High-mass star formation in Orion B triggered by cloud-cloud collision: Merging molecular clouds in NGC 2024

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Abstract

We performed new comprehensive $^{13}$CO($J=2-1$) observations toward NGC 2024, the most active star forming region in Orion B, with an angular resolution of $\sim$100″ obtained with NANTEN2. We found that the associated cloud consists of two independent velocity components. The components are physically connected to the HII region as evidenced by their close correlation with the dark lanes and the emission nebulosity. The two components show complementary distribution with a displacement of $\sim$0.6 pc. Such complementary distribution is typical to colliding clouds discovered in regions of high-mass star formation. We hypothesize that a cloud-cloud collision between the two components triggered the formation of the late O-type stars and early B stars localized within 0.3 pc of the cloud peak. The duration time of the collision is estimated to be 0.3 million years from a ratio of the displacement and the relative velocity $\sim$3 km s$^{-1}$ corrected for probable projection. The high column density of the colliding cloud $\sim$10$^{23}$ cm$^{-2}$ is similar to those in the other high-mass star clusters in RCW 38, Westerlund 2, NGC 3603, and M42, which are likely formed under trigger by cloud-cloud collision. The present results provide an additional
piece of evidence favorable to high-mass star formation by a major cloud-cloud collision in Orion.

**Key words:** ISM: clouds — ISM: kinematics and dynamics — ISM: molecules — stars: formation

## 1 Introduction

### 1.1 The Orion region and high-mass star formation

The Orion region is the nearest most outstanding high-mass star forming region in the solar neighborhood. The HII region NGC 2024 located at 410 pc is the second active HII region next to M42 in Orion and is associated with a reflection nebula NGC 2023 (e.g., Anthony-Twarog 1982; Menten et al. 2007). NGC 2024 is therefore one of the most interesting regions in studying high-mass star formation. A review of the Orion B region is given by Meyer et al. (2008) and references therein.

Observations in radio continuum radiation and recombination lines (Kruegel et al. 1982; Barnes et al. 1989; Bik et al. 2003; Rodriguez et al. 2003) as well as infrared observations indicate that NGC 2024 is ionized by an exciting stars of O8V-B2V (Lada, & Lada 1991; Comeron et al. 1996; Giannini et al. 2000; Haisch et al. 2000; Bik et al. 2003; Kandori et al. 2007). In addition to the high-mass star, hundreds of low-mass stars are identified in the cluster by near-infrared and X ray observations (Lada, & Lada 1991; Skinner et al. 2003). These cluster members consist of at least 300 stars including late O-type stars and early B stars. Most of them are suggested to be in mass accretion phase by 10 µm observations (Haisch et al. 2000; Haisch et al. 2001). Although large visual extinction of 30 magnitudes toward the region (e.g., Johnstone et al. 2006) hampers firmly identifying candidates for the ionizing star of NGC 2024, Bik et al. (2003) identified the exciting star named IRS2b by infrared photometry.

It is probable that the cluster is smaller than the Orion Nebula Cluster which contains ~10 O- / early B-type stars as well as ~2000 member stars (Kroupa 2001; Banerjee, & Kroupa 2018). Near infrared observations of NGC 2024 was used to construct an HR diagram of these stars and the age is estimated to be 1 Myrs or less (Getman et al. 2014). Far infrared observations revealed dense protostellar condensations with a compact distribution, suggesting some external triggering to form them while details remain elusive due to high extinction (e.g., Megeath et al. 2016).

In order to explain the formation of the OB associations in the Orion region, Elmegreen & Lada (1977) presented a scenario of sequential star formation. In the scenario, an ionization shock front driven by OB stars compresses molecular gas in a direction where molecular gas is distributed, often elongated along the Galactic plane, and after a passage of ~20 pc a compressed layer forms
OB stars due to gravitational instability. This scenario explains the age sequence of subgroups of OB associations; in case of Orion the four subgroups Orion Ia, Ib, Ic and Id are separated by 20 pc in the order of age. Brown et al. (1994) made an extensive study of stars in the Orion region and derived new ages and IMFs of the Orion OB associations. Their results showed that the age of Ic is younger than Ib, contrary to the previous results by Blauuw, & Mavridis (1965), which showed the opposite age sequence.

The work raised that the conventional sequential scenario requires reconsideration or modification, even if the scenario may still be largely applicable. On a smaller scale of individual star formation Lee & Chen (2009) presented a study which suggests that Ori-Eri superbubble may be triggering star formation in the apparently interacting small clouds in part of the Orion clouds. We do not have yet a full picture of OB star formation in Orion which assembled gas and stellar datasets comprehensively. So, the formation of the OB association is not fully understood and remains as an open issue.

In the meantime a new picture of star formation in magnetically driven filaments were proposed by Peretto et al. (2012). Most recently, Fukui et al. (2018b) made a detailed analysis of the $^{12}\text{CO}(J=1−0)$ data in the Orion A cloud taken with the NRO 45 m telescope by Shimajiri et al. (2011), and presented an analysis that the Orion A cloud comprises two spatially overlapping components of different velocities. These authors suggested that the ionizing stars of M42 and M43 in Orion A were formed by triggering in collision between two clouds of 7 km s$^{-1}$ velocity difference based on that the two clouds show complementary distribution with a systematic spatial displacement, a typical signature of colliding clouds, for M43. In the Orion B cloud, in NGC 2024, the JCMT covers in CO ($J=3−2$) only 10.8 $\times$ 22.5 arcmin$^2$ (Buckle et al. 2010) and a large-scale view of the molecular gas has not been revealed.

1.2 The orion B cloud

The Orion B cloud also known as the L1630 cloud was not a subject of many large-scale molecular observations. Bally et al. (1991) observed the cloud in the $^{13}\text{CO}(J=1−0)$ transition and Aoyama et al. (2001) in the $^{18}\text{C}O$ $J=1−0$ and HCO$^+$ $J=1−0$ transitions. Kramer et al. (1996) performed $^{12}\text{CO}$ and $^{13}\text{CO}$ $J=2−1$ and $3−2$ observations of the southern part of the Orion B region covering a $\sim40' \times 70'$ area. They revealed physical conditions of molecular clouds in the region for the first time, however the angular resolution and the observing grid is not high (125$''$ and 2', respectively) and thus the distribution was coarse and contrasts of cloud intensities were unclear.
Ripple et al. (2013) used the FCRAO 14 m telescope to map the cloud in the $^{12}$CO($J=1–0$) transition at higher resolution. The $^{12}$CO($J=2–1$) transition was observed at 9' resolution in a large scale by Sakamoto et al. (1994) and Wilson et al. (2005) and was used to derive density and temperature through a comparison with the $^{12}$CO($J=1–0$) transition. Lada et al. (1991) performed an unbiased, systematic survey for dense cores within the Orion B molecular cloud by CS $J=2–1$ transition, and Ikeda et al. (2009) carried out an H$^{13}$CO$^+$ $J=1–0$ core survey in a large area of 1 deg$^2$. Miesch & Bally (1994) presented an investigation of the statistical properties of fluctuating gas motions in Orion B. Recently, Nishimura et al. (2015) made a higher resolution comparative study of the $^{12}$CO($J=1–0$) and $J=2–1$ transitions by using the data taken with the OPU 1.85 m and NANTEN, and derived density and temperature distributions over the whole Orion region including Orion A and Orion B at 3' resolution.

In order to reveal detailed gas kinematics in NGC 2024, we carried out new observations toward NGC 2024 cloud in the $^{12}$CO and $^{13}$CO $J=2–1$ transitions at 1.5' resolution over a large area including whole the NGC 2024 cloud. Section 2 gives details of the observations, Section 3 describes the observational results, Section 4 presents discussion on cloud-cloud collision, and Section 5 concludes the paper.

2 Observation

Observations of the $^{13}$CO($J=2–1$) transition were made with NANTEN2 over an area of $0.55 \times 0.55$ in $l$ and $b$. The data were taken in a period from December 11, 2016 to December 15, 2016. The transition was observed simultaneously with the $^{12}$CO($J=2–1$) emission in the on-the-fly mode in 0.8 second integration per a point with a 30'' grid spacing. The system noise temperature in the Double Side Band was 160 - 220 K toward the zenith. The backend was a digital spectrometer having a bandwidth and resolution of 1 GHz and 61 kHz, respectively. These correspond to a velocity coverage of 1300 km s$^{-1}$ and a velocity resolution of 0.079 km s$^{-1}$. After convolution with a 2-dimensional Gaussian kernel of 54'', the final beam size was $\sim 105''$ (FWHM). Pointing accuracy was measured toward IRC 10216 [$\alpha_{2000} = 9^h 47^m 57^s 406$, $\delta_{2000} = -13^\circ 16' 43'' 56$] everyday and confirmed to be better than 10''. The absolute intensity scale was established by observing OriKL [$\alpha_{2000} = 5^h 35^m 13^s 5$, $\delta_{2000} = -5^\circ 22' 27'' 6$] every hour. The final rms noise level was 0.50 K ch$^{-1}$ at a velocity resolution of 0.079 km s$^{-1}$. We use the Galactic coordinate in the present paper.

3 Results

In this section, we present gas distribution toward NGC 2024. We first review global distribution and properties of molecular gas toward this region.
3.1 Global gas distribution in the NGC 2023/NGC 2024 region

Figure 1a show schematic image of objects seen in optical wavelengths toward the region including NGC 2023 and 2024. NGC 2023 and 2024 are located near the edge of HII region, IC434. The black box indicates the area observed by the NANTEN2. Figure 1b and 1c show integrated intensity distributions of the $^{12}$CO($J=1$–0) emission toward the same region at $4\arcmin$ grid obtained with the NANTEN telescope (Mizuno & Fukui 2004) superposed on optical images obtained by DSS2. These two Figures in different integrating velocity range, $8.7 - 9.4$ km s$^{-1}$ and $11.2 - 11.8$ km s$^{-1}$, present apparently distinct spatial distributions. The higher velocity component exhibits a clear spatial correspondence with the boundary of IC 434, which is a HII region ionized by $\sigma$-Ori indicating the association between them. Figure 1d is a longitude-velocity diagram integrated in latitude. The di-
agram indicates that there are two peaks shown by a dark color. One is a cloud toward NGC 2023 having $V_{\text{LSR}} \gtrsim 10$ km s$^{-1}$ and another is a cloud toward NGC 2024 having $V_{\text{LSR}} \lesssim 10$ km s$^{-1}$. Gas distributions of these two components correspond to Figure 1c and 1b. There are also diffuse emissions at $V_{\text{LSR}} \sim 5$ km s$^{-1}$.

Figures 2a–d show typical $^{12}$CO and $^{13}$CO($J=2–1$) profiles toward two positions P1 and P2 in NGC 2024 and two positions in NGC 2023 obtained from Nishimura et al. (2015). Positions P1 and P2 are explained in Section 3.2. The $^{12}$CO emission is heavily saturated with self-absorption in Figure 2a, while $^{13}$CO showing a single peak seems not to have significant saturations. Indeed some positions in the NGC 2024 region in $^{12}$CO apparently show two velocity components due to self-absorption such as seen in Figure 2a, but the region still has two distinct velocity components in some positions as can be seen in Figure 2b. This means the two velocity components shown in Figure 1b and 1c are not merely caused by self-absorption but existing two clouds. The typical optical depth $\tau(v)$ of $^{13}$CO($J=2–1$) toward NGC 2024 is estimated to be $\leq 0.1$ and only the small area with high brightness temperatures of $\gtrsim 15$ K have optical depths beyond 1, if we assume $T_{\text{ex}} = 30$ K. Therefore, in the present paper, we use only $^{13}$CO, which is not optically-thick for the most part and traces gas
distribution better without self-absorption.

Figures 2c and 2d are line profiles toward two CO intensity peaks in NGC 2023 in Figures 1b and 1c. Both show no significant self-absorption and apparently exhibit a single component. It is possible that two velocity components are merged as the single component in NGC 2023. NGC 2023 is a smaller and younger system compared to NGC 2024 and thus, the angular resolution of the NANTEN telescope is not enough to resolve the two velocity components, although a weak emission is still distinguished at $V_{\text{LSR}} \sim 13$ km s$^{-1}$ in Figure 2d. Only $^{12}$CO spectrum in Figure 2a show a low intensity feature at $V_{\text{LSR}} \sim 5$ km s$^{-1}$. Although this may be the third independent velocity component, the intensity is very low and the distribution is diffuse and thus, this may not play a significant role in the current star formation. Therefore, we do not take into account this component in the following analyses and discussion.

3.2 Molecular gas toward NGC 2024

Figure 3 shows the velocity channel distribution of the $^{13}$CO($J$=2–1) emission obtained from new NANTEN2 observations. We found that the primary peak P1 in 9.05 – 12.86 km s$^{-1}$ at $(l, b)$=(206°50, -16°35) and the secondary peak P2 in 8.41 – 9.68 km s$^{-1}$ at $(l, b)$=(206°37, -16°42). The two positions show integrated $^{13}$CO($J$=2–1) intensity greater than 8 K km s$^{-1}$ in Figure 3. We also found a marked intensity depression D1 in 8.41 – 10.32 km s$^{-1}$ peaked at $(l, b)$=(206°47, -16°40). Toward P1, there is the ionizing source of NGC 2024, IRS2b (Bik et al. 2003). P1 is most likely associated with the source and still might be forming high-mass stars in it (Megeath et al. 2012).

These two peaks and the depression with distinct velocity ranges are clearly seen in the 1st moment map of the $^{13}$CO($J$=2–1) emission shown in Figure 4a. Figures 4a and 4b are intensity-weighted mean velocity and standard deviation velocity distributions, respectively with the contours of integrated intensity (0th moment). We used only voxels with enough high significance levels ($\geq 6\sigma$) to calculate the moments in order to reduce effects of noise fluctuations. Figure 4a shows a systematic velocity gradient: the clouds with the larger galactic longitudes (roughly 206°5 to 206°7) including P1 are red-shifted, and the clouds with the smaller galactic longitudes (roughly 206°2 to 206°5) including P2 are blue-shifted.

We hereafter refer to these clouds as a red cloud and blue cloud, respectively. Velocities of these two clouds are generally consistent with those of two clouds shown in the global structure of NGC 2023 / NGC 2024 region (Figure 1b and 1c). Therefore, the velocity gradient is not a velocity pattern in a single cloud but the velocity originated from two independent clouds with different velocities. P1 is included in the red cloud but the velocity of P1 is relatively lower and close to that of
Fig. 3. Velocity-channel distributions of the $^{13}\text{CO}(J=2\rightarrow1)$ emission toward NGC 2024 obtained with NANTEN2. The contour levels are indicated at the bottom of the Figure. The cross depicts the position of IRS2b. P1, P2 and D1 show the primary peak intensity ($l, b$)=(206°50.3, -16°35), secondary peak intensity ($l, b$)=(206°37.4, -16°42) and intensity depression ($l, b$)=(206°46.4, -16°40) in $^{13}\text{CO}(J=2\rightarrow1)$. 

The cross depicts the position of IRS2b. P1, P2 and D1 show the primary peak intensity ($l, b$)=(206°50.3, -16°35), secondary peak intensity ($l, b$)=(206°37.4, -16°42) and intensity depression ($l, b$)=(206°46.4, -16°40) in $^{13}\text{CO}(J=2\rightarrow1)$. 

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Using these two moment maps, we here define the velocity ranges of these two clouds. From Figure 4a, the red cloud shows velocity greater than 10.3 km s\(^{-1}\) corresponding to the light green to the white, and the blue cloud shows velocity less than 9.5 km s\(^{-1}\) corresponding to the blue to the black. Then, we first defined areas of the red and blue clouds as pixels with \( \geq 10.3 \text{ km s}^{-1} \) and \( \leq 9.5 \text{ km s}^{-1} \), respectively. These areas are indicated as the red and blue transparent colors in Figure 4c.

Next, we calculated an averaged-mean velocities and averaged-standard deviation velocities within the defined areas by using two moment maps (Figures 4a and 4b). Here we adopt the averaged-mean velocities and the averaged-standard deviation velocities as the center velocity \( V_{\text{center}} \) and the velocity width \( dV \) of a cloud, respectively and define the cloud’s velocity range as \( V_{\text{center}} \pm dV \). \( V_{\text{center}}, dV \), velocity range for each cloud are summarized in Table 1. The above method of velocity definition was introduced in (Enokiya et al. 2019) and they properly identified clouds even in more complicated region, namely the Galactic Center including more than four velocity features in the line-of-sight.

**Table 1. Physical parameters of the molecular clouds toward NGC 2024**

| cloud name | \( V_{\text{LSR}} \) [km s\(^{-1}\)] | \( V_{\text{center}} \) [km s\(^{-1}\)] | \( dV \) [km s\(^{-1}\)] | \( N_{\text{H}_2} \) (peak) \( \times 10^{22} \text{ cm}^{-2} \) | Mass \( \times 10^2 \text{ M}_\odot \) |
|------------|---------------------------------|---------------------------------|-----------------|---------------------------------|-----------------|
| blue cloud | 8.5 – 9.7                        | 9.1                             | 0.58            | 1.2                             | 2.8             |
| red cloud  | 10.4 – 11.6                      | 11.0                            | 0.61            | 2.4                             | 2.3             |

Note. — Col.1: Names of clouds. Col.2: Velocity ranges. Col.3: Peak velocities derived from the 1st moment map. Col.4: Velocity line widths derived from the 2nd moment map. Col.5: Maximum molecular column density toward each cloud. Col.6: Molecular mass.
Figure 5. (a, b) Integrated intensity distributions of $^{13}$CO(J=2–1) with the velocity ranges defined as the blue cloud ($8.5 \leq V_{\text{LSR}} \leq 9.7 \text{ km s}^{-1}$) and the red cloud ($10.4 \leq V_{\text{LSR}} \leq 11.6 \text{ km s}^{-1}$). Contour levels are indicated at the bottom of each Figure. (c, d) The same contours as Figure 5a and 5b but superposed on optical images of DSS2 red. The white cross indicates the position of IRS2b.

Figure 4b shows a correlation between velocity dispersions (color) and integrated intensities (contours) other than a filamentary region in the vicinity of P2. The filament indicates higher value of $\geq 1.2 \text{ km s}^{-1}$ due to a overlap of two clouds in the line-of-sight (see Figure 3).

Figures 5a and 5b are integrated intensity distributions of the blue and red clouds, respectively using integration velocity ranges defined above. The blue cloud is a diffuse cloud extending $\sim 2 \text{ pc}$ which has a significant hole (D1) at the bottom center of it. On the other hand, the red cloud mainly consists of a small $\sim 1 \text{ pc}$ clump (P1). Figures 5c and 5d are superpositions of contours of the red and blue clouds on DSS2 r band images.

The DSS2 image shows a major optical dark lane across the HII region. Some of the additional minor dark lanes have a tilt of $\sim 70^\circ$ to the major lane. The blue cloud shows better correlation with
the dark lanes, suggesting that the cloud is located on the near side of the HII region (Figure 5c). The red cloud is most likely associated with the exciting star (IRS2b) and thus lies inside or behind the HII region as shown by its poor correlation with the dark lanes (Figure 5b).

The association between the blue cloud and the HII region is not clear only above observational evidence. However since the column density of the cloud is not so low and it is unnatural to consider that such a relatively dense gas are located between the known nearest clouds, the Orion clouds, and us in the same line-of-sight by chance, it is plausible to consider that the blue cloud is a part of the NGC 2024 system and associated with the HII region.

3.3 physical parameters of molecular clouds

The column densities and masses of the red and blue clouds are derived from our $^{13}$CO($J=2–1$) data as follows: We first assumed that the excitation temperature $T_{\text{ex}}$ of all the $^{13}$CO clouds to be 30 K (LTE approximation) because the maximum value of $T_{\text{mb}}$ is $\sim$20 K in $^{13}$CO($J=2–1$) and a estimated maximum value of $T_{\text{ex}}$ from $^{12}$CO($J=1–0$) is $\sim$30 K. The equivalent brightness temperature $J(T)$ is described as

$$ J(T) = \frac{h}{k_B} \left[ \exp\left( \frac{h\nu}{k_BT} - 1 \right) \right]^{-1}. $$

where $h$, $k_B$, and $\nu$ are Planck constant, Boltzman constant, and the frequency, respectively. From the radiative transfer equation, we obtain optical depth $\tau_\nu$ as follows,

$$ \tau_\nu = -\ln\left( 1 - \frac{T_{\text{mb}}}{J(T_{\text{ex}}) - J(T_{\text{bg}})} \right). $$

Using the $\tau_\nu$, column density $N$ of the molecule can be calculated as

$$ N = \sum_\nu \tau_\nu \Delta\nu \frac{k_BT_{\text{ex}}}{4\pi^3v^2\mu^2} \exp\left( \frac{h\nu J}{2k_BT_{\text{ex}}} \right) \frac{1}{1 - \exp\left( -\frac{h\nu}{k_BT_{\text{ex}}} \right)} \frac{1}{1 - \exp\left( -\frac{h\nu}{k_BT_{\text{ex}}} \right)} . $$

where $V$, $\Delta\nu$, $\mu$, and $J$ are the velocity range of a cloud, the velocity resolution of the data, the electric dipole moment of the molecule, and the rotational transition level, respectively. Substituting $k_B = 1.38 \times 10^{-16}$ (erg/K), $T_{\text{ex}} = 30$ (K), $\nu = 2.20 \times 10^{11}$ (Hz), $\mu = 1.10 \times 10^{-19}$ (esu cm), $h = 6.63 \times 10^{-27}$ (erg s), $J = 1$ into equation (3) gives below

$$ N_{^{13}\text{CO}} = 1.508 \times 10^{16} \sum_\nu \tau_\nu \Delta\nu. $$

Assuming ratio between $N_{\text{H}_2}$ and $N_{^{13}\text{CO}}$ of $5 \times 10^2$ (Dickman 1978), $N_{\text{H}_2}$ is estimated to be

$$ N_{\text{H}_2} = 7.54 \times 10^{21} \sum_\nu \tau_\nu \Delta\nu. $$

The velocity ranges of two clouds which we defined before well represent major features of each clouds (Figures 5a and 5b). However, diffuse emissions are still extending over these velocity
ranges (see Figures 2a and 2b). Therefore, we here adopt $7.50 \leq V_{\text{LSR}} \leq 13.00$ km s$^{-1}$ as the velocity range for deriving column densities and masses of two clouds ($V$ in equation (3)–(5)). We also use red and blue distributions in Figure 4c as the definition of the red and blue clouds in space. Applying above definitions in space and velocity, we obtained typical/peak column densities of the red and blue clouds to be $7.7/240 \times 10^{20}$, $9.3/190 \times 10^{20}$ cm$^{-2}$, respectively. Molecular mass is estimated following equation:

$$M = \mu m_p \sum_i [d^2 \Omega N_{\text{H}_2,i}].$$

(6)

where $\mu_m$, $m_p$, $d$, $\Omega$ and $N_{\text{H}_2,i}$ are the mean molecular weight, proton mass, distance, solid angle subtended a pixel, and column density of molecular hydrogen for the i-th pixel, respectively. We assume a helium abundance of 20 %, which corresponds to $\mu_w = 2.8$, and we take $d = 410$ pc and then get masses of the red and blues clouds of $\sim 230$ and $\sim 280$ $M_\odot$, respectively. These values are not so different compared to that of previous study ($\sim$ a few hundred $M_\odot$; Kramer et al. 1996). These physical parameters are summarized in table 1.

The column density of P1 derived our $^{13}$CO($J=2\rightarrow1$) data are not high ($\sim 2.4 \times 10^{22}$ cm$^{-2}$) compared to the column density derived from Herschel observations ($\sim 1\rightarrow2 \times 10^{23}$ cm$^{-2}$; see Figure 9 of Gratier et al. 2017). Therefore, our values might be lower limits caused by a beam dilution effect due to the coarser angular resolution. Observations with higher angular resolution are required to clarify this.

4 Discussion

In the previous section, we presented not only a global distribution and properties of molecular gas but also gas distribution with finer angular resolution obtained by our new comprehensive $^{13}$CO($J=2\rightarrow1$) observations. The results show that there are prominent molecular features; two intensity peaks P1, P2 and a depression D1. P1 is a major feature of the one of associated clouds, the red cloud, with NGC 2024. P2 and D1 are parts of another associated cloud, the blue cloud, located in front of the HII region.

In the present section, we focus on the origin of marked features and discuss a possible high-mass star formation scenario in this region.

4.1 Complimentary distribution

D1 is an unusual marked hole with sharp intensity gradient toward its surroundings. The interior of it shows almost no significant $^{13}$CO emissions. It is hard to explain that the structure was created
by chance in a process of the self-gravitational evolution of the blue cloud. Such a hole is usually observed toward surroundings of a high-mass star(s) as a result of ionization by its UV radiation. However, there is no known high-mass stars interior of D1 (e.g. Megeath et al. 2012).

Another mechanism to create such a hole is cloud-cloud collision (CCC). If a CCC is operating, we expect some complementary distribution between the hole and a clump, which hollowed the blue cloud and created D1. Therefore, if D1 is created by a CCC, another cloud with a different velocity is required. The only candidate is the red cloud. By eye inspection, we recognize a complementarity between P1 and D1 (see Figures 5a and 5b).

Figure 6 shows that distribution of the blue cloud in blue and P1 in thin orange contours. We found that P1 perfectly fits to D1 if they are displaced ~0.6 pc to the south-west with the angle of 26.57 degree clockwise from the direction of the galactic longitude indicated by a white arrow. The displaced distribution of P1 is shown as thick orange contours. Such a displacement is an observational signature of colliding clouds (Fukui et al. 2018a; Fukui et al. 2018b).

4.2 Possibility of a cloud-cloud collision in NGC 2024

We mentioned that a CCC between the red and blue clouds is a plausible mechanism to create D1. We examine a further applicability of the CCC scenario below.

Fukui et al. (2018b) summarized observational signatures of high-mass star formation under triggering by cloud-cloud collision as follows;
i) Two clouds with supersonic velocity separation associated with young high-mass star(s),
ii) complementary spatial distribution between the two clouds, and
iii) bridge feature connecting the two clouds in velocity.

According to the theoretical simulations of Takahira et al. (2014) and the synthetic observations by Fukui et al. (2018b), an intensity depression is produced by a cloud-cloud collision where a smaller cloud creates a hole in a larger cloud. The displacement between the small cloud and the hole reflects a tilt angle of the relative cloud motion to the line of sight, and synthetic observations of two colliding clouds based on numerical simulations provide details of the collisional interaction between the small cloud and the hole (Fukui et al. 2018b), as described in Section 4.2. The numerical simulation show the collisional front is rapidly compressed and massive clumps which will grow up progenitor of high-mass stars are formed in it. Once two clouds begin to collide, they produce a bridge feature or a V-shaped structure in the position-velocity digram due to the exchange of momenta. Recently, thanks to galactic plane surveys with enough high angular resolution in CO such as FUGIN (Umemoto et al. 2017) and Mopra (Braiding et al. 2018), more than 50 galactic HII regions and clusters that have above signatures triggered by CCC are reported (e.g., Enokiya et al. 2018; Hayashi et al. 2018; Sano et al. 2018; Dewangan et al. 2019).

Now, we have two clouds (the red and blue) with supersonic velocity separation of \( \sim 2 \) km \( s^{-1} \) associating a high-mass star IRS2b and found these two clouds exhibit complementary distribution with a certain displacement.

Figures 7a and 7b are a integrated intensity distribution and the position-velocity diagram of the red and blue clouds in the offset X-Y coordinate. The coordinate was defined by rotating the galactic coordinate counterclockwise to the angle given by the displacement vector (\( \sim 26.57 \) degree) indicated by the white arrow in Figure 6. The position-velocity diagram shows a rotated V-shape connecting the red and blue clouds indicated by a thick black dashed line. The toe of the V shape corresponds to the location of IRS2b.

In conclusion, we suggest that a CCC happened in NGC 2024. It could be argued alternatively that the two velocities are due to acceleration by the late O/early B-type stars and not a cause of a CCC. The cloud velocity and dispersion, however, show no systematic enhancement or variation toward or correlated with the O/B-type stars (see Figure 7b), which is not consistent with a dominant dynamical effect by the stars. The velocity field which does not show particular variation toward the stars is odd, if the stars were the major source of the cloud momentum. So, we do not consider the stellar acceleration, and explore the CCC as a possible scenario in the present paper.
4.3 Triggered star formation by a cloud-cloud collision model

Based on the above results and discussion we hypothesize a collision between the two clouds triggered formation of the late O/early B stars in NGC 2024. For simplicity, if we assume a tilt angle $\theta$ of 45° to the line-of-sight, the cloud relative velocity and the displacement are $1.9 \times \sqrt{2} \simeq 2.7$ km s$^{-1}$ and $0.6 \times \sqrt{2} \simeq 0.8$ pc, respectively. The timescale of the collision is then estimated to be $3 \times 10^5$ yrs from a ratio 0.8 pc/2.7 km s$^{-1}$. A schematic image of the collision in the sky view is shown in Figure 8.

The time scale is consistent with a very small age less than Myr of the young stars in NGC 2024 (Ali et al. 1995; Meyer 1996). If we assume a tilt larger than 60° the velocity becomes 4 km s$^{-1}$ or more, whereas an assumption on the tilt angle does not significantly alter the timescale. The location of the blue cloud in the foreground of the H II region is consistent with an epoch after the collision.

Figure 9 shows the $^{13}$CO clump toward the primary peak P1; this indicates a strong concentration of $\sim 20$ protostars (Megeath et al. 2012), which corresponds to an O-type star IRS2b and probably young B stars (Getman et al. 2014; Bik et al. 2003; Skinner et al. 2003), toward the $^{13}$CO peak P1, showing that the $^{13}$CO clump is forming high-mass stars actively.

In the present scenario, the relative velocity of the clouds is pre-determined in the Galactic environment and the collision is by chance. The gravity of the system is actually not dominant for a set of relevant parameters; the velocity in gravitational balance with an observed cloud mass of 200...
$M_\odot$ and a radius of 1 pc is 1.5 km s$^{-1}$, marginally less than the projection-corrected velocity above.

In the scenario, the major collision took place toward P1 in the red cloud, which was impacted by the blue cloud on the far side of the red cloud. P1 has a high column density of more than $10^{23}$ cm$^{-2}$ and $\sim$ 20 protostars are forming at present (Megeath et al. 2012). The interface layer between the two colliding clouds becomes highly turbulent due to the clumpy distribution in the cloud prior to the collision. The turbulence amplifies the magnetic field according to the numerical simulations of cloud-cloud collision (Inoue & Fukui 2013). The combined contribution of the turbulence and magnetic field realizes high-mass accretion rate of $10^{-3}$ to $10^{-4}$ $M_\odot$/yr, which allows a protostar to overcome the stellar radiation pressure and to grow in mass. The most high-mass star in NGC 2024
IRS2b having $23 \, M_\odot$ (Bik et al. 2003) can be formed in a timescale of $1 \times 10^5$ yrs at an assumed mass accretion rate $2 \times 10^{-4} \, M_\odot$/yrs. The column density at P2 where the collision have not been took place is about half of that at P1, then if we assume D1 had the column density comparable to that of P2 prior to the collision, the collision increased the column density by a factor of two.

The heavy obscuration toward the young stars and the sign of disks of the stars (Meyer 1996) is consistent with the scenario and do not exclude that the stars are still growing in mass via accretion to become O-type stars eventually in $\sim 10^5$ yrs, when ionization by O-type stars may halt further mass accretion.

4.4 NGC 2024 in samples of cloud-cloud collision

We summarized signatures of a CCC suggested in (Fukui et al. 2018b) in subsection 4.2. These signatures are however not always detectable in observational data. The numerical simulations (Takahira et al. 2014, and the synthetic observations by Fukui et al. 2018a) indicate that the two clouds often show a single spectral peak instead of two peaks, because the collision mixes the two clouds in velocity as
a result of momentum exchange between the two clouds (see Figures 3 and 4 in Fukui et al. 2018a).

The trend of a single peak in colliding clouds becomes significant if the projected velocity separation is smaller than the linewidth of the individual clouds. The peak velocity of the merging clouds is governed by the cloud with higher molecular column density (Fukui et al. 2018b). The collisional dissipation further destroys the two clouds (Torii et al. 2015), and in addition, the ionization by the formed O-type star(s) disperses the parent molecular gas within \( \sim 10 \) pc of the O-type stars. As a result, the collision signatures quickly disappear (Figure 4 in Fukui et al. 2016). These effects make it difficult to identify the collision signatures and the initial two clouds, and an apparently single cloud does not contradict with CCC.

In NGC 2024, the projected velocity separation between the two clouds is small, only 2 km s\(^{-1}\), and we see the complementary distribution (Section 4.1). The two clouds appear to be merged toward P1 which shows large velocity dispersion from 8 to 13 km s\(^{-1}\) at 3 K pc level (Figure 7b). Due to the small duration time, the collisional cloud dissipation is still not significant and we see a massive dense clump toward the \( \sim 20 \) protostars as P1 whose molecular mass is estimated to be 60 \( M_\odot \) from \(^{13}\)CO\((J=2–1)\) data by assuming LTE within 0.2 pc. The absence of early O-type stars makes ionization less effective than in O-type star forming regions.

Enokiya et al. (2019) suggested that there is a column density threshold to trigger formation of high-mass stars by CCC. The threshold molecular column density in formation of multiple O-type stars is \( \sim 10^{23} \) cm\(^{-2}\) and that in a single O-type star 10\(^{22} \) cm\(^{-2}\). For column density less than these values no O-type stars are formed in CCC, and only collision toward high column-density gas leads to formation of O-/early B-type stars. High-mass star clusters in RCW38, Westerlund 2, NGC 3603, and M42 have molecular column density of \( \sim 10^{23} \) and some authors suggested these clusters are triggered by CCC (Fukui et al. 2016; Furukawa et al. 2009; Fukui et al. 2014; Fukui et al. 2018b). The high column density in NGC 2024, \( \sim 10^{23} \) cm\(^{-2}\), is consistent with this threshold, and we infer that even more high-mass stars may form in near future if high-mass star formation is continuing in NGC 2024.

Both the red and blue clouds discovered by our work is extending to the NGC 2023 region (Figure 1b, 1c). Therefore it is suggested that a CCC is happening also in this region, although spectra at current spatial resolution show only a single component (Figure 2c and 2d). A further discussion of CCC and high-mass star formation in Orion B will be developed in a forth coming papers on NGC 2023 (Fukui et al. 2020 in prep.) and NGC 2068 / NGC 2071 (Fujita et al. 2019).
5 Conclusions

We carried out new observations of $^{13}\text{CO}(J=2-1)$ transitions in the NGC 2024 region with NANTEN2. These observations cover the whole NGC 2024 region at 0.2 pc resolution. The main results are summarized below.

1. Contrary to the previous observations which suggested a single cloud component, we found a possibility that the cloud comprises two velocity components (a red cloud and blue cloud) with complementary distribution. The projected velocity separation of these clouds is $\sim 2$ km s$^{-1}$. The blue cloud shows good correspondence with several minor dark lanes, indicating that it is on the foreground of the HII region. On the other hand, the red cloud most likely associates with the exciting star IRS2b and is located inside or backside of the HII region.

2. We found that a displacement of $\sim 0.6$ pc in a position angle of $\sim 27^\circ$ of the blue cloud produces a good spatial correspondence between an intensity peak in the red cloud and a depression in the blue cloud forming complementary distribution. These two velocity components seem to be merged into a single velocity component.

3. We hypothesize that collision between the two clouds triggered formation of the $\sim 20$ protostars including IRS2b. The collision timescale is estimated to be $3 \times 10^5$ yrs. The molecular column density toward the $^{13}\text{CO}(J=2-1)$ peak estimated to be higher than $\sim 2 \times 10^{22}$ cm$^{-2}$, possibly $\sim 10^{23}$ cm$^{-2}$, and that in the surrounding regions is $\sim 1 \times 10^{22}$ cm$^{-2}$. The collision realized a high-mass accretion rate of $10^{-4} M_\odot$/yrs as shown by the mechanism presented by Inoue & Fukui (2013), and triggered the O/early B star formation. The number of high-mass star candidates is consistent with that of the expected number by its high column density.

It is important in future to investigate nearby molecular clouds within a few kpc in order to better establish the role of CCC in O-type star formation. The coarse resolution CO data in Figures 1b and 1c does not exclude two velocity components, which might suggest a CCC toward NGC2023. It is therefore important to explore a possibility of CCC at higher resolution toward NGC 2023 also. NGC 2024 is a unique object which is extremely young with an age $\lesssim 10^5$ yrs among those discovered until now. Thanks to the young age the parent cloud remains unionized and we are able to observe its details including the column density. Higher resolution studies with ALMA will shed a new light on the formation of dense clumps and their mass function in the shock-compressed layer by CCC.

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