Large-scale CO $J=1–0$ observations of the giant molecular cloud associated with the infrared ring N35 with the Nobeyama 45-m telescope

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Abstract

We report an observational study of the giant molecular cloud (GMC) associated with the Galactic infrared ring-like structure N35 and two nearby H$\text{II}$ regions G024.392+00.072 (H$\text{II}$ region A) and G024.510-00.060 (H$\text{II}$ region B), using the new CO $J=1–0$ data obtained as a
part of the FOREST Unbiased Galactic Plane Imaging survey with the Nobeyama 45-m telescope (FUGIN) project at a spatial resolution of 21″. Our CO data revealed that the GMC, with a total molecular mass of $2.1 \times 10^6 \, M_\odot$, has two velocity components over $\sim 10$–$15 \, \text{km s}^{-1}$. The majority of molecular gas in the GMC is included in the lower-velocity component (LVC) at $\sim 110$–$114 \, \text{km s}^{-1}$, while the higher-velocity components (HVCs) at $\sim 118$–$126 \, \text{km s}^{-1}$ consist of three smaller molecular clouds which are located near the three H\textsc{ii} regions. The LVC and HVCs show spatially complementary distributions along the line-of-sight, despite large velocity separations of $\sim 5$–$15 \, \text{km s}^{-1}$, and are connected in velocity by the CO emission with intermediate intensities. By comparing the observations with simulations, we discuss a scenario where collisions of the three HVCs with LVC at velocities of $\sim 10$–$15 \, \text{km s}^{-1}$ can provide an interpretation of these two observational signatures. The intermediate velocity features between the LVC and HVCs can be understood as broad bridge features, which indicate the turbulent motion of the gas at the collision interfaces, while the spatially complementary distributions represent the cavities created in the LVC by the HVCs through the collisions. Our model indicates that the three H\textsc{ii} regions were formed after the onset of the collisions, and it is therefore suggested that the high-mass star formation in the GMC was triggered by the collisions.

**Key words:** ISM: clouds — ISM: molecules — radio lines: ISM — stars: formation

1 Introduction

It is of fundamental importance to understand the formation mechanism of high-mass stars in our long-term efforts to elucidate the structure and evolution of galaxies, as high-mass stars are influential in the interstellar medium (ISM); they inject a large amount of energy via ultraviolet (UV) radiation, stellar winds, and supernova explosions.

It is increasingly evident that cloud-cloud collision (CCC) plays an important role on formation of high-mass stars. Observational studies of CCC were carried out in the high-mass star forming regions in the Milky Way (MW) and the Large Magellanic cloud (LMC) (e.g., Loren 1976; Furukawa et al. 2009; Torii et al. 2011; Fukui et al. 2014; Fukui et al. 2017b), which include H\textsc{ii} regions excited by a single O star (e.g., M20: Torii et al. 2011; Torii et al. 2017b, RCW120: Torii et al. 2015), Galactic super star clusters that have a few tens O stars within a small volume (e.g., Westerlund 2: Furukawa et al. 2009; Ohama et al. 2010, NGC3603: Fukui et al. 2014, RCW38: Fukui et al. 2016), large H\textsc{ii}
regions extended for several tens of pc (e.g., W51: Okumura et al. 2001 and Fujita et al. 2017 and NGC6334+NGC6357: Fukui et al. 2017d), the GMCs in the LMC (e.g., Fukui et al. 2015; Saigo et al. 2017), and so on.

In addition, theoretical studies of CCC have been conducted by many researchers (e.g., Stone 1970; Habe and Ohta 1992; Inoue and Fukui 2013; Takahira, Tasker, and Habe 2014; Haworth et al. 2015a). Habe and Ohta (1992) calculated a collision between two clouds with different sizes, followed by Anathpindika (2010) and Takahira, Tasker, and Habe (2014), indicating that CCC can induce formation of dense self-gravitating clumps within a dense gas layer compressed by collision. Formation of the massive clumps in the collisional-compressed layer was also discussed in depth in the magneto-hydrodynamical (MHD) simulations by Inoue and Fukui (2013) and Inoue et al. (2017). Wu et al. (2017) discussed that collision between GMCs increases star formation rate and efficiency. Using a radiative transfer code, Haworth et al. (2015a) and Haworth et al. (2015b) post-processed the CCC model data calculated by Takahira, Tasker, and Habe (2014), demonstrating observational signatures characteristic to CCC. Their discussion was confirmed by the molecular line observations by Torii et al. (2017a), Torii et al. (2017b), and Fukui et al. (2017c) in the Galactic HII regions. Global scale numerical calculations indicate that CCCs can be as frequent as every \( \sim 10 \) Myrs in a MW-like galaxy (Tasker and Tan 2009; Dobbs, Pringle, and Duarte-Cabral 2015).

These studies have shown that CCC is a promising mechanism of the formation of massive dense clumps which lead to the formation of high-mass stars, and it is therefore of crucial importance to enlarge the samples of the CCC regions for comprehensive understanding of CCC and subsequent high-mass star formation in the MW. For such a purpose, infrared ring or bubbling structures distributed in the Galactic plane are important observational targets. Based on the Spitzer infrared observations, Churchwell et al. (2006) and Churchwell et al. (2007) identified about 600 ring-like 8 \( \mu \)m structures in the Galactic plane; this was followed by an expanded catalog of \( \sim 5100 \) rings by Simpson et al. (2012). Deharveng et al. (2010) and Kendrew et al. (2012) discussed that the majority of the identified infrared ring-like structures are associated with the HII regions embedded within the molecular clouds. These infrared ring-like structures therefore provide important sites in which to study high-mass star formation, and molecular line observations in the several infrared ring-like structures, i.e., RCW 120 (N9 in Churchwell et al. 2006) by Torii et al. 2015, N37 by Baug et al. (2016), N18 by Torii et al. (2017a), N49 by Dewangan, Ojha, and Zinchenko (2017), and S116–118 by Fukui et al. (2017a), have indicated that these high-mass star forming regions were likely formed by the triggering of CCC.

In this paper, we report an observational study of the GMC which includes the infrared ring-like structure N35 and nearby HII regions with the CO \( J=1–0 \) data obtained using the Nobeyama
45-m telescope. Figure 1 shows a two color composite image of the Spitzer/GLIMPSE 8 µm emission (green, Benjamin et al. 2003; Churchwell et al. 2009) and the Spitzer/MIPSGAL 24 µm emission (red, Carey et al. 2009) for a large area including N35 and nearby HII regions, where the contours indicate the HI/OH/Recombination line survey of the Milky Way (THOR) 21 cm radio continuum data, which has a beam size of ∼25″ (Beuther et al. 2016). The 24 µm emission, which is attributed to warm dust grains, roughly coincides with the 21 cm distribution, while the 8 µm emission dominated by polycyclic aromatic hydrocarbons (PAHs) surrounds the 21 cm and 24 µm distributions. Observations of the radio recombination line indicates a radial velocity of the ionized gas in N35 as ∼115.7 ± 1.2 km s⁻¹ (Lockman 1989).

Other than N35, there are three HII regions at the south to N35 as shown in Figure 1, i.e., G024.392+00.072, G024.510-00.060, and G024.217-00.053 (Anderson et al. 2014). Radio recombination line observations indicate that the former two have radial velocities of ∼110.0 ± 1.2 (Lockman 1989) and ∼108.1 ± 0.5 km s⁻¹ (Sewilo et al. 2004), respectively, which are similar to that in N35, while the last one has a velocity of ∼82.0 ± 2.4 km s⁻¹ (Lockman 1989), suggesting that it is located
at a different distance from N35. For the sake of convenience, we hereafter refer the former two HII regions, G024.392+00.072 and G024.510-00.060, as “HII region A” and “HII region B”, respectively.

The observed radial velocities of N35 and HII regions A and B, \(\sim 108\text{–}115 \text{ km s}^{-1}\), correspond to the near- and far-kinematic distances of 6.4\text{–}6.9 kpc and 8.6\text{–}9.1 kpc, respectively (Anderson and Bania 2009). Based on the absorption and self-absorption studies of the HI 21 cm profiles, Anderson and Bania (2009) favored the far-kinematic distances in these three HII regions. Following their results, in this paper we adopt the common distance of 8.8 kpc to the three HII regions with an uncertainty of 0.3 kpc, as all of these HII regions are associated with a single GMC as presented later in Section 3 with our new CO data. Assuming a distance of 8.8 kpc, the size of the HII region in N35 is measured as \(7' \approx 18 \text{ pc}\), and the total infrared luminosity of N35 measured by Hattori et al. (2016) can be rescaled to \(\sim 10^{6.7} L_\odot\).

Molecular line observations of N35 was performed by Beaumont and Williams (2010) in the \(^{12}\text{CO} J=3\text{–}2\) transition using the James Clerk Maxwell Telescope (JCMT) telescope for a \(\sim 15' \times 15'\) area centered on N35, indicating that molecular gas at \(\sim 110\text{–}120 \text{ km s}^{-1}\), although detailed distribution and dynamics of molecular gas for a large area of N35 has not been studied. In this study, we present the molecular gas distribution for a \(0.52' \times 0.57'\) region including N35 and HII regions A and B using the CO \(J=1\text{–}0\) data obtained with the Nobeyama 45-m radio telescope at an angular resolution of 21", which corresponds to \(\sim 0.9 \text{ pc}\) at 8.8 kpc. The high spatial resolution provides a wealth of information on distribution and dynamics of the molecular gas, allowing us to investigate high-mass star formation in this region. In section 2 we describe the CO \(J=1\text{–}0\) dataset used in this study, and in section 3 we present the main results of the analyses of the CO dataset and comparisons with the other wavelengths. In section 4 we discuss the results and a summary is presented in section 5. In this paper, we refer to the four points of the compass based on the Galactic coordinates.

## 2 Data set

The \(^{12}\text{CO}, \^{13}\text{CO}, \text{and } C^{18}\text{O} J=1\text{–}0\) dataset presented in this paper was obtained as a part of FOREST Unbiased Galactic plane Imaging survey with the Nobeyama 45-m telescope (FUGIN; for the full description of the observations and data reduction, see Umemoto et al. 2017). FUGIN is a large scale Galactic plane survey of the three CO isotopologues using the FOur-beam REceiver System on the 45-m Telescope receiver (FOREST; Minamidani et al. 2016), which is a four beams, dual-polarization, and two sideband receiver. Typical system temperatures of FOREST were \(\sim 250 \text{ K}\) for \(^{12}\text{CO}\) and \(\sim 150 \text{ K}\) for \(^{13}\text{CO}\) and \(C^{18}\text{O}\). The backend system was the digital spectrometer “SAM45”, which provided a bandwidth of 1 GHz and a resolution of 244.14 kHz, which correspond to \(\sim 2600 \text{ km s}^{-1}\)
and \( \sim 1.3 \text{ km s}^{-1} \), respectively, at 115 GHz. The observations were made in the on-the-fly mode with an output grid size of \( 8.5'' \) in space and \( 0.65 \text{ km s}^{-1} \) in velocity. We smoothed the output data with a two-dimensional Gaussian function to a spatial resolution of \( 25'' \) to improve sensitivities. The final root-mean-square (r.m.s) noise fluctuations of the data were 0.8 K for \(^{12}\text{CO} \) and 0.4 K for \(^{13}\text{CO} \) and \(^{18}\text{C} \) at a channel resolution of 0.65 km s\(^{-1} \).

3 Results

3.1 Large-scale CO distributions

Figure 2 shows intensity distributions of the three CO lines integrated over a velocity range of \( \sim 105-125 \text{ km s}^{-1} \), at which the CO emission associated with N35 and HII regions A and B is pronounced. We identified a GMC in this velocity range which has a size of about 30 pc \( \times \) 50 pc at 8.8 kpc. We hereafter refer the GMC as the “N35 GMC”. As shown in Figures 2(a) and (b), the \(^{12}\text{CO} \) and \(^{13}\text{CO} \) emission in the N35 GMC are enhanced at the eastern rim of the cloud at \( l \sim 24.4^\circ -24.5^\circ \) and \( b \sim 0.05^\circ -0.35^\circ \), forming a ridge feature which is stretched along the north-south direction. N35 is located on the east of this ridge feature, while HII region A is distributed around the southern end of the ridge feature. HII region B is seen at the southeastern rim the GMC. \(^{18}\text{C} \) is widely detected in the N35 GMC (Figure 2(c)), indicating the presence of dense gas.

By assuming an X(CO)-factor of \( 2 \times 10^{20} \text{ cm}^{-2} \text{ (K km s}^{-1})^{-1} \) (Strong and Moskalenko 1998), which is the CO-to-\( \text{H}_2 \) conversion factor, the total molecular mass of the GMC can be calculated as \( \sim 2.1 \times 10^6 M_\odot \) from the \(^{12}\text{CO} \) map in Figure 2(a), where we defined the GMC by drawing a contour at 70 K km s\(^{-1} \). In addition, we measured the total molecular mass of the GMC from the \(^{13}\text{CO} J=1-0 \) data assuming local thermodynamic equilibrium. We estimated the excitation temperature \( T_{\text{ex}} \) of the \(^{13}\text{CO} \) emission at each direction of the defined GMC with the following equation,

\[
T_{\text{ex}}(\text{K}) = \frac{5.53}{\ln\{1 + 5.53/(T(^{12}\text{CO}) + 0.819)\}},
\]

where \( T(^{12}\text{CO}) \) is the peak temperature of the \(^{12}\text{CO} \) profile. The derived \( T_{\text{ex}} \) ranges between 15 and 25 K, and if we assume an abundance ratio between \(^{12}\text{C} \) and \(^{13}\text{C} \) of 55 (Wilson and Rood 1994), the total molecular mass of the GMC can be estimated as \( \sim 1.4 \times 10^6 M_\odot \), which is nearly consistent with the mass estimated from the \(^{12}\text{CO} \) data. The \( \text{H}_2 \) column densities \( N(\text{H}_2) \) tend to increase to \((4-6) \times 10^{22} \text{ cm}^{-2} \) at the regions that have \(^{13}\text{CO} \) integrated intensities larger than \( \sim 70 \text{ K km s}^{-1} \) in the \(^{13}\text{CO} \) map in Figure 2(b), which includes the ridge feature and the gas associated with HII region B, while the other part of the GMC that have lower \(^{13}\text{CO} \) integrated intensities show typical \( N(\text{H}_2) \) of \((2-3) \times 10^{22} \text{ cm}^{-2} \).
Fig. 2. (a) Integrated intensity distributions of the FUGIN CO data for a velocity range of 105–125 km s$^{-1}$. The maps of $^{12}$CO, $^{13}$CO, and C$^{18}$O $J$=1–0 are presented in (a), (b), and (c), respectively. Contours indicate the 8 $\mu$m emission plotted at 150 and 200 MJy str$^{-1}$. Dashed lines in (b) indicate the areas used for the position-velocity diagrams shown in Figure 3.

Fig. 3. Position-velocity diagrams of the $^{13}$CO emission toward the three HII regions, (a) N35, (b) HII region A, and (c) HII region B. Integration ranges in the Galactic latitude are plotted in Figure 2(b) with dashed lines. Horizontal solid lines indicate the velocity ranges shown in Figures 6–8, while vertical dashed lines indicate the extents of the individual HII regions measured in the 21 cm radio continuum map in Figure 1. The arrows with solid lines in (a) and (b) indicate the velocity gradient of molecular gas, while the arrow with dashed lines in (c) depicts the HVC 3.
Figure 3 shows the longitude-velocity diagrams of the $^{13}$CO emission around the three HII regions, N35 and HII regions A and B, where the extents of the HII regions measured with the 21 cm map in Figure 1 are indicated by vertical dashed lines. The integration ranges of these three diagrams are indicated as dashed lines in Figure 2(b) with labels A–C. Figure 3(a) shows a steep velocity gradient of gas at the western part of N35 from $(l,v) \sim (24^\circ.40,110 \text{ km s}^{-1})$ to $(24^\circ.45,121 \text{ km s}^{-1})$, which corresponds $\sim 1.4 \text{ km s}^{-1} \text{ pc}^{-1}$. Velocity gradients are also seen in the gas around HII region A. As indicated by the arrows, there are two velocity gradients. The CO emission is continuously distributed from $(l,v) \sim (24^\circ.30,112 \text{ km s}^{-1})$ to $(l,v) \sim (24^\circ.42,112 \text{ km s}^{-1})$ via $(l,v) \sim (24^\circ.36,118 \text{ km s}^{-1})$, forming an inverted V-shaped velocity distribution of gas. The velocity gradient seen in each side of the inverted V-shaped is measured as $\sim \pm 0.7 \text{ km s}^{-1} \text{ pc}^{-1}$, and HII region A is distributed at the eastern side of the inverted V-shaped at $l \sim 24^\circ.35–24^\circ.41$. On the other hand, although we found no velocity gradient of gas around HII region B in Figure 3(c), we identified a spatially compact emission just west to HII region B at $(l,v) \sim (24^\circ.45,125 \text{ km s}^{-1})$ as indicated by the arrow with dashed line. The compact emission is connected to the molecular gas around 110 km s$^{-1}$ by the diffuse CO emission at the intermediate velocities. These position-velocity diagrams suggest that the N35 GMC has multiple velocity components, and these velocity components are connected with each other by the intermediate velocity emission.

The spatial distributions of the two velocity components are presented in Figure 4 for two velocity ranges, 108–114 km s$^{-1}$ and 118–128 km s$^{-1}$, where the upper and lower panels of the figure show the $^{12}$CO and $^{13}$CO emission, respectively. We also present the velocity channel maps of the $^{12}$CO, $^{13}$CO, and C$^{18}$O emissions for a velocity range from $\sim 102 \text{ km s}^{-1}$ to $\sim 125 \text{ km s}^{-1}$ in Figures A1–A3 in the Appendix as a supplement. In Figures 4(a) and (d) it is seen that the majority of molecular gas in the N35 GMC is included in the lower velocity range, while in the higher velocity range in Figures 4(b) and (e) there are mainly two molecular gas components toward N35 and the southwest of HII region B, which respectively correspond to the higher velocity parts of the velocity gradients seen in the position-velocity diagrams in Figures 3(a) and (b). In addition, the compact CO emission seen at the west of HII region B in Figure 3(c) is seen in the higher velocity range shown in Figures 4(b) and (e). We hereafter refer the larger molecular gas component in the lower velocity range as the “LVC (lower velocity component)”, while the gas components in the higher velocity components the “HVCs (higher velocity components)”. The three HVCs distributed in N35, HII region A, and HII region B are referred as the “HVC 1’, “HVC 2”, and “HVC 3”, respectively, as dubbed in Figure 4(b).

In Figures 4(a) and (d) it is seen that the majority of molecular gas in the N35 GMC is included in the lower velocity range, while in the higher velocity range in Figures 4(b) and (e) there are mainly
two molecular gas components toward N35 and the southwest of HII region B, which respectively correspond to the higher velocity parts of the velocity gradients seen in the position-velocity diagrams in Figures 3(a) and (b). In addition, the compact CO emission seen at the west of HII region B in Figure 3(c) is seen in the higher velocity range shown in Figures 4(b) and (e). We hereafter refer to the larger molecular gas component in the lower velocity range as the “LVC (lower-velocity component)”, and to the gas components in the higher-velocity range as the “HVCs (higher velocity components)”. The three HVCs distributed in N35, HII region A, and HII region B are referred to as “HVC 1”, “HVC 2”, and “HVC 3”, respectively, as dubbed in Figure 4(b).
In N35 the CO emission in the LVC appears to surround the 21 cm radio continuum map (Figures 4(a) and (d)), whereas the HVC 1 which is elongated along the north-south direction coincides with the 21 cm distribution (Figures 4(b) and (e)). The LVC and HVC 1 exhibit complementary distribution, as shown in figures Figures 4(c) and (f). The steep velocity gradient seen in the position-velocity diagram in Figure 3(a) is distributed at the interface of the complementary distribution. Complementary distribution of gas between the LVC and HVCs is also seen around H II regions A and B. The LVC shows an intensity depression toward H II region A, whereas the HVC 2 overlaps the 21 cm emission of H II region A with a shape elongated toward the southwest, showing complementary distribution between these two velocity components. Similar to the case in N35, the velocity gradients seen Figure 3(b) are distributed around the interface of the complementary distribution. The HVC 3 shows a compact circular distribution with radius \( \sim 3 \) pc at \((l,b) \sim (24.45, -0.02)\), and is spatially coincident with the central hole of a ring-like molecular structure in the LVC, the outer radius of which is measured as \( \sim 7-8 \) pc, indicating complementary distribution between the LVC and HVC 3. H II region B is located in the southeast of the ring-like structure of the LVC.

In Figure 5 we plot the first and second moment maps of the \(^{13}\text{CO}\) data, where the \(^{13}\text{CO}\) contour maps of the HVCs are superimposed. In the first moment map in Figure 5(a) it is seen that the three HVCs have velocities of \( \sim 117-120 \) \( \text{km s}^{-1} \). While the HVC 1 shows nearly uniform velocities around 118 \( \text{km s}^{-1} \), the HVC 2 shows a velocity gradient along its elongated shape, with the velocity peaked around its southwestern end. In the second moment map in Figure 5(b), on the other hand, CO emission that have broad velocity widths larger than 3 \( \text{km s}^{-1} \) is detected around the HVCs. These broad velocity features indicate the intermediate-velocity gas components connecting the LVC and HVCs in velocity, which include the steep velocity gradients seen in the position-velocity diagrams of the HVC 1 and HVC 2 in Figures 3(a) and (b), respectively. The obtained velocity dispersions of these intermediate velocity features are significantly larger than the thermal velocity dispersion of the molecular gas, \( \sim 1 \) \( \text{km s}^{-1} \), even if we assume a high gas temperature of 30 K from the molecular line observations of the Galactic H II regions (e.g., Torii et al. 2011; Fukui et al. 2016), suggesting enhancement of turbulent motion of gas in these regions.

3.2 Detailed gas distributions in the three H II regions

In this subsection we present detailed CO distributions of each of the three H II regions, N35, H II region A, and H II region B, including comparisons with the infrared images.
Fig. 5. The first and second moment maps of the $^{13}$CO data are presented in (a) and (b), respectively. These two maps were both created for a velocity range of 105–125 km s$^{-1}$ using the volume pixels (voxels) with $^{13}$CO intensities of higher than 1 K, where the data were smoothed to a velocity resolution of 1.95 km s$^{-1}$ to reduce noise. The contours indicate the $^{13}$CO integrated intensity distributions of the HVCs in 120–128 km s$^{-1}$, and are plotted at the same levels as those in Figure 4(f).

3.2.1 N35

Figure 6(a) shows an enlarged image of N35 in the Spitzer 8 µm and 24 µm emission. The 8 µm emission in N35 mainly consists of three filamentary structures in the east, northwest, and southwest. We hereafter refer to these three filaments as the filaments E, NW, and SW, respectively. Although the exciting source of ionized gas in N35 has not been identified to-date, it is reasonable to assume that it is located around strong and compact peak of the 21 cm emission at $(l, b) \sim (24^\circ 46, 0^\circ 25)$. We obtained the 20 and 21 cm radio flux densities $f_\nu$ of N35 as $\sim 10.1$ Jy and $\sim 7.9$ Jy, respectively, from the web site of the Wide-field Infrared Survey Explorer (WISE) catalog of Galactic HII regions.\(^1\) The $f_\nu$ at these two wavelengths were measured using the Multi-Array Galactic Plane Imaging Survey (MAGPIS) 20 cm data (Helfand et al. 2006) and the Very Large Array (VLA) Galactic Plane Survey (VGPS) 21 cm data (Stil et al. 2006), respectively (see Makai et al. 2017 for details). The authors discussed that their estimates for $\sim 1000$ sources have fractional errors of $\sim 13–49\%$ for the MAGPIS data and 30–92% for the VGPS data. Using the same MAGPIS data, Beaumont and Williams (2010) applied a Bayesian technique to derive the $f_\nu$ of N35 as 7.57 Jy, nearly the same as the estimate in the WISE catalog.

Based on the $f_\nu$ in the WISE catalog, we computed the flux of Lyman continuum photons $N_{Ly}$ with the following equation (Rubin 1968):

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\(^1\) http://astro.phys.wvu.edu/wise/
\[ N_{\text{Ly}} \simeq 6.3 \times 10^{52} \left( \frac{T_e}{10^4 \text{K}} \right)^{-0.45} \left( \frac{\nu}{10^4 \text{GHz}} \right)^{0.1} \left( \frac{L_\nu}{10^{20} \text{WHz}^{-1}} \right), \]

where \( L_\nu \equiv 4\pi D^2 f_\nu \) and \( D \) is the distance to N35, 8.8 kpc. We assumed an electron temperature \( T_e \) of 8000 K. The \( N_{\text{Ly}} \) of N35 were derived as \( \sim 10^{49.83} \text{ s}^{-1} \) for the MAGPIS 20 cm data and \( \sim 10^{49.72} \text{ s}^{-1} \) for the VGPS 21 cm data as summarized in Table 1. These figures indicate that the exciting source of N35 has a spectral type of earlier than O3V (Martins, Schaerer, and Hillier 2005), if we assume a single object. Note that if we vary the distance between 8.6 and 9.1 kpc, the derived \( N_{\text{Ly}} \) is changed by \( \pm \sim 5\% \).

Detailed CO distributions in N35 are shown in Figures 6(b), (c), and (d) for three velocity ranges, 108–114, 114–117, and 117–124 km s\(^{-1}\), respectively. The first and last velocity ranges, in Figures 6(a) and (c), cover the LVC and HVC 1, respectively, as indicated by horizontal lines in Figure 3(a), while the intermediate-velocity gas is shown in the second velocity range in Figures 6(b). In Figure 6 we plotted the Spitzer red sources identified by Robitaille et al. (2008) with diamonds, as well as the CH\(_3\)OH maser sources with crosses (Breen et al. 2015). Note that a statistical study by Robitaille et al. (2008) indicated that the cataloged Spitzer red sources includes 50–70\% of YSOs and 30–50\% of asymptotic giant branch stars.

In Figure 6(b) the LVC appears to surround the filament NW and SW, while the HVC 1 in Figure 6(d) has a vertically elongated bow-like structure, which harbors a clumpy structure at the corresponding direction of the bright 8 \( \mu \)m spot within the filament SW at \((l, b) \sim (24^\circ 46, 0^\circ 20)\). A CH\(_3\)OH maser source is located just at the east of the peak, implying massive star formation. There is another CH\(_3\)OH maser source around the northern end of the filament NW at \((l, b) \sim (24^\circ 54, 0^\circ 31)\), which is spatially coincident with a Spitzer red source. The molecular counterpart of these sources are detected in the LVC in Figure 6(b) These observed signatures indicate that the LVC and HVC 1 are physically associated with N35, and the complementary distribution and the steep velocity gradient between the LVC and HVC 1 suggest physical interaction between these two. In the intermediate-velocity range in Figure 6(c), the CO emission shows a vertically straight feature at \( l \sim 24^\circ 43 \). The northern half of the straight feature corresponds to the diffuse 8 \( \mu \)m emission seen at \( b > 0^\circ 25 \) (Figure 6(a)), while the southern part shows a possible association with a Spitzer red source at \( b \sim 0^\circ 2 \).

### 3.2.2 H\( ^\text{II} \) region A

Detailed CO distributions around H\( ^\text{II} \) region A are shown in Figure 7 for three velocity ranges of 110–114, 114–118, and 118–128 km s\(^{-1}\), where the LVC is shown in (b), while the HVC 2 and intermediate velocity features are in (d) and (c), respectively (see the horizontal lines in Figure 3(b)). The 8 \( \mu \)m emission in this H\( ^\text{II} \) region consists of three distinct features. The brightest feature is located at
Fig. 6. (a) A two color composite image of N35. Green and red show the Spitzer 8 $\mu$m and 24 $\mu$m data, respectively. The black green contours indicate the 8 $\mu$m emission, which are plotted at 150, 200, 250, and 300 MJy sr$^{-1}$, while the white contours show the THOR 21 cm radio continuum emission plotted at the same levels as those in Figure 1. (b–d) Integrated intensity distributions of the $^{13}$CO emission in N35 for three velocity ranges, (b) 110–114 km s$^{-1}$, (c) 114–118 km s$^{-1}$, and (d) 118–124 km s$^{-1}$. These velocity ranges are plotted with solid lines in Figure 3(a). The black contours indicate the 8 $\mu$m emission plotted at the same level as (a). The crosses depict the CH$_3$OH masers identified by Breen et al. (2015), while the diamonds show the Spitzer red sources cataloged by Robitaille et al. (2008).
Fig. 7. Same as Figure 6 but for H II region A. The velocity ranges in (b), (c), and (d) are 109–114 km s$^{-1}$, 114–120 km s$^{-1}$, and 120–128 km s$^{-1}$, respectively.

$(l, b) \sim (24^\circ.40, 0^\circ.04–0^\circ.10)$ with an elongated shape along the north-south direction. We hereafter refer to this source “HII region A1”, as labelled in Figure 7(a). HII region A1 is associated with a radio continuum source of size $\sim 6$ pc, and the 24 $\mu$m emission is distributed to the west of the 8 $\mu$m feature. The second source, hereafter “HII region A2”, is distributed to the west of HII region A1 by $\sim 3$ pc. It is smaller than HII region A1, with a size measured as $\sim 3$ pc, and is associated with the 24 $\mu$m and 21 cm emission. The third 8 $\mu$m feature (“HII region A3”) is located at $(l, b) \sim (24^\circ.45, 0^\circ.10)$ and has relatively weak emission. HII regions A2 and A3 are cataloged as “candidate” HII regions G024.356+00.048 and G024.454+00.106, respectively, in the WISE Galactic HII region catalog (Anderson et al. 2014; Makai et al. 2017). The WISE HII region catalog indicate the $f_\nu$ measured with the MAGPIS 20 cm and VGPS 21 cm data as 3.1 Jy and 4.3 Jy, respectively, for HII regions A1, and 0.18 Jy and 0.27 Jy for HII regions A2, as summarized in Table 1 (Makai et al. 2017). The $N_{\text{H}_2}$ of HII regions A1 and A2 were then computed as $\sim 10^{49.31–49.46} s^{-1}$ and $10^{48.08–48.25} s^{-1}$, respectively, in the same manner as adopted for N35 in Section 3.2.1. The corresponding spectral types can be estimated as O4V–O5V and O8V–O8.5V, respectively. As the 21 cm emission is not
detected in HII region A3, its $N_{\text{HII}}$ cannot be measured.

The 8 $\mu$m emission of HII region A1 is traced by the bright CO emission in the LVC as seen in Figure 7(b), which is connected to a curved structure of the LVC elongated to the northwest. A CH$_3$OH maser is detected at a local CO peak in this structure at $(l, b) \sim (24^\circ33, 0^\circ14)$. The CO emission in the intermediate-velocity range in Figure 7(c) shows extended distribution centered on HII region A2 with a size of $\sim$8–9 pc. In this velocity range, another CO component is seen at $l \sim 24^\circ43$ and $b > 0^\circ10$, which corresponds to the southern half of the straight feature seen in Figure 6(b). HII region A3 is located to the east of the southern tip of this straight feature, implying interaction between these two. Gas distribution of the HVC 2 in Figure 7(d) shows elongated distribution toward the southwest, which has a CO peak at the corresponding direction of HII region A2. Compared to the gas distribution in the LVC in Figure 7(b), the northern part of the HVC 2 is surrounded by the
Table 1. H II region properties

| Region          | H II region       | $f_\nu$ (20 cm) (Jy) | log $N_{ly}$ (20 cm) (log s$^{-1}$) | $f_\nu$ (21 cm) (Jy) | log $N_{ly}$ (21 cm) (log s$^{-1}$) | Spectral type |
|-----------------|-------------------|----------------------|-------------------------------------|----------------------|-------------------------------------|---------------|
| N35             | G024.484+00.213   | 10.1                 | 49.83                               | 7.9                  | 49.72                               | < O3V         |
| H II region A1  | G024.392+00.072   | 3.1                  | 49.31                               | 4.3                  | 49.46                               | O4V–O5V       |
| H II region A2  | G024.356+00.048   | 0.18                 | 48.08                               | 0.27                 | 48.25                               | O8V–O8.5V     |
| H II region B   | G024.510-00.060   | 0.68                 | 48.66                               | 0.84                 | 48.75                               | O6.5V–O7V     |

(1) Name of the region in this paper. (2) Name of the H II region or H II region candidate. (3-4) The $f_\nu$ and log $N_{ly}$ of the H II region measured using the MAGPIS 20 cm data. The $f_\nu$ was obtained from the WISE catalog web site (Makai et al. 2017). (5-6) Same as (3-4) but for the VGPS 21 cm data (Stil et al. 2006). (7) Spectral type of the exciting source computed from $N_{ly}$ listed in (3) and (5) assuming a single object (Martins, Schaerer, and Hillier 2005).

A curved feature of the LVC, indicating complementary distribution as shown in Figures 4(c) and (f). As seen in Figures 3 and 5, the LVC and HVC 2 are connected with each other in velocity, and physical interaction between these two is suggested.

3.2.3 H II region B

CO distributions toward H II region B is shown in Figures 8(b), (c), and (d) for three velocity ranges, 105–113, 112–120, and 120–128 km s$^{-1}$, respectively. H II region B shown in Figure 8(a) has bright and compact 8 $\mu$m peaks at $(l,b) \sim (24.50°, -0.04°)$ and $(24.50°, -0.06°)$. The 24 $\mu$m and 21 cm emission is enhanced toward the northern 8 $\mu$m peak, and the 24 $\mu$m is extended to the east by $\sim 3$ pc. We calculated the $N_{ly}$ of H II region B as $10^{48.66} - 10^{48.75}$ s$^{-1}$ using the $f_\nu$ of 0.68 Jy at 20 cm and 0.84 Jy at 21 cm from the WISE H II region catalog (Makai et al. 2017), which correspond to a spectral type of O6.5V–O7.5V if we assume a single object (Table 1).

As shown in Figure 8(b) in a velocity range of 105–113 km s$^{-1}$, molecular gas in the LVC shows a ring-like morphology with a radius of $\sim 6$ pc. The ring is closed in $^{12}$CO, whereas it is opened to the north in $^{13}$CO as shown in Figures 4(c) and (f). The two 8 $\mu$m sources of H II region B are located to the east and the southeast of a bright CO clump embedded within the eastern rim of the ring structure in the LVC. The CO clump is associated with a CH$_3$OH maser as depicted by cross in Figure 8, implying massive star formation. Spatial distribution of the HVC 3 is presented in Figure 8(d) for a velocity range of 120–128 km s$^{-1}$. A Spitzer red source which is spatially coincident with the HVC 3 suggest star formation in the HVC 3. The radius of the HVC 3, $\sim 3$ pc, is consistent with the inner radius of the ring structure in the LVC, showing complementary distribution. The LVC and HVC 3 are separated in velocity by the CO features with intermediate intensities shown in Figure 8(c).
4 Discussion

In the previous sections we revealed that the Galactic infrared ring-like structure N35 is associated with a large GMC of a total molecular mass $\sim 2.1 \times 10^6 M_\odot$ at a distance of 8.8 kpc. The GMC includes two other HII regions, HII region A and HII region B, which lay to the south of N35. Our FUGIN CO $J=1-0$ data indicates that the GMC has two velocity components, the LVC and HVCs, and these two velocity components are connected with each other by the intermediate-velocity features. In addition, the LVC and HVCs show spatially complementary distributions, although these are separated by 5–15 km s$^{-1}$ in velocity. These observational properties suggests physical interactions between the LVC and HVCs.

4.1 The cloud-cloud collision model

We here propose a CCC model as an idea that explains the observational signatures in the N35 GMC. Recent studies on numerical calculations and molecular line observations revealed two observational signatures characteristic to CCC (e.g., Torii et al. 2017a; Fukui et al. 2017c; Haworth et al. 2015a). One is “broad bridge feature in position-velocity diagrams”, and the other is “complementary distribution between two clouds with different velocities”. A broad bridge feature is gas at intermediate velocities between two clouds that are spatially coincident but separated in velocity. Figure 9 shows the schematics of CCC, as well as cartoons of the position-velocity diagram in which a broad bridge...
When two clouds with different sizes collide, a smaller cloud drives into a larger cloud, resulting in a dense compressed layer, as the entirety of the smaller cloud undergoes collision quite quickly. The compressed smaller cloud continues to move into the larger cloud, forming a thin turbulent layer with velocities that are intermediate between the smaller cloud and the larger cloud. The intermediate-velocity gas is replenished as long as the collision continues. At a viewing angle parallel to the colliding axis, an observer sees two velocity peaks separated by lower intensity intermediate-velocity emission in the position-velocity diagrams, which corresponds to the broad bridge features. Several observational studies reported detections of broad bridge features in the CCC regions (e.g., Torii et al. 2017a; Torii et al. 2017b; Fukui et al. 2017c; Fukui et al. 2017d).

Another signature of CCC, complementary distribution, was discussed by Torii et al. (2017b) and Fukui et al. (2017c) based on comparisons between molecular line observations and numerical calculations of CCC (Takahira, Tasker, and Habe 2014; Haworth et al. 2015a; Haworth et al. 2015b). When the smaller cloud drives into the larger cloud, it forms a cavity in the larger cloud, the size of which corresponds to that of the smaller cloud. If the observer has a viewing angle parallel to the collisional axis so that the two colliding clouds are spatially coincident along the line-of-sight, the larger cloud shows a ring distribution with an inner-radius that corresponds to the radius of the smaller cloud, forming a complementary distribution between these two clouds.

As the cavity that forms in the larger cloud is seen as an intensity depression in the position-velocity diagram (see Figure 9), Torii et al. (2017a) discussed that two colliding clouds shows a “V”-shaped gas distribution in the position-velocity diagram, and each side of the V-shaped structure is observed as a velocity gradient. Figure 10 shows a position-velocity diagram of the synthetic CO $J=1–0$ cube data generated by Haworth et al. (2015b) using the CCC model with a colliding velocity of $10 \text{ km s}^{-1}$ calculated by Takahira, Tasker, and Habe (2014), where the viewing angle is set to parallel to the colliding axis. In Figure 10 the larger cloud and the smaller cloud can be seen around velocities of zero and one, respectively, and the CO emission overall shows an inverted V-shaped gas distribution.

### 4.2 CCCs in the N35 GMC

We here discuss that the observed complementary distribution and intermediate velocity features between the LVC and HVCs can be interpreted by the CCC model. Figure 11 shows schematics of the collisions we propose here. We assume collisions between a large GMC extended for $\sim 30 \text{ pc} \times 50 \text{ pc}$ and three smaller clouds at colliding velocities of $\sim 10–15 \text{ km s}^{-1}$, with an observer viewing angle almost parallel to the line-of-sight. The first case corresponds to the LVC, while the latter three are the
Fig. 10. The position-velocity diagram of the synthetic CO $J=1-0$ data produced by Haworth et al. (2015b) based on the 10 km s$^{-1}$ CCC model in Takahira, Tasker, and Habe (2014). The integration range in $Y$ is set to be same with the size of the smaller cloud. The labels of the $X$ and $V$ axes are normalized with the radius of the small cloud as 3.5 pc and the velocity difference between the small cloud and the large cloud as 4 km s$^{-1}$, respectively.

Fig. 11. Schematic picture of the cloud-cloud collisions in the GMC, where star formation is not included.

HVCs (Figure 4). We derived the masses of the HVCs 1, 2, and 3 as about $1.3 \times 10^5 \, M_\odot$, $0.3 \times 10^5 \, M_\odot$, and $0.1 \times 10^4 \, M_\odot$, respectively, from the $^{12}$CO integrated intensity map in Figure 4(b), assuming an X-factor of $2 \times 10^{20} \, \text{cm}^{-2} \, (\text{K km s}^{-1})^{-1}$ (Strong and Moskalenko 1998).

As presented in Figures 6–8, the LVC has holes or rings near the individual HII regions. The western rim of N35 is surrounded by the CO emission in the LVC (Figure 6(b)), forming a hole, while HII region A is embedded within the western rim of the ring-like gas structure in the LVC, which is opened to the south (Figure 7(b)). HII region B is seen at the western rim of another ring-like structure in the LVC (Figure 8(b)). As these holes/rings show complementary distribution with the HVCs,
these can be interpreted as the cavities created by the collisions between the LVC and HVCs (see Figure 9). Fukui et al. (2017c) pointed out that two colliding clouds sometimes show displacement depending on on the inclination angle of the relative motion to the line-of-sight. However, the present complementary distributions seen in the three HVCs show no clear displacement. It is therefore suggested that the relative motion between the LVC and HVCs are almost parallel to the line-of-sight.

The velocity distribution of gas between the LVC and HVCs also support for the present CCC scenario. In N35 the velocity gradient of gas seen in the position-velocity diagram in Figure 3(a) can be interpreted as one side of the inverted V-shaped gas distribution in Figure 10. This is the case for an offset collision, which means that the HVC 1 is not perfectly coincident with the LVC along the line-of-sight. The velocity gradients seen between the LVC and HVC 2 in Figure 3(b) are similar to the inverted V-shaped gas distribution of the model data in Figure 10. As the southwestern part of the HVC 2 is not overlapping the LVC along the line-of-sight, it is likely that only the northern part of this cloud is colliding with the LVC, suggesting that the southern part of the HVC 2 holds the initial condition of the cloud prior to the collision. In HII region B, as the ring-like structure of the LVC is closed in the $^{12}$CO emission (Figures 5 and 4), indicating that entirety of the HVC 3 undergoes the collision. As shown in the position-velocity diagram in Figure 3(c), the velocity distribution of the HVC 3 connected to the LVC by the intermediate velocity feature resembles the cartoon position-velocity diagram in Figure 9.

The timescale of the collision in each HVC can be calculated as the crossing time of the two colliding clouds. If we tentatively assume the size of the LVC and HVC 1 along the line-of-sight as 30 pc and 10 pc, respectively, the timescale for the HVC 1 to punch the LVC can be derived as $(30 \text{ pc} + 10 \text{ pc}) / 8 \text{ km s}^{-1} \simeq 5 \text{ Myr}$. As the detection of the intermediate velocity emission indicates that the collision of the HVC 1 still continues, the present timescale of the collision is probably shorter than this estimate. Similarly, the timescales of the collisions can be computed as less than $(30 \text{ pc} + 10 \text{ pc}) / 5 \text{ km s}^{-1} \simeq 8 \text{ Myr}$ and $(30 \text{ pc} + 3 \text{ pc}) / 16 \text{ km s}^{-1} \simeq 2.1 \text{ Myr}$, respectively.

It is unclear whether the HVCs could indeed penetrate the LVC in the future as results of the collisions, as the deceleration of the collisions owing to momentum conservation, as discussed by Haworth et al. (2015a), is sometimes very effective. However, the escape velocity $v_{\text{esc}}$ from the N35 GMC can be calculated as $v_{\text{esc}} = \sqrt{2GM/r} \sim 26 \text{ km s}^{-1}$ by assuming a mass $M$ of $2.1 \times 10^6 M_\odot$ and a radius $r$ of 25 pc, which is much higher than the observed velocity separations between the LVC and HVCs, indicating gravitational binding between the LVC and HVCs. This implies that in the future the LVC and HVCs will be merged into one, becoming a single GMC, even if the HVCs will be able to penetrate the LVC.
4.3 Ages of the H II regions in the N35 GMC

It is of interest to investigate possibilities that the CCCs discussed in Figure 11 triggered the high-mass star formation in the N35 GMC. The formation timescale of an H II region is usually estimated using a D-type expansion model, and we here adopt the analytical model of the D-type expansion formulated by Hosokawa and Inutsuka (2006)

$$r_{\text{HII}}(t) = r_{\text{St}} \left(1 + \frac{7}{4} \sqrt{\frac{4}{3}} \frac{c_i t}{r_{\text{St}}} \right)^{4/7}, \quad (3)$$

where $r_{\text{St}}$ is the Strömgren radius calculated from $N_{\text{Ly}}$ and ambient gas density $n_0$, and $c_i$ is the isothermal sound speed, which corresponds to $\sim 11.5 \text{ km s}^{-1}$ at $T_e$ of 8000 K.

It is noted that, based on the three-dimensional simulations of H II expansion within the clouds with fractal density distributions, Walch et al. (2012) discussed that the $r_{\text{HII}}$ tracks the uniform density solution quite closely for all the test cases, suggesting that pc-scale mean gas density is a crucial parameter for the $r_{\text{HII}}$ evolution. In the N35 GMC, the ridge feature seen at $l \sim 24^\circ 4–24^\circ 5$ in Figures 2(a) and (b) have higher $N(\text{H}_2)$ of $(4–5) \times 10^{22} \text{ cm}^{-2}$ as discussed in Section 3.1. Given the width of the ridge feature of $\sim 6$ pc, the mean gas densities can be estimated as $\sim 2100–3200 \text{ cm}^{-3}$. As N35 and H II region A are located close to the ridge feature, and the gas associated with H II region B has similar $N(\text{H}_2)$ as the ridge feature, we here deemed the derived densities $2100–3200 \text{ cm}^{-3}$ as $n_0$.

In Figure 12 we show evolutionary tracks of the H II regions using the Hosokawa-Inutsuka model. The black curves in the upper and lower panels respectively indicate the full ranges of the radius of the H II region $r_{\text{HII}}$ and the expanding velocity of the H II region $v_{\text{exp}}$ as functions of time, which were computed with the $N_{\text{Ly}}$ obtained from the MAGPIS 20 cm and VGPS 21 cm data (Table 1). We also plotted uniform $\pm 50\%$ uncertainties for the $r_{\text{HII}}$ and $v_{\text{exp}}$ as the gray curves in Figure 12. In each of the lower panels the filled area in red indicates the time and $r_{\text{exp}}$ at which $r_{\text{HII}}$ is consistent with the observed size of the H II region, which is shown as the filled red areas in the corresponding upper panel. As pointed out by Bisbas et al. (2015), the Hosokawa-Inutsuka model is an approximation of the model of Raga, Cantó, and Rodríguez (2012) at an early evolutionary stage of H II expansion. At a later time the Raga model, which takes into account the pressure acting from the neutral gas within the expanding shell on the ionized gas, indicates that the H II expansion is stagnated at $r_{\text{stag}} = r_{\text{St}} \left(\frac{8}{3}\right)^{2/3} \left(\frac{c_n}{c_i}\right)^{4/3}$, where $c_n$ is the sound speed of the neutral gas, which was calculated assuming a neutral gas temperature of 30 K from the molecular line observations of the Galactic H II regions (e.g., Torii et al. 2011; Fukui et al. 2016). The computed $r_{\text{stag}}$ values are plotted as gray-green shades in Figure 12(a)–(d), showing that the observed $r_{\text{HII}}$ in all four H II regions are smaller than the computed
and it is therefore suggested that the early-phase approximation of the Raga model, which corresponds to the Hosokawa-Inutsuka model, can be applied to these HII regions in the N35 GMC.

In Figure 12(a) the curves of the Hosokawa-Inutsuka model indicate an evolutionary timescale of N35 as $\sim 0.7–3.0$ Myr, where we assumed the $r_{\text{HII}}$ of N35 as 4–8 pc by considering the uncertainty on the location of the exciting source in N35. The corresponding $v_{\text{exp}}$ measured as $\sim 1.5–3$ km s$^{-1}$ shown in Figure 12(e) is also consistent with the observations, as the observed velocity dispersion toward N35 is as large as $\sim 8$ km s$^{-1}$ as indicated by the horizontal dotted black line in Figure 12(e). Figures 12(b)–(d) show that HII region A1 has timescales of 0.2–0.6 My, while HII region A2 and B indicate even shorter timescales; $< 0.3$ Myr and $< 0.5$ Myr, respectively. The estimated $v_{\text{exp}}$ in each of these three HII regions is also consistent with the measured velocity dispersions (Figures 12(f)–(h)).

The relatively longer timescale of N35 estimated in Figure 12 is due to the larger size of N35 and the assumption of the common $n_0$. As shown in Figure 4, N35 is located at the eastern rim of the N35 GMC, and the eastern part of N35 appears to not be interacting with the N35 GMC. In addition, Beaumont and Williams (2010) discussed that the infrared ring-like structures, including N35, have two-dimensional ring-like morphologies. These observational signatures suggest that N35 has been evolving through the diffuse ISM surrounding the N35 GMC. It is therefore preferable to assume lower $n_0$ in estimating the evolutionary timescale of N35, and if we tentatively assume $n_0$ of 500 cm$^{-3}$, the estimated timescale of N35 is decreased to $\sim 0.2–1.0$ My (see curves with dashed lines in Figures 12(a) and (e)), which is rather similar to the figures in the other HII regions derived assuming $n_0$ of 2100–3200 cm$^{-3}$. As HII regions A1, A2, and B have smaller sizes than N35 and yet embedded within the N35 GMC, the assumption of $n_0 = 2100–3200$ cm$^{-3}$ is rather reasonable.

### 4.4 High-mass star formation triggered by CCCs

In the previous subsection, the formation timescales of the HII regions in the N35 GMC were estimated as $\sim 1$ Myr or less, much shorter than the collisional timescales estimated in the three HVCs, suggesting that the exciting stars of the four HII regions were formed after the onset of the collisions. This is consistent with the hypothesis that the formation of these exciting stars were triggered by the CCCs between the LVC and HVCs. In the CCC model, dense gas clumps are formed within the compressed layer at the interface of the collision, at which the bridge features at intermediate velocities and/or complementary distribution between two clouds can be seen unless the cloud dispersal by the stellar feedback is significant. The dense clumps gains high mass accretion rates such as $10^{-4}–10^{-3}$ $M_\odot$ yr$^{-1}$ as demonstrated by Inoue et al. (2017), which satisfies the theoretical requirement to overcome the radiation pressure feedback of the forming O star (e.g., Wolfire and Cassinelli...
Fig. 12. Evolutionary tracks of the four HII regions associated with the N35 GMC are presented using the D-type expansion equation provided by Hosokawa and Inutsuka (2006), in which we assumed the \( N_0 \) listed in Table 1. Black curves in the upper and lower panels show the \( r_{\text{HII}} \) and \( v_{\text{exp}} \) at \( n_0 = 2100-3200 \text{ cm}^{-3} \) as functions of time in Myr, respectively, while the dashed black curve in panel (a) is the case for \( n_0 = 500 \text{ cm}^{-3} \). The gray curves indicate the \( \pm 50\% \) uncertainties of the \( r_{\text{HII}} \) and \( v_{\text{exp}} \) curves. The radii of the HII regions measured from the THOR 21 cm data are shown by filled red areas in the upper panels (Figure 1, while the measured velocity dispersion toward the HII regions are indicated as horizontal dotted black lines in the lower panels. The red areas in the lower panels indicate the time and \( v_{\text{exp}} \) at which \( r_{\text{HII}} \) corresponds to the observed radii of the HII regions. The gray-green shades in the upper panels show the stage of the HII regions (see the text).

1986; McKee and Tan 2003; Hosokawa, Yorke, and Omukai 2010), and high-mass stars are finally formed at short timescales of \( \sim 0.1 \text{ Myr} \).

The HVC 1 in N35 appears to be overlapping the peak of the 21 cm emission, at which the exciting source of N35 is possibly located, and it is consistent with the scenario that the high-mass star(s) in N35 was (were) formed at the colliding part between the LVC and HVC 1. HII region A1 is located at the western rim of the ring-like structure of the LVC, while HII region A2 is seen at the center of the HVC 2, suggesting that HII region A1 was formed on the side of the cavity created by the collision, while HII region A2 was born at the bottom of the cavity. Similar to HII region A1, it is suggested that HII region B, which is embedded in the east of the ring-like structure in the LVC (Figure 8), was formed at the eastern side of the cavity created in the LVC by the HVC 3. Further observations with high spatial resolution at a 0.1-pc scale are necessary to reveal distributions and dynamics of the gas at the colliding regions between the LVC and HVCs, which will allow us to investigate the detailed physical process of the CCCs and related high-mass star formation.
In summary, the collisions between the LVC and HVCs have started since less than \( \sim 0.1 \) Myr ago, and the high-mass stars which energize the HII regions in the N35 GMC were formed at short timescales of \( \sim 0.1 \) Myr within the dense gas layer created through the strong compression at the colliding interface. As these three regions show the intermediate velocity features, i.e., the broad bridge features, in the position-velocity diagrams (Figure 3), indicating that the collisions still continue, further star formation including high-mass stars will possibly be triggered in the N35 GMC in the future. As shown in Figures 6–8, associations of the CH$_3$OH masers as well as the Spitzer red sources with the N35 GMC around colliding parts lend more credence to the formation of stars in the colliding parts in the next generation.

5 Summary

The conclusions of the present study are summarized as follows.

1. We analyzed the CO \( J=1–0 \) data, which was obtained as a part of the FUGIN project using the Nobeyama 45-m telescope, in the Galactic infrared ring-like structure N35 and the two nearby HII regions, G024.392+00.072 (HII region A) and G024.510-00.060 (HII region B). We revealed that these three HII regions are associated with a GMC (the N35 GMC) which has a total molecular mass of \( 2.1 \times 10^6 \) \( M_\odot \) at 8.8 kpc.

2. Our CO data indicates that the N35 GMC has two velocity components, i.e., i.e., the LVC and HVC, between \( \sim 110–126 \) km s\(^{-1}\). The majority of molecular gas in the N35 GMC is included in the LVC, having a large size of \( \sim 30 \times 50 \) pc at \( \sim 110–114 \) km s\(^{-1}\), while the three HVCs (HVC 1, HVC 2, and HVC—,3) with smaller sizes were identified at \( \sim 120–126 \) km s\(^{-1}\) around the three HII regions. The LVC has holes or rings around the HII regions, and these holes/rings are spatially coincident with the three HVCs, showing complementary distributions between the two clouds along the line-of-sight. In addition, the LVC and HVCs are connected in velocity by the CO emission with intermediate intensities around the interface of the complementary distribution. The intermediate-velocity features in N35 and HII region A show steep velocity gradients, while that in HII region B is coincident with the HVC 3 along the line-of-sight.

3. We discussed that the observed complementary distributions and intermediate velocity features between the two velocity components can be interpreted by the collisions between the LVC and HVCs at velocities of \( \sim 5–15 \) km s\(^{-1}\). Compared to the theoretical works on CCC, we assumed collisions between a GMC extended for \( \sim 30 \) pc \( \times \) 50 pc and three smaller clouds. The former GMC corresponds to the LVC, while the latter are the HVCs. In this model, the gas at the intermediate velocities between the LVC and HVCs can be interpreted as a broad bridge feature, which
is the gas in the thin turbulent layer formed at the interface of the two colliding clouds, and the complementary distributions of gas indicate the cavities created in the LVC through the collisions.

4. The timescales of the collisions can be estimated as less than about 5 Myr, 8 Myr, and 2 Myr in N35, HII region A, and HII region B, respectively. These figures are significantly larger than the ages of these HII regions, less than ~1 Myr, estimated assuming an analytical model of HII expansion, suggesting that the high-mass stars which energize these HII regions were formed by the triggering of the collisions.

5. Broad bridge features at intermediate velocities suggest that the collisions in the present GMC are still continuing. As the N35 GMC shows associations with CH3OH masers and Spitzer red sources, further star formation triggered by the collisions are possibly occurring.

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Appendix 1 Channel maps

We present the velocity channel maps of the $^{12}$CO, $^{13}$CO, and C$^{18}$O emission of the N35 GMC in Figures A1, A2, and A3, respectively, for a velocity range between 102 and 125 km s$^{-1}$. The contours indicate the 90 cm radio continuum emissions.
Fig. A1. Velocity channel maps of the $^{12}$CO emission. The contours indicate the 21 cm radio continuum emission which start at $3\sigma$ with steps of $1.5\sigma$, which respectively corresponds to 45 and 22.5 mJy beam$^{-1}$. 
Fig. A2. Same as Figure A1 but for $^{13}\text{CO}$.
Fig. A3. Same as Figure A1 but for $^{18}\text{O}$. 