Gravitionally Unstable Condensations Revealed by ALMA in the TUKH122 Prestellar Core in the Orion A Cloud

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Abstract

We have investigated the TUKH122 prestellar core in the Orion A cloud using ALMA 3 mm dust continuum, N2H+ (J = 1–0), and CH3OH (J_K = 2_K – 1_K) molecular-line observations. Previous studies showed that TUKH122 is likely on the verge of star formation because the turbulence is almost dissipated and chemically evolved among other starless cores in the Orion A cloud. By combining ALMA 12 m and ACA data, we recover extended emission with a resolution of ~5″ corresponding to 0.01 pc and identify six condensations with a mass range of 0.1–0.4M_⊙ and a radius of ≤0.01 pc. These condensations are gravitationally bound following a virial analysis and are embedded in the filament, including the elongated core with a mass of ~29 M_⊙ and a radial density profile of ρ^-1.6 derived by Herschel. The separation of these condensations is ~0.035 pc, consistent with the thermal Jeans length at a density of 4.4 x 10^5 cm^-3. This density is similar to the central part of the core. We also find a tendency for the N2H+ molecule to deplete at the dust peak condensation. This condensation may be beginning to collapse because the line width becomes broader. Therefore, the fragmentation still occurs in the prestellar core by thermal Jeans instability, and multiple stars are formed within the TUKH122 prestellar core. The CH3OH emission shows a large shell-like distribution and surrounds these condensations, suggesting that the CH3OH molecule formed on dust grains is released into the gas phase by nonthermal desorption such as photoevaporation caused by cosmic-ray-induced UV radiation.

Key words: ISM: clouds – ISM: individual objects (Orion Nebula, Orion Molecular Cloud) – ISM: molecules – ISM: structure – stars: formation

1. Introduction

To understand star formation processes, it is of great importance to reveal the initial conditions of star formation. In nearby dark clouds at a distance of ~100 pc, many observations have been performed using molecular lines and continuum emission and identified dense cores (or molecular dense cores) as birthplaces of stars (e.g., Myers & Benson 1983; Benson & Myers 1989; Ward-Thompson et al. 1994; Caselli et al. 2002; Onishi et al. 2002). One of the most important things to understand about dense core properties is the density structure. On the basis of near-infrared observations, Alves et al. (2001) showed that the Bonnor–Ebert sphere model (Ebert 1955; Bonnor 1956) can explain the observed radial column density profile of Barnard 68. Many nearby dense cores have also shown the Bonnor–Ebert structure (Kandori et al. 2005). The Bonnor–Ebert shape consists of a flat central region surrounded by a steeper outer region of ρ ∝ r^-2. Such a simple dense core is suggested to form a single protostar, binary stars, and multiple stars by gravitational collapse (e.g., Matsumoto & Hanawa 2003).

The dense cores may be the most simplified description to determine the star-forming process and are often assumed as the initial conditions for simulations. Therefore, the simple density structure can be applied to these isolated objects, except for multiple-star systems (e.g., Tokuda et al. 2014, 2016; Dunham et al. 2016; Kirk et al. 2017). Recently, Pineda et al. (2010, 2011, 2015) discovered the quiescent thermal dense core B5 in Perseus, showing a quadruple-star system inside the core with the NH3 high-resolution observations. They suggested that the multiple-star system is formed because the coherent core is fragmented into dense filaments with a length of 5000 au. Taking into account these results, the fragmentation in the prestellar stage of dense cores may be needed to be a multiple-star system. Therefore, it is important to reveal the smallest and densest parts of the dense cores where stars are born.

However, the properties of dense cores in various star-forming environments have not been fully explored yet. The majority of stars are thought to be produced through the formation of clusters (Lada & Lada 2003). In particular, giant molecular clouds (GMCs) are well known to be major sites of star formation in our Galaxy and often show star cluster formation, including massive stars. Therefore, it is essential to observe the dense cores embedded in GMCs to reveal the initial conditions of star formation. Furthermore, the observational targets should be dense cores on the verge of star formation.

To search for dense cores with the initial conditions of star formation in GMCs, chemical evolution may be one of the most powerful tools to determine the evolutionary stages of the dense cores. A pioneering study on the chemical evolution in dark clouds was done by Suzuki (1983) and Suzuki et al. (1992). They suggested that carbon-chain molecules such as CCS, HC3N, and HC5N are abundant in dense cores in the early stages of star formation because reactions involving
5. To make high spatial resolution images recovering the fragmented. Tatematsu et al. 2012

stars represent the locations of protostars identified by Spitzer (Megeath et al. 2012).

atomic or ionized carbon are effective in the early stage and easily depleted onto dust in the later stage (Aikawa et al. 2001). They also suggested that the $N$-bearing molecule NH$_3$ is abundant in dense cores in the later stage because the N$_2$ molecule (the precursor to $N$-bearing molecules) is slowly formed. Tatematsu et al. (1993, 2014b) showed that $N$(N$_2$H$^+$/N(CCS) may indicate the chemical evolutionary stage. Similarly, Ohashi et al. (2014) found that the NH$_3$/CCS column density ratio is anticorrelated with the CCS line width and suggested that chemical evolution and turbulence dissipation can be indicators of the dynamical evolution of cores. Therefore, if we can identify dense cores that are rich in $N$-bearing molecules and poor in carbon-chain molecules without protostars, these cores will tell us the initial conditions of star formation.

Based on these studies, such cores are searched for in the Orion A cloud, the Vela C molecular cloud complex, and Planck cold clumps (Ohashi et al. 2014, 2016b; Tatematsu et al. 2014b, 2017). In particular, the Orion A cloud is a good target because it is one of the nearest GMCs to the Earth and has been well studied. Tatematsu et al. (2014b) found a dense core (TUKH122) having the largest value of $N$(N$_2$H$^+$/N(CCS) among the starless dense cores in the Orion A cloud. TUKH122 has $N$(N$_2$H$^+$/N(CCS) $\sim$3 (typical starless dense cores have $\sim$1.5) and is located in the L1641 South region (see Figure 1). TUKH122 could be the dense core closest to star formation in our samples. Note that no IRAC, MIPS, or SDSS sources are detected toward TUKH122 (e.g., Megeath et al. 2012, 2016; Da Rio et al. 2016), suggesting that it is in the prestellar phase.

Detailed observations have been performed toward TUKH122 with the VLA and Nobeyama 45 m telescope. The VLA NH$_3$ observations have identified an oval core with a size of 0.1 pc and condensations with a size of 0.03 pc embedded in the parent CS clump. The line width of NH$_3$ is narrow ($\sim$0.2 km s$^{-1}$), and both the core and condensation are gravitationally bound (Tatematsu et al. 2014a). The single-pointing NH$_3$ observations covering the whole main core with 0.05 km s$^{-1}$ velocity resolution identified not only the thermal narrow component but also a turbulent component, suggesting the sharp transition from the parent clump to the quiescent dense core (Ohashi et al. 2016c). These results suggested that the TUKH122 core is on the verge of star formation and is one of the good targets to investigate the physical conditions and fragmentation process if this core forms multiple stars. However, these observations were not enough to reveal the density distribution or fragmentation due to the resolution and sensitivity.

Recently, the Herschel Space Observatory revealed that filaments are ubiquitous in star-forming clouds and that dense cores are embedded in the filaments (e.g., André et al. 2010; Arzoumanian et al. 2011; Hill et al. 2011). Therefore, TUKH122 is also important to understanding dense core formation in the filaments in GMCs.

In this paper, we report ALMA observations toward TUKH122 at Band 3 with an $\sim$5″ beam. Note that we will follow the nomenclature of Ohashi et al. (2016a) and refer to cores as an entity of 0.01–0.1 pc. We also refer to a dense condensation as an entity of $\lesssim$0.01 pc. The distance of the Orion A cloud is derived to be 418 pc (Kim et al. 2008).

In Section 2, we describe the observations and data reduction. In Section 3, we present and describe the dust continuum data taken by the Herschel, ACA, and ALMA observations, as well as the molecular-line maps of the ACA and ALMA data. In Section 4, we discuss the formation processes of condensations in the core and a possible scenario of multiple-star systems. Our conclusions are summarized in Section 5.

2. Observations

TUKH122 was observed with the ALMA 12 m Array on 2016 March 10–12 in the C36-2/3 configuration with a total of 38 antennas and with the 7 m Array of the Atacama Compact Array (ACA; also known as the Morita Array; Iguchi et al. 2009) on 2016 May 28, August 27, and September 1–7 with a total of 10 antennas (Cycle 3 program, Project ID: 2015.1.01025.S). The number of 12 m pointings for the mosaic mapping was five. The Band 3 receivers were used. The system temperature was in the range of 40–140 K. The correlator was set to have four spectral windows (two windows for continuum, one for N$_2$H$^+$, and one for CH$_3$OH). The velocity resolution of the molecular-line observations was set to $\sim$0.098 km s$^{-1}$. The four quasars (J0423–0120, J0522–3627, J0854+2006, and J0510+1800) were observed for bandpass calibration. The object J0542–0913 was observed for phase calibration. Flux calibration was performed using J0423–0120, J0510+1800, J0522–3627, and Uranus.

The reduction and calibration of the data were done with CASA version 4.5.3 (McMullin et al. 2007) in a standard manner. All images were reconstructed with the CASA task CLEAN using natural weighting. To improve the sensitivity, we also used uv tapering (50 kÅ for the molecular lines and 20 kÅ for the continuum) for CLEAN. The pixel size was set to 0"/5. To make high spatial resolution images recovering the extended emission, we combine the ALMA 12 m and ACA in the uv plane. The resultant spatial resolutions are written in each section. The synthesized beams and the sensitivities of the dust continuum and molecular lines are listed in Table 1.

3. Results

Figure 2 shows the dust continuum maps toward the TUKH122 region at different scales with Herschel and ALMA. The various observations with the different spatial resolutions reveal the different structures from filament to condensation. Figure 2(a) shows the location of TUKH122 on the Herschel 250 µm map (Gould Belt Survey Archive; André...
et al. 2010; Polychroni et al. 2013; Roy et al. 2013) overlaid with ACA 3 mm dust continuum emission contours. We find a filamentary structure along the north–south direction with a length of ~0.6 pc, shown in the green box, which is wider than the ALMA observed field.

Figures 2(b) and (c) show the 3 mm dust continuum images obtained by the ACA 7 m array and ALMA 12 m, respectively. The beam size is $17'' \times 10''$ (P.A. = $-86^\circ$) for ACA and $5''0 \times 4''6$ (P.A. = $-61^\circ$) for ALMA. These images are not corrected by the primary beam pattern to keep the same noise level within the images. The ACA observations show the simple elongated structure (~$0.12 \text{ pc} \times 0.048 \text{ pc}$ in FWHM) toward the TUKH122 region. In the 12 m array data (Figure 2(c)), compact condensations are clearly seen, whereas such components are not spatially resolved in the 7 m array data. The ALMA 12 m observations only reveal the small condensations within the core.

The oval structure of the TUKH122 core was already reported by Tatamatsu et al. (2014a) with VLA NH$_3$ observations. Figure 3 shows the ACA 7 m 3 mm dust continuum image with the VLA NH$_3$ integrated intensity contours. The 3 mm dust continuum emission taken by ACA is extended compared with the VLA NH$_3$ emission, which may be explained by filtering out in the VLA interferometric data. These oval structures are consistent with the typical dense core found in the low-mass star-forming region.

We suggest that the TUKH122 core is embedded in a parent filament having larger-scale emission. However, it is difficult to distinguish the core emission component from the filament. Therefore, the Herschel and ACA observations trace the combination of the filament and core components. Most emission may be from the core because the TUKH122 core has already been formed.

Figure 4 shows the 3 mm dust continuum image obtained by the ALMA-ACA combined data. The contours start at 3$\sigma$ with intervals of 1$\sigma$. The 1$\sigma$ noise level is 40 $\mu$Jy beam$^{-1}$, and the beam size is $5''7 \times 5''2$ (P.A. = $-66^\circ$).

### 3.1. Analysis of the Herschel and ALMA Continuum Data

To derive the dust temperature and mass of the ALMA-ACA observing region by using the $\text{Herschel}$ 250, 350, and 500 $\mu$m data, we adopt a dust opacity of 5.5 cm$^2$ g$^{-1}$ at 350 $\mu$m and 2.7 cm$^2$ g$^{-1}$ at 500 $\mu$m modeled by Ormel et al. (2007). These values have been shown to reproduce well the observed spectral energy distribution (SED) from 2.2 to 850 $\mu$m in the Orion A cloud, as suggested by Lombardi et al. (2014). The mass $M$ and dust temperature $T_d$ are computed with

$$M = \frac{F_\nu d^2}{\kappa B_\nu(T_d)} f_d,$$

where $F_\nu$ is the observed flux in Jy, $d$ is the distance to the target, $B_\nu(T_d)$ is the Planck function, $\kappa$ is the dust opacity, and $f_d$ is the gas-to-dust mass ratio (assumed to be 100). By calculating the flux density within the ALMA observed field, the dust temperature of TUKH122 is derived to be 12 K, consistent with the previous results of $T_{\text{kin}}$ = 11 K obtained by NH$_3$ spectra (Ohashi et al. 2016c). The mass is also derived to be $\sim 29 M_\odot$. In spite of the observational studies that dust temperature is often higher than gas temperature because of averaging the line of sight of the dust, the similar temperature between gas and dust may suggest that this region is widely isothermal.

The plane-of-the-sky orientation of the filament and elongated core is measured to be a position angle of P.A. = 146$^\circ.3$ derived by 2D Gaussian fitting on the $\text{Herschel}$ image. The directions parallel and perpendicular to the filamentary structure are shown in Figure 5.

To investigate the density structure of this region, Figure 6 shows the column density profiles perpendicular to the filamentary structure. The column density profiles are derived with the ALMA-ACA and $\text{Herschel}$ observations by using Equation (1), assuming the surface is of the ALMA-ACA beam size of $5''2$ and the $\text{Herschel}$ beam size of $18''$. We measure a radial column density profile in the southwest direction (P.A. = 236$^\circ.3$) perpendicular to the filament. Then, the profile is calculated by averaging the flux densities within 15$''$ width at each distance from the peak position (see also Figure 5). We do not use the data of the northeast side because several protostars may affect the density and temperature on this side (see Figure 2).

Figure 6 shows that the $\text{Herschel}$ observations recover extended emission at a distance larger than 0.1 pc, while the ALMA-ACA observations only detect dense gas within 0.1 pc. This is consistent with the results that the ALMA 12 m and ACA 7 m observations are not sensitive to the extended envelope for scales larger than 0.1 pc. We also find that the column densities of the ALMA-ACA observations are higher than those of the $\text{Herschel}$ observations inside 0.02 pc. This would most likely be caused by the low resolution of the $\text{Herschel}$ observation because the ALMA-ACA observations have three times better spatial resolution than $\text{Herschel}$. For example, $\text{Herschel}$ does not resolve the 0.04 pc scale condensation found in this study.

To understand the density structure of the parent filament with the core, we plot the Plummer-like function as the red and black lines in the figure. The Plummer-like profile is defined as

$$\rho(r) = \frac{\rho_c}{[1 + (r/R_p)^2]^{p/2}},$$
and the corresponding surface density profile is

\[ \Sigma(r) = A \frac{\rho_{c} R_{f}}{[1 + (r/R_{f})^p]^{(p-1)/2}}, \]  

where \( A \) is a numerical factor. The numerical factor of \( A \) depends on the density slope \( p \): \( A = \pi \) corresponds to \( p = 2 \), while \( A = \pi/2 \) corresponds to \( p = 4 \) (Arzoumanian et al. 2011). We derive the column density assuming a mean molecular weight of 2.33. The profile is determined by the central density \( \rho_{c} \), the radius \( R_{f} \), and the density slope \( p \) (Nutter et al. 2008; Arzoumanian et al. 2011). Note that the isothermal hydrostatic filament has \( p = 4 \) (Stodólkiewicz 1963; Ostriker 1964). Recently, the Herschel observations suggested \( p \sim 2 \) (e.g., Arzoumanian et al. 2011) and that the dynamical contraction makes a flatter density slope. In Figure 6, the red line shows the power law of \( p = 1.6 \), while the black line shows the power law of \( p = 4.0 \), nicely fitting the data plotted. The FWHM of the Herschel data fitting is 0.16 pc. On the other hand, the ALMA-ACA observations show a thinner and steeper filament due to the missing flux.

The slope of \( p = 4.0 \) is consistent with the isothermal hydrostatic filament or the density profile of prestellar cores.

**Figure 2.** (a) Herschel 250 μm dust continuum image toward the southern part of the Orion A cloud. The black contour shows the ALMA 12 m observed field toward TUKH122. The star symbols represent the protostars identified by Spitzer. The contours show the ACA 3 mm dust continuum emission as the same as panel (b). The green box shows the parent filamentary region. (b) The ACA 7 m 3 mm dust continuum image without the primary beam correction toward the TUKH122 core. The contours start at 3σ with intervals of 3σ. The 1σ noise level is 87 μJy beam\(^{-1}\). The bottom left circle represents the beam size of 17″ × 10″ (P.A. = −66°) corresponding to 0.035 pc × 0.02 pc. (c) The 3 mm dust continuum image without the primary beam correction toward the TUKH122 core obtained by the ALMA 12 m array. The contours start at 3σ with intervals of 1σ. The 1σ noise level is 43 μJy beam\(^{-1}\). The bottom left circle represents the beam size of 570 × 470 (P.A. = −61°) corresponding to 0.01 pc × 0.0094 pc. The combined ALMA image is shown in Figure 4.

**Figure 3.** The color map shows the ACA 7 m 3 mm dust continuum image without the primary beam correction toward the TUKH122 core. The contours show the NH₃ integrated intensity map. The lowest contour level and interval are 2.4 mJy beam\(^{-1}\) km s\(^{-1}\).

**Figure 4.** The ALMA-ACA combined 3 mm dust continuum image toward the TUKH122 core without the primary beam correction. The contours start at 3σ with intervals of 1σ. The 1σ noise level is 40 μJy beam\(^{-1}\). The red contours represent the condensations. The bottom left circle represents the beam size of 570 × 470 (P.A. = −66°).
The radius is calculated from the surface area of the beam-size of the ALMA-ACA combined data and bars show the maximum and minimum distributions of the pro-Herschel \((\text{interval})\). The directions parallel and perpendicular to the filament direction are shown in Figure 5.

Figure 5. The color map is the same as in Figure 4. The contours show the Herschel 250 \(\mu\text{m}\) dust continuum and start at 260 MJy \(\text{sr}^{-1}\) with 20 MJy \(\text{sr}^{-1}\) intervals. The directions parallel and perpendicular to the filamentary structure are also shown with a width of 15°.

Figure 6. Column density profiles perpendicular to the filament direction taken by ALMA-ACA observations and the Herschel 250 \(\mu\text{m}\) observations. Error bars show the maximum and minimum distributions of the profiles in each region. The black and red lines represent the Plummer-like function with power laws of 4.0 and 1.6, respectively. The dashed lines represent the beam patterns of the ALMA-ACA combined data and Herschel 250 \(\mu\text{m}\) data.

(Whitworth & Ward-Thompson 2001). However, the ALMA-ACA observations only recover 8.4 \(M_\odot\) out of a total of \(~29 \ M_\odot\). It is difficult to distinguish the density structure of the TUKH122 core from the parent filament by these observations due to the missing flux. We cannot discuss the density profile or the power law of the ALMA-ACA observations. We only show that the missing flux is not the background emission but the surrounding gas associated with the filament.

It is possible that the power law of \(p = 1.6\) indicates the dynamical contraction of the filament rather than the background effect. The filament actually forms the dense core and condensations. Therefore, we indicate that the power law of \(p = 1.6\) is the radial profile of the parent filament that already forms the elongated core.

### 3.2. The 3 mm Dust Continuum Emission Seen by ALMA

To identify dense condensations precisely, we apply the dendrogram method (Rosolowsky et al. 2008) to the combined 3 mm dust continuum image. The dendrogram traces local maxima and describes hierarchical structures, which have been shown to be more robust against noise and user-defined parameters (e.g., Goodman et al. 2009; Pineda et al. 2009). This method gives three types of structures: leaf, branch, and trunk. We define “leaves” as “condensations” in this paper because the leaf is the smallest structure. We adopt a threshold of 3\(\sigma\) and 1\(\sigma\) interval steps. The minimum number of pixels is \(3 \times \theta_{\text{beam}}\). In addition, we select the condensations as the robust ones when they can be identified as detection above 3\(\sigma\) with ALMA 12 m data. The identified condensations are shown in Figure 4 as the red contours and listed in Table 2.

The mass of the 3 mm dust condensations is computed with Equation (1) at a dust temperature \(T_d = 12\ \text{K}\). We adopt a dust opacity of 0.0755 cm\(^2\) g\(^{-1}\), assuming a dust emissivity index of \(\beta = 2\) (Ormel et al. 2007). As a result, the condensation mass ranges from 0.1 to 0.4 \(M_\odot\). The typical deconvolved radius is \(r \sim 2 \mu\text{m}\). The radius is calculated from the surface area of the identified condensations. The \(H_2\) densities are \(n \sim 10^{4\pm7}\ \text{cm}^{-3}\), which are of the order of or higher than those of typical low-mass prestellar cores (e.g., Onishi et al. 2002; Enoch et al. 2008). The condensation in the center of TUKH122, MM4, is the most massive and has \(\sim 0.4 \ M_\odot\). Note that the deconvolved radius of \(r \sim 2 \mu\text{m}\) is very close to the beam-size radius. The condensations MM1, MM2, and MM6 show that the peak intensities have larger values than the total fluxes (see also Table 2). These results indicate that these three condensations (MM1, MM2, and MM6) are not well resolved with our observations. However, the distances between the condensations are larger than the beam size, indicating that we can determine the locations of the condensations with our observations. We find an interesting trend that the northern condensations (MM1, MM2, and MM3) have \(0.1\sim0.2 \ M_\odot\) while the southern condensations (MM4 and MM5) have \(\sim 0.4 \ M_\odot\). We discuss the different mass distribution along the filament in the following section.

The total mass of TUKH122 is derived to be 8.4 \(M_\odot\) (2.5 \(M_\odot\) for ALMA 12 m data) using the ALMA-ACA combined data. Taking into account the total mass of TUKH122 \(\sim 29 \ M_\odot\) estimated by Herschel, there is still a large fraction of flux that is not recovered by ALMA. In order to check how the condensation masses vary, we combine our ALMA and ACA data with the Herschel 250 \(\mu\text{m}\) data using feather in CASA. Note that we rescale the 250 \(\mu\text{m}\) flux to the 3 mm flux assuming the dust temperature of 12 K and ice-covered silicate-graphite conglomerate grains with a dust emissivity index of \(\beta = 2\) modeled by Ormel et al. (2007). We confirm that the total mass is recovered to be \(\sim 29 \ M_\odot\). Then, we apply the dendrogram method to the 3 mm continuum image in the same way as the above. We find that the condensation mass ranges from 0.1 to 0.7 \(M_\odot\). The MM1 to MM4 condensations increase in mass only \(\sim 10\%\), but MM5 increases \(\sim 60\%\) in mass, suggesting that the condensation masses do not change even when we add the total power, except for MM5. However, we should also note that if condensations have relatively extended structures, as MM5 does, the masses may be underestimated due to the missing flux.

We also study the dynamical stability of these condensations. Assuming a uniform density structure, the virial mass can
be estimated as

$$M_{\text{vir}} = 210 \times \left( \frac{r}{\text{pc}} \right) \times \left( \frac{\Delta v}{\text{km s}^{-1}} \right)^2 M_\odot,$$

where $r$ is the radius and $\Delta v$ is the line width (MacLaren et al. 1988). The line width is derived by Gaussian fitting of the CH$_3$OH (J$_e = 2_0 - 1_0$, A$^+$) emission because this line is optically thin. The centroid velocity, line width, and virial mass are shown in Table 2. As shown in the table, the condensation mass is much higher than the virial mass. Therefore, these condensations are not in virial equilibrium and may collapse immediately unless the magnetic field counterbalances gravity.

3.3. The Molecular-line Emission of N$_2$H$^+$ and CH$_3$OH

Figure 7 shows in color the velocity-integrated intensity maps of N$_2$H$^+$ ($J = 1-0$, $F_1 = 1-1$, $F = 0-1$) and CH$_3$OH ($J_e = 2_0 - 1_0$, A$^+$) emission without the primary beam corrections. The ALMA 12 m and ACA 7 m data are combined. The $F_1 = 1-1$, $F = 0-1$ transition line is the weakest hyperfine component; hence, its optical depth is the smallest. The contours are the 3 mm dust continuum (same as Figure 4). The 3 mm dust continuum and the N$_2$H$^+$ transition maps show that the intensities concentrate at the central part and have the same peak position. On the other hand, the CH$_3$OH emission is weak at the central part of the TUKH122 core, resembling a shell-like structure that surrounds the continuum and N$_2$H$^+$ emission. These configurations are quite similar to the starless cores of L1498, L1517B, and L1544 (Tafalla et al. 2006; Vastel et al. 2014; Spezzano et al. 2016), indicating that the CH$_3$OH and N$_2$H$^+$ molecules have chemical differentiation.

The CH$_3$OH molecule is suggested to be formed on the surface of dust grains via successive hydrogenation of CO (e.g., Watanabe & Kouchi 2002) and is released by external heating.
...the VLA CCS integrated intensity map corner, the synthesized beam of 4...shell-like structure. According to this mechanism, the column density of gaseous photoevaporation caused by cosmic-ray-induced UV radiation. Liberated into the gas phase by nonthermal desorption, such as

\[ F \leq 0, F = 1-2, 2-1, 1-1 \]  

Figure 9. The \( \text{N}_2\text{H}^+ (J = 1-0) \) profile at the MM4 peak position. The velocity resolution is 0.098 km s\(^{-1}\).
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Figure 10. Color maps of the optical depth ($\tau$), LSR velocity ($V_{\text{LSR}}$), and line width ($\Delta v$) of $N_2H^+$ $J = 1-0$, $F_1 = 1-1$, $F = 0-1$ emission derived from Gaussian fitting of the weakest hyperfine component. The contours are the 3 mm dust continuum emission from 3$\sigma$ with 2$\sigma$ steps. The fitting is performed for the pixels above 5$\sigma$. The optical depth is derived by assuming that the maximum intensity of $N_2H^+$ $J = 1-0$ corresponds to the excitation temperature.

Figure 11. Same as Figure 9 but at the MM5 position.

Figure 12. The black line represents the $N_2H^+$ $F_1 = 2-1$, $F = 3-2$ profile at the MM5 position with a rest frequency of 93.173777 GHz, and the green line represents the $F_1 = 1-1$, $F = 0-1$ profile with a rest frequency of 93.171621 GHz.

Thus, the double-peak feature seen in the strongest hyperfine component would be caused by a self-absorption effect. In a similar case, a self-absorption in NH$_3$ was found toward the IRDC G028.23–00.19 prestellar clump (Sanhueza et al. 2017). The self-absorption of the $N_2H^+$ and NH$_3$ lines suggests that the inner region has a higher density and excitation temperature than the surrounding $N_2H^+$ or NH$_3$ emission regions.

We also find that the optical depth is not correlated well with the dust continuum emission. The MM4 is the peak position in the dust continuum, but the optical depth seems to be lower than that in the surrounding region, which may suggest a lower ionization degree in the dense part of the core or the depletion of $N_2H^+$ at the densest parts. The $N$-bearing molecules of $N_2H^+$ and NH$_3$ are suggested to be depleted at a density of $\gtrsim 10^{10}$ cm$^{-3}$ (e.g., Bergin et al. 2002; Pagani et al. 2005).

In the color map of $V_{\text{LSR}}$, there is no evident velocity variation along the filament. Systematic velocity fluctuations are also not found along the ridge of the continuum image. This could be due to the impossibility of tracing velocity fields using optically thick lines (most regions have $\tau \gtrsim 1$) or the insufficient velocity resolution (0.098 km s$^{-1}$) of our observation to identify infall or fragment motions. On the other hand, in the line-width map, we find that the line width increases toward the condensations. Because the central condensation does not have a high optical depth ($\tau \sim 1$) in comparison with the surrounding part, a broad line width is not due to the saturation effect of the line but indicates motions (infall, expansion, or turbulent) toward the condensation. Considering that the $N_2H^+$ molecule is partially depleted and the line width becomes broader toward MM4, this condensation may be beginning to collapse. However, our current velocity resolution and the molecular lines are not enough to resolve and investigate the motions in detail. It is highly necessary to investigate the nature of the enhanced line width, i.e., the presence of a blue-skewed profile suggesting infall, with higher spectral resolution.

Even though $N_2H^+$ is highly optically thick, we roughly estimate the $N_2H^+$ abundance at the dust peak position. In the dust peak, we assume an excitation temperature of $T_{\text{ex}} = 5.8$ K from the maximum intensity. The optical depth of the $F_1 = 1-1$, $F = 0-1$ line is derived to be $\tau = 0.9 \pm 0.1$. Then, the column density can be calculated by following Sanhueza et al. (2012) and Mangum & Shirley (2015). We derive $N_{N_2H^+} = (3.4 \pm 0.4) \times 10^{13}$ cm$^{-2}$. On the other hand, the 3 mm dust continuum shows $N(H_2) = 9.9 \times 10^{22}$ cm$^{-2}$.

Therefore, the $N_2H^+$ abundance is derived to be
Asuming that the CH$_3$OH abundance can be even lower at the central part because this value is the average over the whole region. Therefore, the CH$_3$OH abundance is $X(\text{CH}_3\text{OH}) = (3.4 \pm 0.4) \times 10^{-10}$, which is similar to other low-mass star-forming regions (e.g., Caselli et al. 2002; Tafalla et al. 2002; Keto et al. 2004; Tafalla et al. 2006; Friesen et al. 2010).

### 3.3.2. Analysis of CH$_3$OH Spectra

The CH$_3$OH transitions observed are $(2_1-1_1 E)$, $(2_0-1_0 A^+)$, and $(2_0-1_0 E)$. Assuming local thermodynamic equilibrium (LTE) and optically thin conditions, we can estimate the column density ($N_{\text{CH}_3\text{OH}}$) and rotation temperature ($T_{\text{rot}}$) using the rotation diagram technique (e.g., Blake et al. 1987). However, CH$_3$OH $(2_0-1_0 E)$ has a low signal-to-noise ratio. In order to have a significant detection in all three lines, we average the profiles from the whole region inside the 5σ contour of the ACA 3 mm dust continuum image.

The averaging region is shown by the magenta contour in Figure 13. Following the population diagram methods (e.g., Goldsmith & Langer 1999), we fit the three CH$_3$OH lines. We follow the procedure described in Sanhueza et al. (2013), which is optimized for cold gas. The obtained column density and rotation temperature are $N_{\text{CH}_3\text{OH}} = (1.1 \pm 0.1) \times 10^{13}$ cm$^{-2}$ and $T_{\text{rot}} = 10.8 \pm 0.4$ K. This rotation temperature is consistent with $T_{\text{rot}} = 10.6$ K, derived by using the NH$_3$ ($J, K = 1, 1$) and ($J, K = 2, 2$) lines (Ohashi et al. 2016c). The rotation temperature is the same even if different molecular lines are used, suggesting the isothermal core with the LTE condition. The optical depth of the strongest transition $(2_0-1_0 A^+)$ is <0.1; hence, it is optically thin. The average H$_2$ column density is derived to be $N(\text{H}_2) = 3.8 \times 10^{22}$ cm$^{-2}$ from the 3 mm dust continuum observations. Therefore, the CH$_3$OH abundance is $X(\text{CH}_3\text{OH}) \approx 2.9 \times 10^{-10}$. Soma et al. (2015) estimated the abundance of CH$_3$OH to be $\sim 10^{-10}$ toward the cold quiescent core, TMC-1 (CP). Tafalla et al. (2006) also estimated the abundance to be $X(\text{CH}_3\text{OH}) \approx 6 \times 10^{-10}$ in the L1498 and L1517B prestellar cores. TUKH122 has a similar CH$_3$OH abundance to these prestellar cores. In particular, the CH$_3$OH abundance can be even lower at the central part because this value is the average over the whole region. Assuming that the CH$_3$OH $(2_0-1_0 A^+)$ line is optically thin and $T_{\text{rot}} = 10.8$ K, we estimate the column density, $N_{\text{CH}_3\text{OH}}$, at the dust peak position MM4 by using the rotation temperature derived above. By comparing the velocity-integrated intensities, the column density is derived to be $N_{\text{CH}_3\text{OH}} = 1.3 \times 10^{13}$ cm$^{-2}$ at this dust peak position, and then the CH$_3$OH abundance is $X(\text{CH}_3\text{OH}) \approx 1.3 \times 10^{-10}$.

Figure 13 shows color maps of the peak intensity, $V_{\text{LSR}}$, and line width of CH$_3$OH. The peak temperature map clearly shows the shell-like structure, and the dust condensations are located within this shell. The $V_{\text{LSR}}$ map shows some systematic variations within the core. The northern edge is slightly redshifted in velocity, while the southern edge is blueshifted, suggesting core rotation or gas inflow motions along the filamentary structure. Furthermore, the southeastern side is blueshifted velocity, while the southwestern side is redshifted. The velocity structure is complicated, but the velocity difference might indicate the contraction or twisted motions of the core.

The line-width map shows no systemic variations along the filament. However, the dust peak position (MM4) has a broad line width of $\Delta v \sim 0.4$ km s$^{-1}$, which is the same tendency as that in N$_2$H$^+$. These broad line widths would thus suggest infall motions. Interestingly, the line-width color maps of N$_2$H$^+$ and CH$_3$OH show a small value of $\Delta v \lesssim 0.2$ km s$^{-1}$ at the edge of the condensations, and our velocity resolution marginally resolves the lines. The line width of 0.2 km s$^{-1}$ is close to the thermal motion because thermal line width corresponds to 0.14 km s$^{-1}$ for N$_2$H$^+$ and 0.13 km s$^{-1}$ for CH$_3$OH at 12 K. The narrow line width of the core edge indicates that the turbulence is almost dissipated in the filament, and the nonthermal motions within the core could indicate infall motions or some systemic velocity variations, such as rotation and fragmentation.

The important difference between TUKH122 and the other prestellar cores in nearby clouds is that TUKH122 consists of at least three dense condensations within the one CH$_3$OH shell. The TUKH122 core is more massive than low-mass dense cores (e.g., Onishi et al. 2002; Alves et al. 2007), even though the size is comparable, implying that the TUKH122 core is denser. The denser core would enhance the CH$_3$OH shell structure because UV radiation is only irradiated on the outer layer of the core.
4. Discussion

4.1. Density Profile

To investigate the formation of the condensations, we study the density structure along the filament. Figure 14 shows the column density profiles taken from the maximum position along the filament direction (see also Figure 5). The reference position here is the MM4 condensation corresponding to the peak flux in the ALMA-ACA observations. The Herschel single-dish observations indicate an almost flat density structure due to the large beam size. On the other hand, the ALMA-ACA observations show column density variations. The green line represents a sinusoidal column density variation with an interval of 0.035 pc to visually match the observed variations. The southern part (MM3, MM4, and MM5) seems to be nicely fitted by this sinusoidal variation.

The interval of 0.035 pc is consistent with the separations between neighbor sources in the OMC-2 and 3 regions (Takahashi et al. 2013; Kainulainen et al. 2017). In OMC-1, another part of the Orion A cloud, a separation of \( \sim 0.01 \) pc was reported by Teixeira et al. (2016) and Palau et al. (2017). Since OMC-1 is the most massive part in the Orion A cloud, the fragmentation might occur at denser regions, and the separations would then become shorter. The separations and fragmentation processes have also been studied in other regions, including high-mass star-forming regions, and suggested to be governed by thermal Jeans processes (e.g., Kainulainen et al. 2013; Beuther et al. 2015; Palau et al. 2015; Busquet et al. 2016). Assuming that the fragmentation occurs by the Jeans instability, we can estimate the separation of the fragment at this region. With the assumption of an infinite size and a uniform density, the Jeans length is described as follows (Jeans 1902):

\[
\lambda_{\text{Jeans}} = \sqrt{\frac{\pi c_s^2}{G \rho_0}}. \tag{5}
\]

where \( G \) is the gravitational constant, \( \rho_0 \) is the mean density, and \( c_s \) is the sound speed of 0.2 km s\(^{-1}\) at 12 K. Takahashi et al. (2013) also analyzed the Jeans length in the case of an infinitely long static and cylindrical isothermal cloud following Nakamura et al. (1993) and Wiseman & Ho (1998) and described as

\[
\lambda_{\text{Jeans}} \sim \frac{20 c_s}{\sqrt{4 \pi G \rho_0}}. \tag{6}
\]

From the column density profile of the ALMA-ACA observations in Figure 6, we derive the central density, \( \rho_c \sim 5.5 \times 10^4 \text{ cm}^{-3} \), assuming the numerical factor of \( A = \pi/2 \). The Jeans length is derived to be \( \sim 0.031 \) pc and \( \sim 0.099 \) pc, respectively, following Equations (5) and (6), assuming a temperature of 12 K. The thermal Jeans instability with an assumption of an infinite and a uniform density, Equation (5), would be better explained to form the condensations. Therefore, the fragmentation occurs within the elongated core having a density of \( \sim 10^5 \text{ cm}^{-3} \), and the denser condensations with a density of \( \sim 10^6 \text{ cm}^{-3} \) are formed by the thermal Jeans instability. Note that, assuming \( \lambda_{\text{Jeans}} = 0.035 \) pc, the density is derived to be \( n(H_2) \sim 4.4 \times 10^6 \text{ cm}^{-3} \) from Equation (5).

The northern part (MM1 and MM2) seems to have a shorter interval of \( \sim 0.02 \) pc. An inclination might cause a shorter interval even if these condensations have the same interval of \( \sim 0.035 \) pc, or the Jeans instability at higher densities may occur. We should also note that these northern condensations are located on the CH\(_3\)OH shell structure, suggesting the edge of the TUKH122 core. Therefore, the edge instabilities may also affect the separation of the condensations (Pon et al. 2011, 2012). The lower-mass condensations with shorter intervals may be formed in the edge region.

We also discuss the possibility of whether the condensations will merge or not. From the CH\(_3\)OH observations, the relative velocities of the surrounding condensations for MM4 are 0.02–0.05 km s\(^{-1}\). To merge the condensations, we need at least \( 4 \times 10^5 \) yr, assuming a separation of 0.02 pc and velocity of 0.05 km s\(^{-1}\). On the other hand, the freefall time at a density of \( 10^6 \text{ cm}^{-3} \) will be 4 \( \times 10^3 \) yr. Therefore, star formation can be started before these condensations merge. It is unlikely that these condensations merge to a larger scale. However, the magnetic field may be supporting the condensations and makes the star formation timescale longer (e.g., Crutcher et al. 2004; Ward-Thompson et al. 2007). It is suggested that the ambipolar diffusion timescale is about 10 times longer than the freefall time (Nakano 1998). In this case, the merging might be possible.

4.2. Possibility of Multiple Star Formation

In the previous section, we identified the six condensations with a mass of \( \sim 0.1–0.4 M_\odot \) in the core, and they are gravitationally bound. However, the total mass of the condensations is only 1.2 \( M_\odot \), and a large portion of the mass is located outside of them. One possibility for the small mass fraction of the condensations is that we may only detect the peak region of the condensations, and the condensations may have larger radius and mass. For example, if the condensations have an unstable Bonnor–Ebert sphere, they have a large contrast in density between the center and outer part. The condensations might be able to identify only the center part due to our spatial resolutions and sensitivities. Actually, the size of the condensations is derived to be \( r \sim 0.006 \) pc even though we find a separation of 0.02–0.035 pc between them. If we use the separations as the size of these condensations, the mass is derived to be 0.3–1 \( M_\odot \). Even if the condensations have masses of 0.3–1 \( M_\odot \), they only have a small amount of the mass, and the virial parameters are still lower than unity. These condensations may collapse immediately. Another possibility is that very low-mass stars (\( \sim 0.03–0.1 M_\odot \)) are formed in these condensations in this region. In either case, a multiple-star
system may be formed in the core along the filament. We suggest that fragmentation is still important in the dense core to form multiple stars.

### 5. Conclusions

We have presented the ALMA high spatial resolution observations of the 3 mm dust continuum, the hyperfine-component lines of N$_2$H$^+$ ($J = 1-0$), and the CH$_3$OH ($J = 2_k-1_k$) lines toward the TUKH122 core. This core is likely on the verge of star formation because the turbulence is almost completely dissipated and it is a chemically evolved core among starless cores in the Orion A cloud. Our main results are summarized as follows.

1. The column density profile perpendicular to the parent filamentary structure including the elongated core is similar to the Plummer-like function. The *Herschel* observations show a power law of $p = 1.6$, while the ALMA-ACA observations show a power law of $p = 4.0$. This difference will be explained in terms of the missing flux of the interferometric observations. The condensations are embedded in the parent elongated core.

2. ALMA 12 m dust continuum emission shows compact dense condensations, while the ACA 7 m image shows the oval structure due to the larger beam size and recovering the extended emission. By combining these data and applying the dendrogram method, we find condensations within the core with a mass range of 0.1–0.4 $M_\odot$, and a deconvolved radius of 0.003–0.01 pc along the filament. The densities are $n \approx 10^{6−7}$ cm$^{-3}$, which are an order of magnitude higher than typical low-mass prestellar cores.

3. We find different distributions between N$_2$H$^+$ and CH$_3$OH emission. The N$_2$H$^+$ distribution is similar to the dust continuum but seems to be frozen out in the dust peak MM4, while the CH$_3$OH distribution shows a shell-like structure. The extended CH$_3$OH distribution suggests that the CH$_3$OH molecule formed on dust grains is released into the gas phase by nonthermal desorption such as that caused by cosmic-ray-induced UV radiation. We also find the absorption feature in the N$_2$H$^+$ $F_1 = 2 − 1$, $F = 3 − 2$ component toward the condensation MM5 due to the self-absorption effect. Even though N$_2$H$^+$ has been used as an optically thin dense gas tracer, we show that this molecule becomes optically thick in this core.

4. The separations of these condensations are $\sim 0.035$ pc in the southern part, which is similar to that in the OMC-2/3 region, the active star-forming region in the Orion A cloud. The Jeans length corresponds to $n(H_2) \approx 4.4 \times 10^4$ cm$^{-3}$, which is almost consistent with that of the central density of the core. Therefore, the fragmentation still occurs in the prestellar core by thermal Jeans instability at a density of $\sim 10^5$ cm$^{-3}$, and the denser condensations with a density of $10^6$–$7 \times 10^5$ cm$^{-3}$ are formed. In the northern part, corresponding to the CH$_3$OH shell region, we find that the condensations are less massive with shorter intervals, which may imply that the edge instabilities affect the fragmentation.

5. The condensations are not in virial equilibrium and may collapse immediately unless the magnetic field counterbalances gravity. However, the total mass of the condensations is a small fraction of the total TUK122 core mass. The condensations might identify only the central part due to our spatial resolutions and sensitivities, and they may have masses of 0.3–1 $M_\odot$. Another possibility is that the very low-mass stars ($\sim 0.03–0.1$ $M_\odot$) are formed in the small condensations in this region. In either case, multiple stars may be formed in the core. We suggest that the fragment due to the thermal instability is still important to form a multiple-star system.

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