^{13}\text{CH}_3\text{CN}$  and  $\text{HC}^{13}\text{CN}$

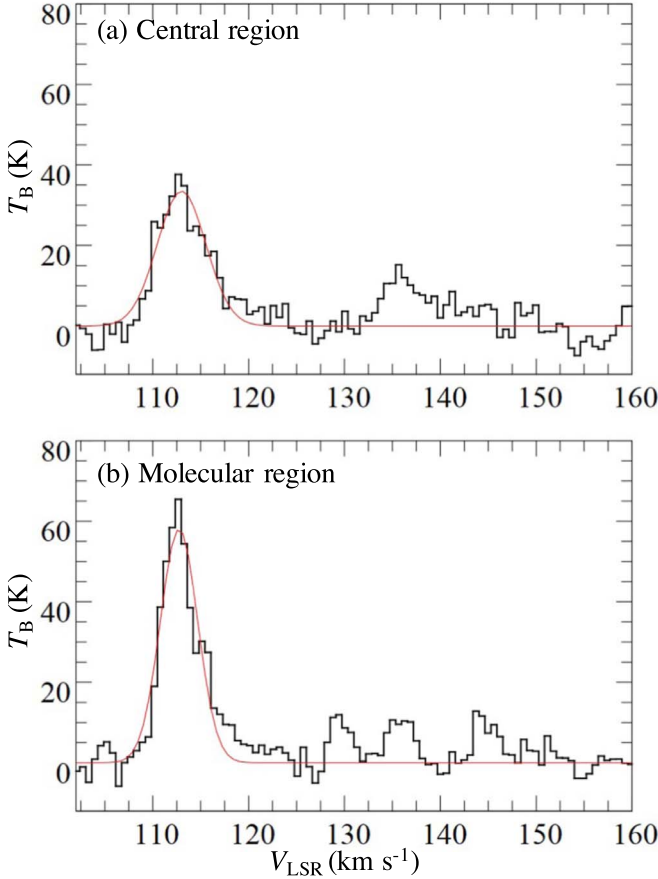
Line	Central Region		Molecular Region	
	$T_B$ (K)	$\Delta v$ (km s $^{-1}$ )	$T_B$ (K)	$\Delta v$ (km s $^{-1}$ )
$^{13}\text{CH}_3\text{CN}$ ( $J_K = 13_K - 12_K$ )				
$K = 0$	$36.0 \pm 4.4$	$2.7 \pm 0.5$	$63.1 \pm 3.7$	$3.0 \pm 0.3$
$K = 1$	$32.1 \pm 3.1$	$5.4 \pm 0.9$	$60.6 \pm 3.4$	$3.8 \pm 0.3$
$K = 2$	$32.6 \pm 3.8$	$3.6 \pm 0.6$	$52.6 \pm 3.7$	$3.5 \pm 0.3$
$K = 3$	$38.7 \pm 3.0$	$5.7 \pm 0.5$	$63.5 \pm 3.7$	$3.7 \pm 0.3$
$K = 4$	$30.2 \pm 3.3$	$4.8 \pm 0.8$	$46.1 \pm 3.4$	$3.9 \pm 0.4$
$K = 5$	$18.3 \pm 2.7$	$7.3 \pm 1.6$	$33.6 \pm 3.9$	$2.8 \pm 0.5$
$K = 6$	$33.5 \pm 3.4$	$4.6 \pm 0.8$	$37.6 \pm 3.4$	$3.9 \pm 0.5$
$\text{HC}^{13}\text{CN}$ ( $J = 26 - 25$ )				
$J = 26 - 25$	$33.4 \pm 1.7$	$6.0 \pm 0.4$	$58.1 \pm 3.0$	$4.6 \pm 0.3$

**Note.** Errors indicate the standard deviation.

rotational temperature of  $334^{+80}_{-90}$  K derived by Moscadelli et al. (2021). Their results are applicable, as Moscadelli et al. (2021) analyzed the  $^{13}\text{CH}_3\text{CN}$  spectra at the HC H II region within a  $0''.1$  radius, which is the same region as we have analyzed. The column density of  $^{13}\text{CH}_3\text{CN}$  at the HC H II region is derived to be  $(3.8 \pm 0.9) \times 10^{15} \text{ cm}^{-2}$ . This column density is consistent with the previous result within the uncertainties ( $5.01^{+1.2}_{-1.5} \times 10^{15} \text{ cm}^{-2}$ ; Moscadelli et al. 2021). The rotational temperature and column density at the molecular region are derived to be  $334^{+139}_{-76}$  K and  $4.5^{+4.5}_{-1.9} \times 10^{15} \text{ cm}^{-2}$ , respectively, by the rotational diagram fitting for our data.

The derived rotational temperatures at the two positions are much higher than the sublimation temperature of  $\text{CH}_3\text{CN}$  ( $\approx 95 \text{ K}^{15}$ ), which is different from results in the disks around the Herbig Ae and T Tauri stars (Bergner et al. 2018; Loomis et al. 2018; Ilee et al. 2021). Such high rotational temperatures of  $^{13}\text{CH}_3\text{CN}$  indicate that  $\text{CH}_3\text{CN}$ , including its isotopologues, thermally desorbs from dust grains rather than photodesorption by the UV radiation around the G24 HC H II region.

<sup>15</sup> We took the sublimation temperature from a hot-core model by Taniguchi et al. (2019a).



**Figure 5.** Spectra of  $\text{HC}^{13}\text{CCN}$  ( $J = 26 - 25$ ) obtained by averaging over a  $0''.1$  radius at the center of the central and molecular regions in panels (a) and (b), respectively. The red curves show the results of the Gaussian fit.

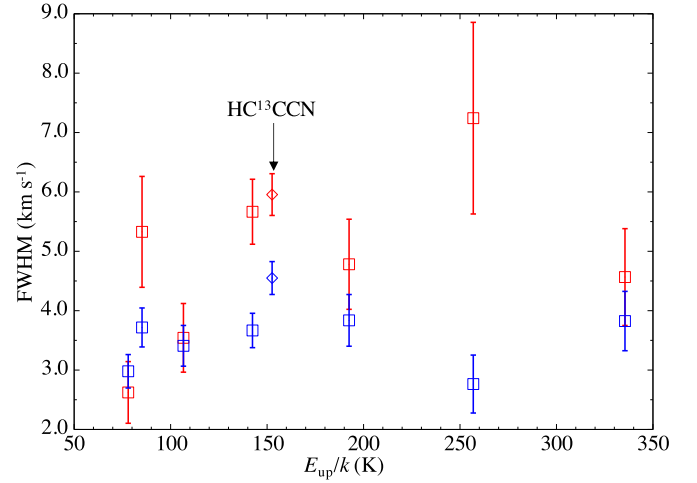
Figure 5 shows spectra of the  $\text{HC}^{13}\text{CCN}$  ( $J = 26 - 25$ ) line at the central and molecular regions, obtained by the same method as that for  $^{13}\text{CH}_3\text{CN}$ . We fitted the spectra with a Gaussian profile, and the fitting results are shown as red curves in Figure 5. Table 2 summarizes the line parameters obtained by the fitting. The  $V_{\text{LSR}}$  values of this line are  $113.0 \pm 0.15$   $\text{km s}^{-1}$  and  $112.7 \pm 0.12$   $\text{km s}^{-1}$  at the central and molecular regions, respectively.

As we have only one rotational transition line of  $\text{HC}^{13}\text{CCN}$ , we need a reasonable assumption of its excitation temperature to derive its column density. If the emission region of  $^{13}\text{CH}_3\text{CN}$  coincides with that of  $\text{HC}^{13}\text{CCN}$  and the local thermodynamic equilibrium (LTE) condition is achieved, we can use the excitation temperature of  $^{13}\text{CH}_3\text{CN}$  as the reference value. Therefore, we compare their line widths of  $^{13}\text{CH}_3\text{CN}$  and  $\text{HC}^{13}\text{CCN}$  to examine their spatial coincidence.

Figure 6 shows relationships between the FWHM and the upper-state energy of the  $^{13}\text{CH}_3\text{CN}$  and  $\text{HC}^{13}\text{CCN}$  lines. We derive the FWHM using

$$\text{FWHM} = \sqrt{(\Delta v_{\text{obs}})^2 - (\Delta v_{\text{inst}})^2}, \quad (2)$$

where  $\Delta v_{\text{obs}}$  and  $\Delta v_{\text{inst}}$  are the observed line widths and the instrumental velocity width ( $0.63$   $\text{km s}^{-1}$ ), respectively. There are no clear dependencies of the line width on the upper-state energy. The value of the  $K = 5$  line of  $^{13}\text{CH}_3\text{CN}$  and its error toward the central region are slightly larger than those of the other lines, which may be due to the contamination of another line (panel (a)



**Figure 6.** Plot of the upper-state energy ( $E_{\text{up}}$ ) vs. the FWHM of the  $^{13}\text{CH}_3\text{CN}$  and  $\text{HC}^{13}\text{CCN}$  lines. The red and blue plots represent data points of the central and molecular regions, respectively. The square and diamond signs indicate the  $^{13}\text{CH}_3\text{CN}$  and  $\text{HC}^{13}\text{CCN}$  data, respectively.

of Figure 4). The line widths at the central region are generally larger than those at the molecular region, and the line widths of the  $\text{HC}^{13}\text{CCN}$  line are comparable to those of  $^{13}\text{CH}_3\text{CN}$ . Thus, we hereafter assume the excitation temperature of  $\text{HC}^{13}\text{CCN}$  is the same as the  $^{13}\text{CH}_3\text{CN}$ 's rotational temperature.

We derived the column densities of  $\text{HC}^{13}\text{CCN}$  at the two positions assuming the LTE condition (Goldsmith & Langer 1999). We used the following formulae;

$$\tau = -\ln \left[ 1 - \frac{T_{\text{B}}}{J(T_{\text{ex}}) - J(T_{\text{bg}})} \right], \quad (3)$$

where

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

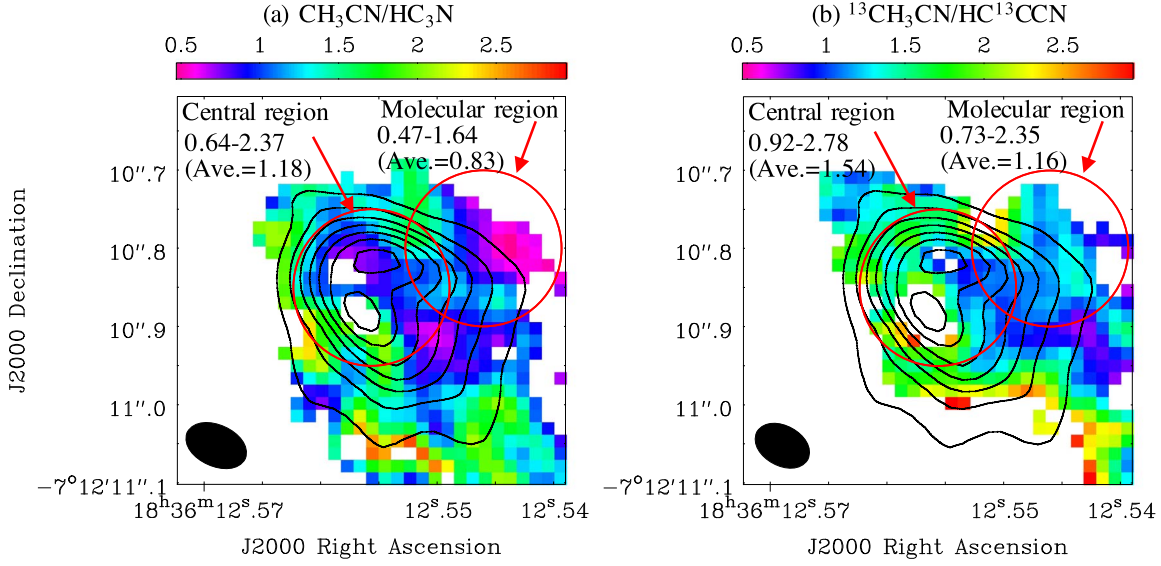
and

$$N = \tau \frac{3h\Delta\nu}{8\pi^3} \sqrt{\frac{\pi}{4\ln 2}} Q(T_{\text{ex}}) \frac{1}{\mu^2} \frac{1}{J_{\text{lower}} + 1} \times \exp\left(\frac{E_{\text{lower}}}{kT_{\text{ex}}}\right) \left\{ 1 - \exp\left(-\frac{h\nu}{kT_{\text{ex}}}\right) \right\}^{-1}. \quad (5)$$

In Equation (3),  $\tau$  denotes the optical depth, and  $T_{\text{B}}$  the peak intensities summarized in Table 2.  $T_{\text{ex}}$  and  $T_{\text{bg}}$  are the excitation temperature and the cosmic microwave background temperature (2.73 K). We calculated three cases of excitation temperatures ( $T_{\text{ex}}$ ,  $T_{\text{ex}} \pm T_{\text{ex}}(\text{error})$ ) for each position.  $J(T)$  in Equation (4) is the effective temperature equivalent to that in the Rayleigh-Jeans law. In Equation (5),  $N$  is the column density,  $\Delta\nu$  is the line width,  $Q(T_{\text{ex}})$  is the partition function at  $T_{\text{ex}}$ ,  $\mu$  is the permanent electric dipole moment, and  $E_{\text{lower}}$  is the energy of the lower rotational energy level. The electric dipole moment of  $\text{HC}^{13}\text{CCN}$  is 3.732 Debye (CDMS database; Müller et al. 2005).

Table 3 summarizes the derived column densities of  $\text{HC}^{13}\text{CCN}$  and the peak optical depth ( $\tau$ ) at each position. We confirmed that the  $\text{HC}^{13}\text{CCN}$  line is optically thin. The derived column densities at the molecular region are slightly higher than those at the central region, as in the case of  $^{13}\text{CH}_3\text{CN}$  (see Figure 4).





**Figure 7.** Maps of the moment 0 ratios between (a)  $\text{CH}_3\text{CN}$  ( $v_8 = 1$ ,  $J_{K,l} = 12_{6,1} - 11_{6,1}$ ) and  $\text{HC}_3\text{N}$  ( $v_7 = 2$ ,  $J = 24 - 23$ ,  $l = 2e$ ) (panels (d) and (c) of Figure 1, respectively) and (b)  $^{13}\text{CH}_3\text{CN}$  ( $J_K = 13_3 - 12_3$ ) and  $\text{HC}^{13}\text{CCN}$  ( $J = 26 - 25$ ) (panels (c) and (a) of Figure 10, respectively) toward G24. The red circles represent the central and molecular regions. The indicated values are minimum, maximum, and average values in each region. The average values are calculated based on the total fluxes in each moment 0 map. The black contours indicate the continuum emission from  $20\sigma$  to  $80\sigma$ .

**Table 3**  
Column Density and Optical Depth of  $\text{HC}^{13}\text{CCN}$

Central Region			Molecular Region		
$T_{\text{ex}}$ (K) <sup>a</sup>	$N$ ( $\text{cm}^{-2}$ )	$\tau$	$T_{\text{ex}}$ (K) <sup>a</sup>	$N$ ( $\text{cm}^{-2}$ )	$\tau$
334	$(1.08 \pm 0.08) \times 10^{15}$	0.107	334	$(1.48 \pm 0.12) \times 10^{15}$	0.195
244	$(9.4 \pm 0.7) \times 10^{14}$	0.151	258	$(1.36 \pm 0.11) \times 10^{15}$	0.262
414	$(1.20 \pm 0.09) \times 10^{15}$	0.086	473	$(1.78 \pm 0.14) \times 10^{15}$	0.133

**Notes.** Errors indicate the standard deviation.

<sup>a</sup> Excitation temperatures ( $T_{\text{ex}}$ ) are taken from the results of  $^{13}\text{CH}_3\text{CN}$ .

### 3.3.2. The $\text{CH}_3\text{CN}/\text{HC}_3\text{N}$ Abundance Ratios in G24

The  $N(^{13}\text{CH}_3\text{CN})/N(\text{HC}^{13}\text{CCN})$  ratios are derived to be  $3.47 \pm 0.46$  and  $3.10^{+3.68}_{-1.62}$  at the central and molecular regions, respectively, using the results in Section 3.3.1. If there are no effects of the  $^{13}\text{C}$  isotopic fractionation in each molecule (e.g., Taniguchi et al. 2016, 2017) and the selective photodissociation of  $^{13}\text{CH}_3\text{CN}$  and  $\text{HC}^{13}\text{CCN}$ , the  $N(^{13}\text{CH}_3\text{CN})/N(\text{HC}^{13}\text{CCN})$  ratio reflects the  $\text{CH}_3\text{CN}/\text{HC}_3\text{N}$  abundance ratio. In the case of G24 with the strong UV radiation field, it is likely that the effect of the  $^{13}\text{C}$  isotopic fractionation of  $\text{HC}_3\text{N}$  is negligible (Taniguchi et al. 2019a, 2021a).

In order to confirm the  $\text{CH}_3\text{CN}/\text{HC}_3\text{N}$  abundance ratios around G24, we investigated the  $\text{CH}_3\text{CN}/\text{HC}_3\text{N}$  ratios using the moment 0 maps of their vibrationally excited lines. These lines have similar upper-state energies ( $\sim 770$  K, Table 1). In addition, the estimated gas density traced by the  $\text{CH}_3\text{CN}$  ( $v_8 = 1$ ) lines is around  $10^9 \text{ cm}^{-3}$  (Moscadelli et al. 2021), and the critical density of the  $\text{HC}_3\text{N}$  ( $v_7 = 2$ ) lines is  $\geq 4 \times 10^8 \text{ cm}^{-3}$  (Wyrowski et al. 1999). Hence, these vibrationally excited lines of  $\text{CH}_3\text{CN}$  and  $\text{HC}_3\text{N}$  likely trace similar regions around G24, and their excitation conditions are expected to be equivalent. If these lines are optically thin, this integrated-intensity ratio would be comparable to their abundance ratio. Panel (a) of Figure 7 shows the map of the ratio between the  $\text{CH}_3\text{CN}$

moment 0 map (panel (d) of Figure 1) and that of  $\text{HC}_3\text{N}$  (panel (c) of Figure 1) toward G24. We included only pixels with above  $3\sigma$  detection of both species. We also show the same map but between the  $^{13}\text{CH}_3\text{CN}$  ( $J_K = 13_3 - 12_3$ ) and  $\text{HC}^{13}\text{CCN}$  ( $J = 26 - 25$ ) lines (panels (c) and (a) of Figure 10, respectively), in order to cross check the results. We used the  $^{13}\text{CH}_3\text{CN}$  ( $J_K = 13_3 - 12_3$ ) line, because it has the closest upper-state energy to the  $\text{HC}^{13}\text{CCN}$  ( $J = 26 - 25$ ) line (see Table 1).

The  $\text{CH}_3\text{CN}/\text{HC}_3\text{N}$  ratios including their  $^{13}\text{C}$  isotopologues cannot be derived near the continuum peak due to the below  $3\sigma$  detection of  $\text{HC}_3\text{N}$ , which could indicate the efficient  $\text{HC}_3\text{N}$  destruction at the central region. In panel (a), the  $\text{CH}_3\text{CN}/\text{HC}_3\text{N}$  ratio shows lower values in the molecular region ( $\approx 0.5$ – $1.6$ , the average value is 0.83) compared to those in the central region ( $\approx 0.6$ – $2.4$ , the average value is 1.18). This marginal difference in the  $\text{CH}_3\text{CN}/\text{HC}_3\text{N}$  ratio between the two regions suggests that the UV photodissociation and/or reactions with ions increase the  $\text{CH}_3\text{CN}/\text{HC}_3\text{N}$  abundance ratio in the region irradiated by the strong UV radiation. This can be caused by the following two reasons;

1.  $\text{HC}_3\text{N}$  could be more efficiently destroyed at the central region, because the UV photodissociation rate of  $\text{HC}_3\text{N}$  is

higher than that of  $\text{CH}_3\text{CN}$  by a factor of  $\sim 2.4$  (Table 2 in Le Gal et al. 2019).

2.  $\text{HC}_3\text{N}$  is destroyed by reactions with ions ( $\text{H}^+$ ,  $\text{H}_3^+$ ,  $\text{HCO}^+$ ), which should be abundant in ionized regions (Taniguchi et al. 2019a).

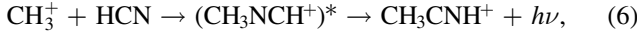
The  $^{13}\text{CH}_3\text{CN}/\text{HC}^{13}\text{CCN}$  ratios are derived to be  $\approx 0.9$ – $2.8$  (the average value is 1.54) and  $\approx 0.7$ – $2.4$  (the average value is 1.16) at the central and molecular regions, respectively (panel (b) of Figure 7). The  $^{13}\text{CH}_3\text{CN}/\text{HC}^{13}\text{CCN}$  ratio at the molecular region is lower than that at the central region, as seen in panel (a), and this tendency is also consistent with the  $N(^{13}\text{CH}_3\text{CN})/N(\text{HC}^{13}\text{CCN})$  ratios.

We adopt the  $N(^{13}\text{CH}_3\text{CN})/N(\text{HC}^{13}\text{CCN})$  column density ratio as representative values in G24 in the following section, because the  $\text{CH}_3\text{CN}/\text{HC}_3\text{N}$  ratio based on the moment 0 maps may be affected by the effect of the optically thickness.

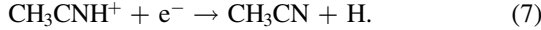
### 3.3.3. Comparisons of the $\text{CH}_3\text{CN}/\text{HC}_3\text{N}$ Abundance Ratios Among the High- and Lower-mass Protostellar Disks

We compare the  $\text{CH}_3\text{CN}/\text{HC}_3\text{N}$  abundance ratios in the disk structure of G24 to those in disks around lower-mass stars, i.e., Herbig Ae stars and T Tauri stars, and investigate chemical properties of the molecular disk around G24.

In disks around lower-mass stars, a main formation mechanism of  $\text{CH}_3\text{CN}$  is considered to be dust-surface reactions (Bergner et al. 2018; Loomis et al. 2018); (1) the successive hydrogenation reaction of  $\text{C}_2\text{N}$  and (2) a radical–radical reaction between  $\text{CH}_3$  and  $\text{CN}$ . Gas-phase routes have been also investigated (Bergner et al. 2018; Loomis et al. 2018):

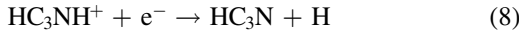


followed by

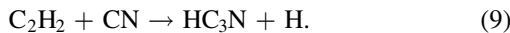


However, Loomis et al. (2018) concluded that the dust-surface routes are more efficient than the gas-phase ones. The  $\text{CH}_3\text{CN}$  formed on dust surfaces sublimates into the gas phase by thermal desorption or photoevaporation. As the excitation temperatures of  $\text{CH}_3\text{CN}$  are lower than its sublimation temperature in disks around lower-mass stars, the primary path would be photoevaporation in such disks.

On the other hand, for  $\text{HC}_3\text{N}$ , only gas-phase formation routes are known, including the ion–molecule reactions and the neutral–neutral reactions (Loomis et al. 2018; Le Gal et al. 2019). For example, the following reactions are considered to contribute to the  $\text{HC}_3\text{N}$  formation:

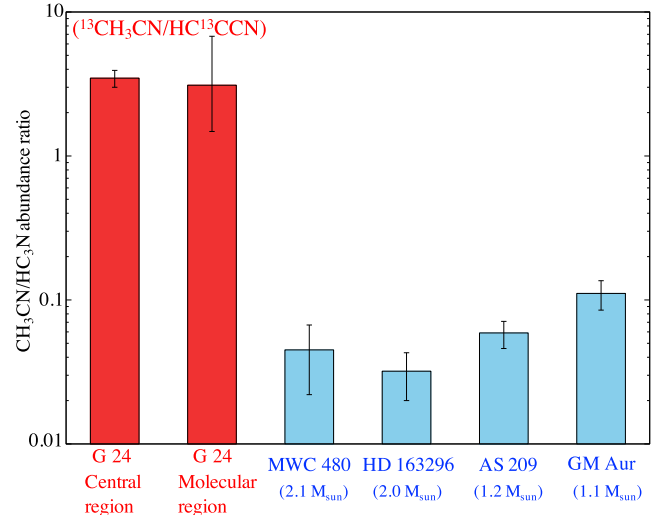
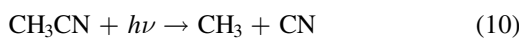


or



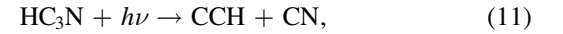
The  $\text{HC}_3\text{NH}^+$  ion is formed by various ion–molecule reactions (e.g.,  $\text{C}_2\text{H}_2^+ + \text{HCN}$ ,  $\text{C}_3\text{H}_n^+ + \text{N}$  ( $n = 3, 4, 5$ ); Taniguchi et al. 2016, 2017).

Both  $\text{CH}_3\text{CN}$  and  $\text{HC}_3\text{N}$  are destroyed by the UV photodissociation:



**Figure 8.** Comparisons of the  $\text{CH}_3\text{CN}/\text{HC}_3\text{N}$  abundance ratio among disks with different stellar masses. Values except for G24 are taken from Ilee et al. (2021). The stellar masses of Herbig Ae and T Tauri stars are taken from Öberg et al. (2021).

and

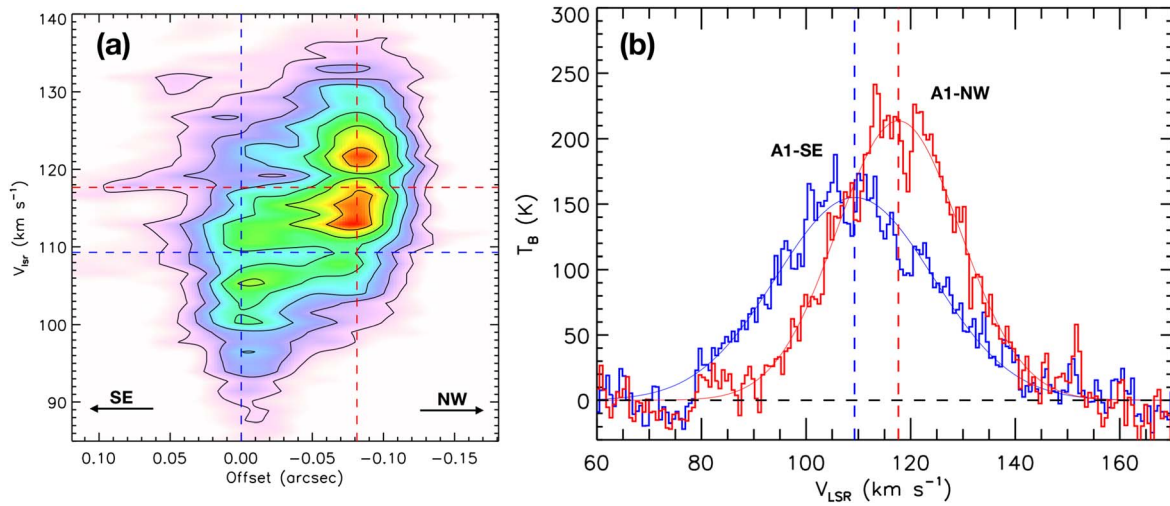


respectively.  $\text{HC}_3\text{N}$  is also destroyed by ions, such as  $\text{H}^+$ ,  $\text{H}_3^+$ ,  $\text{HCO}^+$ , in higher  $A_v$  regimes ( $A_v \geq 4$  mag; Le Gal et al. 2019). The reaction with  $\text{C}^+$  could destroy  $\text{CH}_3\text{CN}$  (Loomis et al. 2018), but its contribution is not dominant in the chemical network simulation conducted by Le Gal et al. (2019).

Figure 8 shows comparisons of the  $\text{CH}_3\text{CN}/\text{HC}_3\text{N}$  abundance ratio among protostellar disks with different stellar masses. The abundance ratios in Herbig Ae and T Tauri stars are taken from Ilee et al. (2021). MWC 480 and HD 163296 are Herbig Ae stars, and AS 209 and GM Aur are T Tauri stars, respectively. The derived  $N(^{13}\text{CH}_3\text{CN})/N(\text{HC}^{13}\text{CCN})$  ratios around G24 ( $\sim 3.0$ – $3.5$ ) are higher than the  $\text{CH}_3\text{CN}/\text{HC}_3\text{N}$  abundance ratios in the other disks ( $\sim 0.03$ – $0.11$ ) by more than 1 order of magnitude. As discussed in Section 3.3.2, there are differences in the  $\text{CH}_3\text{CN}/\text{HC}_3\text{N}$  ratio around the G24 HC H II region by a factor of a few among different methods, but the  $\text{CH}_3\text{CN}/\text{HC}_3\text{N}$  ratios around G24 are clearly higher than those in the disks around the lower-mass stars.

One possible explanation for the high  $\text{CH}_3\text{CN}/\text{HC}_3\text{N}$  abundance ratio around G24 is that the thermal sublimation mechanism enhances the gas-phase  $\text{CH}_3\text{CN}$  abundance around the massive star, while the photoevaporation is important for sublimation of  $\text{CH}_3\text{CN}$  in the other disks. In addition,  $\text{HC}_3\text{N}$  could be more efficiently destroyed around the massive star, because of the higher UV photodissociation rate of  $\text{HC}_3\text{N}$  than that of  $\text{CH}_3\text{CN}$ , as we have already discussed in Section 3.3.2.  $\text{HC}_3\text{N}$  is also destroyed by reactions with ions ( $\text{H}^+$ ,  $\text{H}_3^+$ ,  $\text{HCO}^+$ ), which should be abundant in ionized regions.

We also compare the  $\text{CH}_3\text{CN}/\text{HC}_3\text{N}$  ratios around G24 to that of the Orion Hot Core (i.e., envelope scale; Crockett et al. 2014). The Orion Hot Core is associated with Source I, and its mass was estimated to be around  $15 M_{\odot}$  (Bally et al. 2020). In addition, the disk structure has been detected around this source (Wright et al. 2020). Thus, it seems to be a good source to compare the chemical composition to G24. The  $\text{CH}_3\text{CN}$  and  $\text{HC}_3\text{N}$  abundances with respect to  $\text{H}_2$  at the Orion Hot Core



**Figure 9.** (a) Position–velocity diagram of the H30 $\alpha$  emission along a strip connecting the two continuum peaks with a width of  $0''.01$ . The dashed lines in blue and red colors mark the locations and center velocities of the southeast peak and the northwest peak, respectively. (b) H30 $\alpha$  spectra at the two continuum peak positions (blue: southeast peak, named as A1-SE; red: northwest peak, named as A1-NW). The solid thin lines show the Gaussian fitting to the spectra, with the central velocities marked by the vertical dashed lines ( $v_{\text{center}} = 109.3 \pm 0.3 \text{ km s}^{-1}$  for A1-SE and  $v_{\text{center}} = 117.7 \pm 0.2 \text{ km s}^{-1}$  for A1-NW).

were derived to be  $3.0 \times 10^{-8}$  and  $8.1 \times 10^{-9}$ , respectively ( $N(\text{H}_2) = 3.1 \times 10^{23} \text{ cm}^{-2}$ ; Crockett et al. 2014). Hence, the  $\text{CH}_3\text{CN}/\text{HC}_3\text{N}$  abundance ratio is calculated at 3.7. This value is comparable to the  $\text{CH}_3\text{CN}/\text{HC}_3\text{N}$  ratios around G24 ( $\sim 3.0$ – $3.5$ ). The similar  $\text{CH}_3\text{CN}/\text{HC}_3\text{N}$  ratios between the central and molecular regions in G24, and between G24 and the Orion Hot Core imply the following two possibilities:

1. The disk chemistry may be inherited from the envelope.
2. The chemical processes at the envelope scale may be similar to those at the disk scale due to the powerful central source.

Here, we demonstrate the possibility of the different nitrile chemistry between massive stars and lower-mass stars, i.e., Herbig Ae and T Tauri stars. However, we have data of both  $\text{CH}_3\text{CN}$  and  $\text{HC}_3\text{N}$  toward only one massive star. In order to confirm the nitrile chemistry in disk structures around massive stars, we need to increase source samples. Future observations covering several lines, which enable us to derive accurate column densities and excitation temperatures of  $\text{CH}_3\text{CN}$  and  $\text{HC}_3\text{N}$ , are necessary to understand the disk chemistry around massive stars. These observations will help us to reveal the massive star formation processes.

### 3.4. The Possibility of a Binary System

As shown in panel (a) of Figure 1, the two peaks with the separation of  $\sim 0''.1$  are detected in the 1.38 mm continuum emission. Panel (a) of Figure 9 shows the  $P$ – $V$  diagram of the H30 $\alpha$  emission along a direction connecting the two continuum peaks ( $\text{PA} = -31^\circ$ ). It clearly shows that the H30 $\alpha$  emission associated with the southeast peak is blueshifted by  $\sim 10 \text{ km s}^{-1}$  from the northwest peak.

Moscadelli et al. (2021) interpreted this velocity gradient as the ionized disk rotation around a massive protostar. Assuming an edge-on orientation, they derived the dynamical mass of  $\sim 17 M_\odot$ , which should be the minimum mass considering the possible inclination. Consistent with this dynamical mass evaluation, Cesaroni et al. (2019) suggested an O9.5 star based on the derived Lyman continuum rate of  $5.3 \times 10^{47} \text{ s}^{-1}$ . We also constructed the spectral energy distribution (SED) toward

**Table 4**  
Background-subtracted Flux Densities Derived at Each Wavelength for the SED Plot

Wavelength ( $\mu\text{m}$ )	Flux Density (Jy)
Spitzer	
3.6	0.02 (0.13)
4.5	0.20 (0.33)
8.0	0.58 (4.13)
24.0	6.81 (12.00)
WISE	
3.4	0.01 (0.08)
4.6	0.27 (0.43)
11.5	0.49 (5.31)
22.0	6.92 (30.06)
Herschel	
70.0	1352.47 (1539.58)
160.0	2046.43 (2487.86)
500.0	43.32 (86.73)

**Note.** The values in parenthesis are fluxes without the continuum subtraction. The photometric aperture radius was fixed at  $16''$ , which was based on the  $70 \mu\text{m}$  Herschel image.

this source to retrieve the stellar mass and other physical properties, using infrared data from Spitzer, Wide-field Infrared Survey Explorer (WISE), and Herschel (Table 4 in Appendix C) and fitting the SED with the Zhang & Tan (2018) model (see Appendix C for the details). The best models of the SED fitting suggested the stellar masses of  $16$ – $24 M_\odot$  with the bolometric luminosities of a few times  $10^5 L_\odot$  (see Figure 13 and Table 5 in Appendix C), which is also consistent with the dynamical mass estimation with the Keplerian disk by Moscadelli et al. (2021). The agreement of the independent analyses supports the presence of a  $\sim 20 M_\odot$  star with the ionized-gas disk in the center of the G24 HC H II region.

However, this ionized disk scenario does not explain the presence of the two continuum peaks well. An alternative interpretation would be that the kinematic structure of H30 $\alpha$  consists of two ionized disks associated with two massive

**Table 5**  
Parameters of the Five Best-fitted Models

$\chi^2$	$M_c$ ( $M_\odot$ )	$\Sigma_{\text{cl}}$ ( $\text{g cm}^{-2}$ )	$R_c$ (pc)	$m_*$ ( $M_\odot$ )	$\theta_{\text{view}}$ ( $^\circ$ )	$A_V$ (mag)	$M_{\text{env}}$ ( $M_\odot$ )	$\theta_{\text{w,esc}}$ ( $^\circ$ )	$\dot{M}_{\text{disk}}$ ( $M_\odot \text{ yr}^{-1}$ )	$L_{\text{bol,iso}}$ ( $L_\odot$ )	$L_{\text{bol}}$ ( $L_\odot$ )
1.11	480	3.160	0.09	24	13	361.92	440.54	12	$2.0 \times 10^{-3}$	$1.1 \times 10^6$	$2.9 \times 10^5$
1.38	400	3.160	0.08	24	13	350.15	361.65	13	$1.9 \times 10^{-3}$	$1.3 \times 10^6$	$3.0 \times 10^5$
1.93	320	3.160	0.07	24	13	325.19	276.82	15	$1.8 \times 10^{-3}$	$1.8 \times 10^6$	$3.1 \times 10^5$
2.37	400	3.160	0.08	16	62	0.00	368.90	10	$1.5 \times 10^{-3}$	$8.8 \times 10^4$	$1.0 \times 10^5$
2.72	480	1.000	0.16	24	22	217.99	433.43	15	$8.2 \times 10^{-4}$	$1.9 \times 10^5$	$2.1 \times 10^5$

young stars orbiting around each other, i.e., a binary system. In fact, instead of one single velocity gradient across  $\sim 0''.1$ , the  $P$ - $V$  diagram appears to be more consistent with two separate components with the velocity offset (i.e., the orbital motion), each of which has its own velocity gradient (i.e., the rotation of each disk). It is worth briefly discussing the possibility of the binary system in G24, considering its asymmetric structures and the high binary rate of massive stars.

We can derive the total mass of the binary system assuming that the protostars locate at the continuum peaks and their velocity offset is due to the orbital motion. The peak separation is  $0''.08$  or  $\Delta S \simeq 540$  au, which is a project separation. We estimate their velocity offset as  $\Delta V \simeq 8.4 \text{ km s}^{-1}$  from the  $\text{H}30\alpha$  spectra at the peak locations (panel (b) of Figure 9). Considering a circular Kepler orbit, we derive the total dynamical mass as  $M_{\text{tot}} = \Delta V^2 \Delta S / G \simeq 43 M_\odot$ , where  $G$  is the gravitational constant. This formula is different from that in the disk scenario by a factor of 8, i.e.,  $M_c = \Delta V^2 \Delta S / (8G)$  (where  $M_c$  is the stellar mass at the disk center; see Section 4.1 of Moscadelli et al. 2021), because  $\Delta S$  represents the separation of the two sources while it is the diameter of the ionized disk in the disk scenario. Since free-free and  $\text{H}30\alpha$  emissions trace the surrounding ionized gas rather than the protostar itself, the actual positions of the protostars might be slightly off the continuum emission peaks. Considering such  $\Delta S$  uncertainty of  $\sim 100$  au (or  $0''.015$ ) and the  $\Delta V$  fitting error of  $0.36 \text{ km s}^{-1}$ , we estimate that the mass range of  $M_{\text{tot}} \simeq 34\text{--}51 M_\odot$  is consistent with the binary scenario. We note that the circular orbit perpendicular to the plane of sky are assumed here, and thus we consider those as the minimum masses.

The total values of the Lyman continuum rate and the infrared luminosity can also provide constraints on the stellar masses of the binary. Moscadelli et al. (2018) and Cesaroni et al. (2019) estimated a total Lyman continuum rate of  $(5.3\text{--}7.2) \times 10^{47} \text{ s}^{-1}$  by fitting the radio to millimeter SED. As the two peaks have similar brightness in the continuum and  $\text{H}30\alpha$  total emissions, the two massive stars in the binary should have similar masses, and therefore similar Lyman continuum rate of  $\sim 3 \times 10^{47} \text{ s}^{-1}$ . Such a Lyman continuum rate corresponds to a zero-age main-sequence (ZAMS) mass of  $18 M_\odot$ , making a total mass of  $36 M_\odot$  for the binary, which is close to the minimum dynamical mass estimated above. If the binary stars have not reached the ZAMS phase, their masses can be higher because their Lyman continuum rate would be lower than those in the ZAMS phase at the same masses (e.g., Tanaka et al. 2016). As discussed in Appendix C, we conducted the infrared SED fitting. The mass estimation from this fitting is not applicable for the binary system because it assumed a single-star system. However, the obtained total bolometric luminosity of a few  $\times 10^5 L_\odot$  is reasonable even for

the multiple-source system (Table 5). Considering the proto-stellar evolution, the luminosity of a massive protostar with  $\sim 15\text{--}20 M_\odot$  would be as bright as  $10^5 L_\odot$  (e.g., Zhang & Tan 2018), which is again consistent with the estimation of the dynamical mass.

The systemic velocity of G24 measured from the outer molecular emissions is  $\sim 112 \text{ km s}^{-1}$ . If we assume that the line-of-sight velocity of the mass center of the binary is  $112 \text{ km s}^{-1}$ , the mass ratio between the primary and secondary would be about 2:1 from the central velocity of each continuum peak. Considering the dynamical mass of  $>37 M_\odot$ , we evaluate  $\gtrsim 24 M_\odot$  for A1-SE and  $\gtrsim 12 M_\odot$  for A1-NW. However, such analysis is susceptible to the determination of the line center velocities of  $\text{H}30\alpha$ , which have FWHMs of  $30\text{--}35 \text{ km s}^{-1}$ , as well as the binary system velocity. Therefore, it is still difficult to accurately determine the masses of the individual stars via dynamics.

We note that the binary scenario does not necessarily contradict the other features of G24. In the case of the binary star scenario, the rotating structure traced by  $\text{CH}_3\text{CN}$  and  $\text{HC}_3\text{N}$  is a circumbinary disk surrounding the two massive stars. The  $P$ - $V$  diagrams of the molecular lines are roughly consistent with the Keplerian rotation with  $\sim 20 M_\odot$ , but the disk is assumed to be perpendicular to the sky in these diagrams (Figure 3; Figure 4 of Moscadelli et al. 2021). Hence, the value of  $20 M_\odot$  is the minimum enclosed mass, and the total dynamical mass of  $>37 M_\odot$  from the  $\text{H}30\alpha$  emission is acceptable. The presence of a single jet perpendicular to the molecular disk reported by Moscadelli et al. (2018, 2021) does not exclude the binary scenario. For example, in the forming massive binary system IRAS 16547–4247, one of the binary stars launches a single jet nearly perpendicular to the circumbinary disk, while the other star shows no jet feature, despite both protostars show almost the same levels of continuum and line emissions (Tanaka et al. 2020). If this is also happening in G24, one star may be supplied with more material from the circumstellar disk. Such an asymmetric infalling structure at  $<1000$  au could cause the asymmetric UV field suggested in the larger scale.

Similar to the binary scenario for G24, Zhang et al. (2019b) reported a forming massive binary IRAS 07299–1651 with each member traced by hydrogen recombination lines showing velocity offset caused by orbital motion. In IRAS 07299–1651, the line emissions from the two stars are well separated that allows analyzing the circumstellar disk rotation of the primary star. However, in G24, the  $\text{H}30\alpha$  emissions from the continuum peaks have already spread out and merged together, making it difficult to analyze the detailed kinematic structures of the ionized gas, i.e., the circumstellar disks and their circumbinary disk. We speculate that G24 is more massive than IRAS 07299–1651, and thus the ionized gas is more extended.



Therefore, although we suggest the possibility of the binary system in G24, we cannot confirm such a scenario with the current data set. Future higher-angular-resolution observations may help to confirm this point.

#### 4. Conclusions

We have analyzed the ALMA archival data in Band 6 toward the G24 HC H II region. The vibrationally excited lines of HC<sub>3</sub>N ( $\nu_7 = 2$ ,  $J = 24 - 23$ ) have been detected around the G24 HC H II region. The main results and conclusions of this paper are as follows.

1. We have compared the moment 0 map and the  $P$ - $V$  diagram of the HC<sub>3</sub>N ( $\nu_7 = 2$ ,  $J = 24 - 23$ ,  $l = 2e$ ) line and the CH<sub>3</sub>CN ( $\nu_8 = 1$ ,  $J_{K,l} = 12_{6,1} - 11_{6,1}$ ) line. Features in the spatial distributions and the  $P$ - $V$  diagram of HC<sub>3</sub>N are similar to those of CH<sub>3</sub>CN. Thus, the HC<sub>3</sub>N emission is tracing the molecular disk around the G24 HC H II region previously identified by the CH<sub>3</sub>CN lines. These results indicate that the HC<sub>3</sub>N emission can be used as a disk tracer for massive protostars even at the evolutionary stage of the HC H II region.
2. We have derived the column density ratios of  $^{13}\text{CH}_3\text{CN}/\text{HC}^{13}\text{CCN}$  at the two representative regions, the central and molecular regions, which are determined based on the continuum map and the HC<sub>3</sub>N moment 0 map, respectively. The ratios are derived to be  $3.47 \pm 0.46$  and  $3.10^{+3.68}_{-1.62}$  at the central and molecular regions, respectively. We have also derived the integrated-intensity ratios between the CH<sub>3</sub>CN ( $\nu_8 = 1$ ,  $J_{K,l} = 12_{6,1} - 11_{6,1}$ ) and HC<sub>3</sub>N ( $\nu_7 = 2$ ,  $J = 24 - 23$ ,  $l = 2e$ ) lines and between the  $^{13}\text{CH}_3\text{CN}$  ( $J_K = 13_3 - 12_3$ ) and HC<sup>13</sup>CCN ( $J = 26 - 25$ ) lines. All of the CH<sub>3</sub>CN/HC<sub>3</sub>N ratios derived based on integrated intensity and column density show the higher values at the central region than those at the molecular region. These results suggest that HC<sub>3</sub>N is more efficiently destroyed in the region irradiated by the strong UV radiation.
3. We have compared the  $^{13}\text{CH}_3\text{CN}/\text{HC}^{13}\text{CCN}$  abundance ratios around G24 to the CH<sub>3</sub>CN/HC<sub>3</sub>N abundance ratios in the disks around Herbig Ae and T Tauri stars. The abundance ratios around G24 are higher than those in the other disks by more than 1 order of magnitude. The difference between the G24 HC H II region and the other disks is caused by (1) efficient thermal desorption of CH<sub>3</sub>CN in hot and dense region around the G24 HC H II region, and (2) rapid destruction of HC<sub>3</sub>N in the region irradiated by the strong UV radiation around the G24 HC H II region.
4. Based on the two peaks of the free-free emission and their H30 $\alpha$  kinematics in the central ionized region, we briefly discussed the possibility that it is composed of a binary system. We evaluated the total dynamical mass is  $\gtrsim 37 M_\odot$ , which is consistent with the total bolometric luminosity and the Lyman continuum. However, we cannot confirm the binary scenario with the current data set. This is because the H30 $\alpha$  emissions extended from the two continuum peaks merge in the position-velocity

space, which makes the detailed dynamical analysis challenging.

We have shown that HC<sub>3</sub>N can be used as a disk tracer even for massive protostars. The nitrile species, CH<sub>3</sub>CN and HC<sub>3</sub>N, are mainly formed by different formation processes (dust-surface reactions versus gas-phase reactions), and thus, the CH<sub>3</sub>CN/HC<sub>3</sub>N abundance ratio will be able to become a useful tracer for physical structures of disks around massive protostars. We need to increase source samples of massive stars as well as lower-mass stars, in order to understand the nitrile chemistry and the connection between physics and chemistry in disk structures.

This paper makes use of the following ALMA data: ADS/JAO.ALMA#2018.1.00745.S. ALMA is a partnership of ESO (representing its member states), NSF (USA), and NINS (Japan), together with NRC (Canada), MOST, and ASIAA (Taiwan), and KASI (Republic of Korea), in cooperation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI/NRAO, and NAOJ. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. Data analysis was in part carried out on the Multiwavelength Data Analysis System operated by the Astronomy Data Center (ADC), National Astronomical Observatory of Japan. We thank the anonymous referee whose valuable comments helped improve the paper.

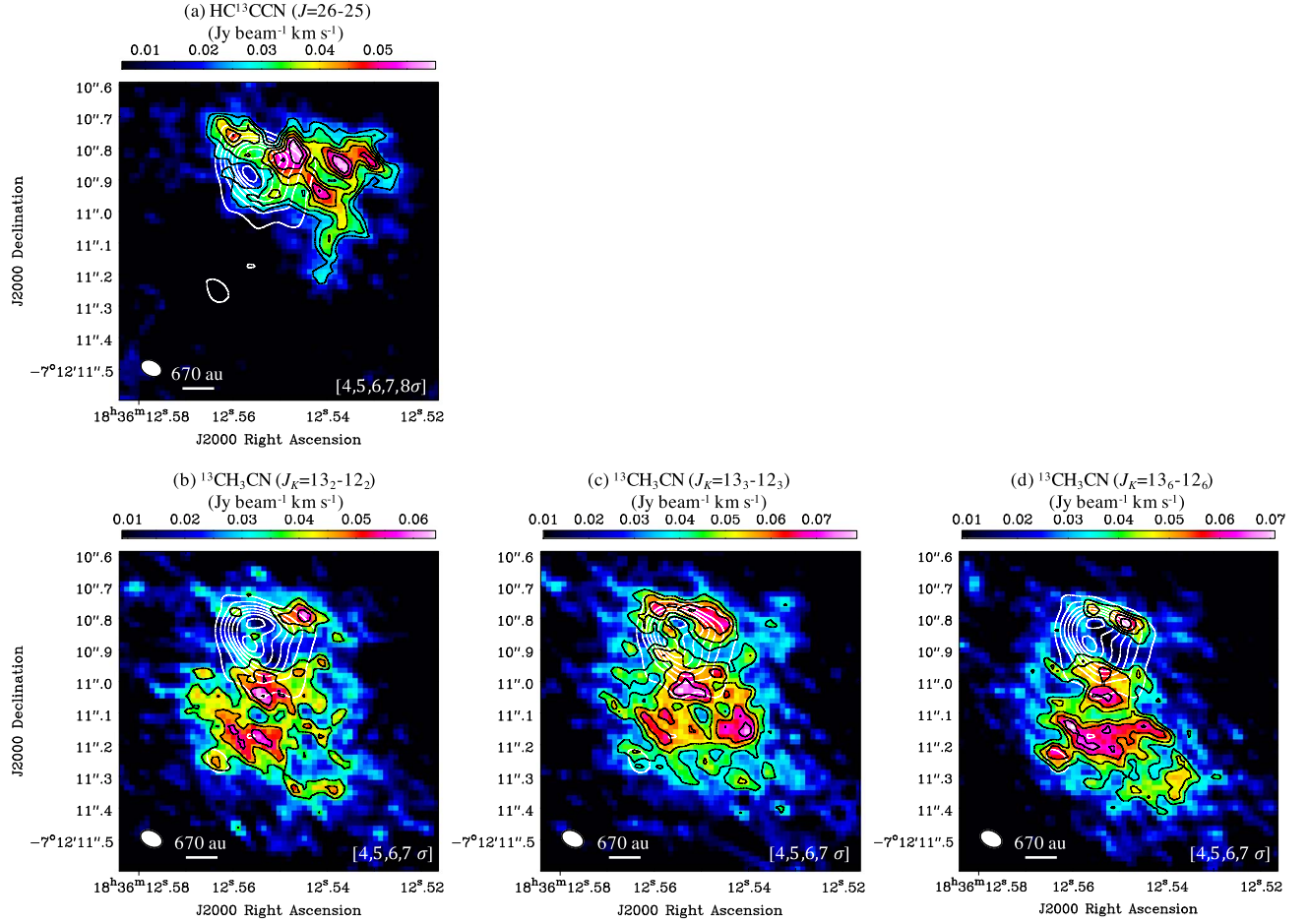
K.T. appreciates the support by JSPS KAKENHI grant No. JP20K14523. K.T. thanks Dr. Yusuke Miyamoto (East Asian ALMA Regional Center/National Astronomical Observatory of Japan) for his kind support for our data reduction at the ADC. K.E.I.T. acknowledges the support by JSPS KAKENHI grant Nos. JP19K14760, JP19H05080, JP21H00058, and JP21H01145. R.F. acknowledges funding from the European Union's Horizon 2020 research and innovation program under the Marie Skłodowska-Curie grant agreement No. 101032092. J.C.T. acknowledges support from ERC project MSTAR and VR grant 2017-04522. S.T. is supported by JSPS KAKENHI grant Nos. JP21H00048 and JP21H04495. L.M. acknowledges the financial support of DAE and DST-SERB research grants (SRG/2021/002116 and MTR/2021/000864) of the Government of India.

*Facility:* Atacama Large Millimeter/submillimeter Array (ALMA).

*Software:* Common Astronomy Software Applications package (CASA; McMullin et al. 2007), Astropy (Astropy Collaboration et al. 2013, 2018); this research made use of Photutils, version 1.0.0, an Astropy package for detection and photometry of astronomical sources (Bradley et al. 2020).

#### Appendix A Moment 0 Maps of the $^{13}\text{C}$ Isotopologues

Figure 10 shows moment 0 maps of HC<sup>13</sup>CCN and  $^{13}\text{CH}_3\text{CN}$  toward the G24 HC H II region. We only show three lines of  $^{13}\text{CH}_3\text{CN}$  ( $J_K = 13_K - 12_K$ ,  $K = 2, 3, 6$ ), because these lines are not contaminated by other lines.

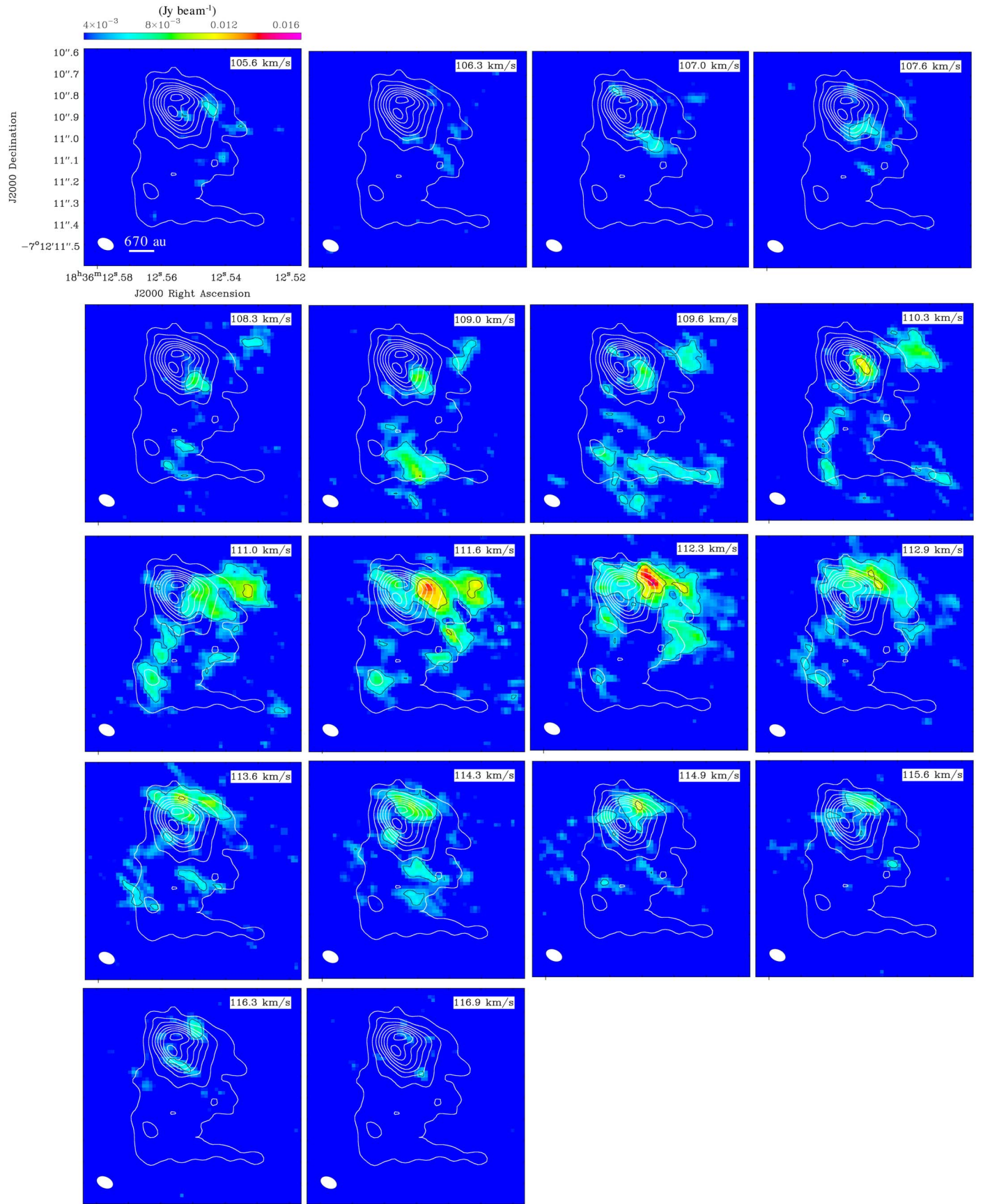


**Figure 10.** Moment 0 images of (a) HC<sup>13</sup>CCN ( $J = 26 - 25$ ), (b) <sup>13</sup>CH<sub>3</sub>CN ( $J_K = 13_2 - 12_2$ ), (c) <sup>13</sup>CH<sub>3</sub>CN ( $J_K = 13_3 - 12_3$ ), and (d) <sup>13</sup>CH<sub>3</sub>CN ( $J_K = 13_6 - 12_6$ ), respectively. The rms noise levels are 7 mJy beam<sup>-1</sup> km s<sup>-1</sup> for panel (a), 9 mJy beam<sup>-1</sup> km s<sup>-1</sup> for panels (b) and (d), and 10 mJy beam<sup>-1</sup> km s<sup>-1</sup> for panel (c), respectively. The black contour levels are indicated in each panel. The white contours indicate the continuum image from 20σ to 80σ, in steps of 10σ. The filled white ellipses indicate angular resolution of 0''.068 × 0''.048 for panel (a), and 0''.074 × 0''.051 for the other panels, respectively. The linear scale is given for 0''.1 corresponding to 670 au.

## Appendix B

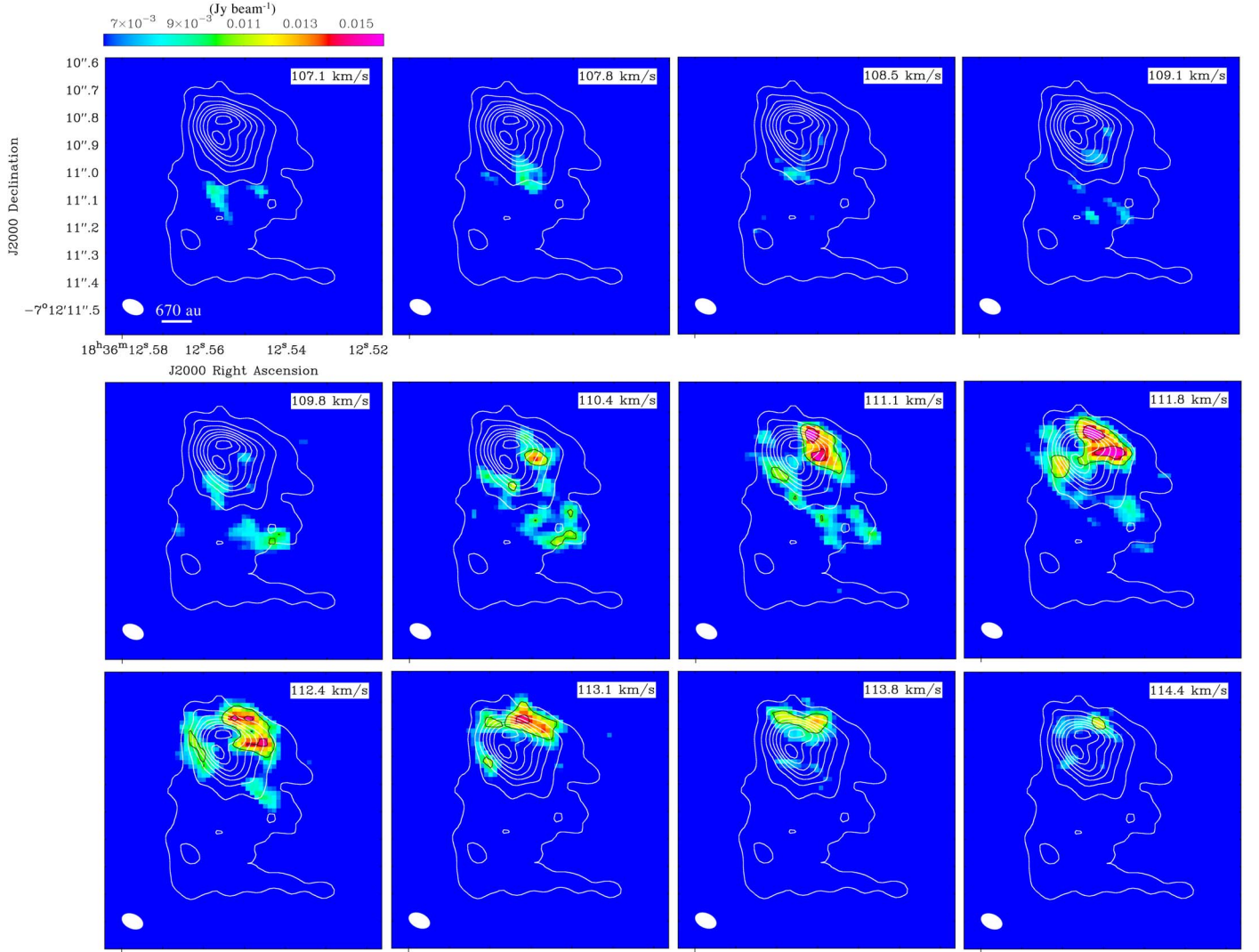
### Channel Maps of the Vibrationally Excited Lines

Figures 11 and 12 show channel maps of the vibrationally excited lines of HC<sub>3</sub>N ( $v_7 = 2$ ,  $J = 24 - 23$ ,  $l = 2e$ ) and CH<sub>3</sub>CN ( $v_8 = 1$ ,  $J_{K,l} = 12_{6,1} - 11_{6,1}$ ), respectively.



**Figure 11.** Channel maps of the  $\text{HC}_3\text{N}$  ( $v_7 = 2$ ,  $J = 24 - 23$ ,  $l = 2e$ ) line ranging from 105.6 to 116.9  $\text{km s}^{-1}$ . The black contours indicate the signal levels from  $5\sigma$  in steps of  $5\sigma$ . The noise level is  $1.1 \text{ mJy beam}^{-1}$ . The white contours indicate the continuum image from  $10\sigma$  to  $80\sigma$ , in steps of  $10\sigma$ . The filled white ellipses indicate angular resolution of  $0''.079 \times 0''.053$ . The linear scale is given for  $0''.1$  corresponding to 670 au.





**Figure 12.** Channel maps of the  $\text{CH}_3\text{CN}$  ( $v_8 = 1$ ,  $J_{K_L} = 12_{6,1} - 11_{6,1}$ ) line ranging from 107.1 to 115.1  $\text{km s}^{-1}$ . The black contours indicate the signal levels from  $5\sigma$  in steps of  $2\sigma$ . The noise level is  $2.0 \text{ mJy beam}^{-1}$ . The white contours indicate the continuum image from  $10\sigma$  to  $80\sigma$ , in steps of  $10\sigma$ . The filled white ellipses indicate angular resolution of  $0''.082 \times 0''.053$ . The linear scale is given for  $0''.1$  corresponding to 670 au.

### Appendix C SED Fitting Toward the G24 HC H II Region

In order to retrieve physical information from the HC H II region, we constructed the SED and subsequently fitted the Zhang & Tan (2018) model grid. We first measured the flux density in Spitzer, WISE, and Herschel data (Table 4). To do this, we performed circular aperture photometry fixing the aperture radius to  $16''$  to all wavelengths, following the fiducial method in De Buizer et al. (2017) and Liu et al. (2019, 2020). The aperture size was chosen to enclose most of the flux in the  $70 \mu\text{m}$  Herschel image and variations of 30% in the aperture radius to larger size did not affect significantly the final flux obtained. The standard method in performing circular aperture photometry also subtracts the background emission that is evaluated in an annulus from one to two aperture radii. The background-subtracted flux densities are reported in the second column of Table 4 and are the ones used in the SED fitting (we also report in the same column the flux densities without background subtraction in parenthesis). Once the fluxes were measured, we fitted to the SED model grid that provides estimates of key protostellar properties. We used the

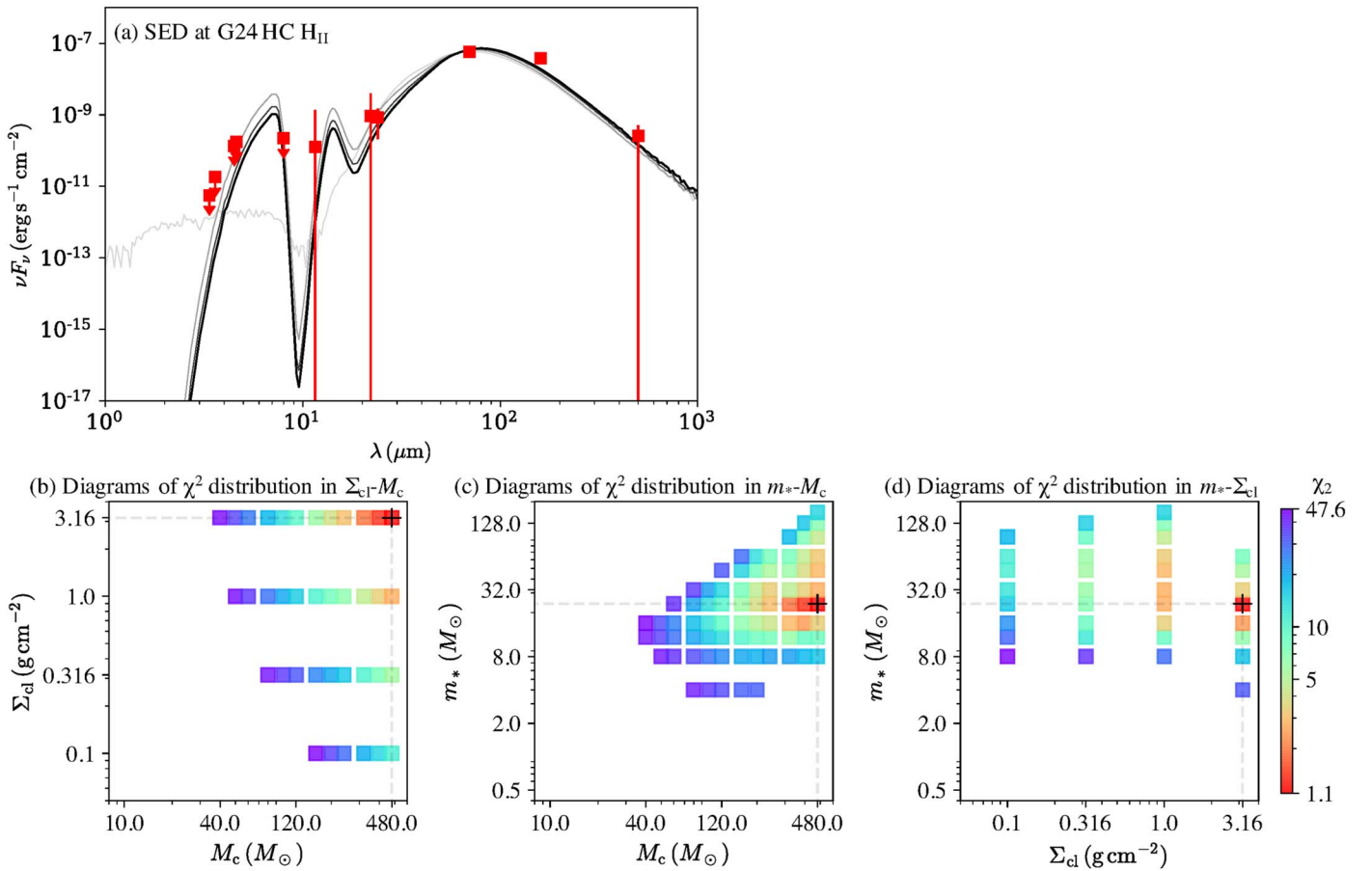
Zhang & Tan (2018) model grid and developed an improved version written in python called *sedcreator*<sup>16</sup> based on the original code written in IDL.<sup>17</sup> The details of this package will be publicly available in a forthcoming paper (R. Fedriani et al. 2022, in preparation). The Zhang & Tan (2018) model grid is based on the assumption that massive stars are formed from massive prestellar cores supported by internal pressure. The model grid self-consistently includes the evolutionary sequences of protostar, disk, envelope, and outflow cavity. The constrained free parameters of the model grid are: initial core mass ( $M_c$ ), environmental clump mass surface density ( $\Sigma_{cl}$ ), current protostellar mass ( $m_*$ ), viewing angle with respect to the outflow axis ( $\theta_{\text{view}}$ ), and amount of foreground extinction ( $A_V$ ).

By minimizing the  $\chi^2$  function defined in Equation (4) of Zhang & Tan (2018) for each physical model, we find that the best five models are consistent with a  $M_c$  ranging from 320 to  $480 M_\odot$ , a  $\Sigma_{cl}$  with  $1.0\text{--}3.16 \text{ g cm}^{-2}$ , and most importantly a current protostellar mass of  $16\text{--}24 M_\odot$  (Table 5). The intrinsic

<sup>16</sup> <https://github.com/fedriani/sedcreator> or <https://pypi.org/project/sedcreator/>.

<sup>17</sup> <https://zenodo.org/record/1134877#.YRJ4ZMza84>





**Figure 13.** (a) SEDs of the five best models with the observations represented as red squares. The best-fit model is shown with a solid black line and the next four best models are shown with solid gray lines. (b)–(d) Diagrams of  $\chi^2$  distribution in  $\Sigma_{\text{cl}}-M_c$  space,  $m_*-M_c$  space, and  $m_*-\Sigma_{\text{cl}}$  space, respectively. The black crosses indicate the locations of the best model.

bolometric luminosity is also a few  $\times 10^5 L_\odot$ , i.e., which is the level associated with such massive protostars. This further supports the findings from the  $P$ – $V$  analysis from the molecular emission. Panel (a) of Figure 13 shows the best five models, with the best model represented with thick black line, and the observations as red squares. The error bars are set to be the larger of either 10% of the clump background-subtracted flux density to account for calibration error, or the value of the estimated clump background flux density. Note that all data points below  $\lambda < 8 \mu\text{m}$  are treated as upper limits (see, e.g., De Buizer et al. 2017). Panels (b)–(d) of Figure 13 show the 2D distribution of the three main physical parameters, i.e.,  $M_c$ ,  $\Sigma_{\text{cl}}$ , and  $m_*$ .

### ORCID iDs

Kotomi Taniguchi <https://orcid.org/0000-0003-4402-6475>  
 Kei E. I. Tanaka <https://orcid.org/0000-0002-6907-0926>  
 Yichen Zhang <https://orcid.org/0000-0001-7511-0034>  
 Rubén Fedriani <https://orcid.org/0000-0003-4040-4934>  
 Jonathan C. Tan <https://orcid.org/0000-0002-3389-9142>  
 Shigehisa Takakuwa <https://orcid.org/0000-0003-0845-128X>  
 Fumitaka Nakamura <https://orcid.org/0000-0001-5431-2294>  
 Masao Saito <https://orcid.org/0000-0003-0769-8627>  
 Liton Majumdar <https://orcid.org/0000-0001-7031-8039>  
 Eric Herbst <https://orcid.org/0000-0002-4649-2536>

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