High-mass star formation in Orion possibly triggered by cloud–cloud collision III; NGC2068 and NGC2071

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Abstract

We carried out a molecular line study toward the high-mass star forming regions with reflection nebulae, NGC2068 and NGC2071, in Orion with NANTEN2 in the $^{13}$CO($J = 2 − 1$)transition. The $^{13}$CO distribution shows that there are two velocity components at 8.25 km s$^{-1}$ and 11.5 km s$^{-1}$. The blue-shifted component is in the northeast associated with NGC2071, and the red-shifted component is in the southwest associated with NGC2068. The two clouds have a gap of $\sim 1$ pc in total intensity distribution, suggesting that they are detached at present. A detailed spatial comparison between them indicates that the two show complementary distribution; the
blue-shifted component lies toward an intensity depression in the northwest of the red-shifted component, where we find that a displacement of 0.6 pc makes the two clouds fit well with each other. Based on these results we hypothesize that the two components collided with each other at a projected relative velocity 2.5 km s$^{-1}$. The timescale of the collision is estimated to be $2 \times 10^5$ yrs for an assumed angle 45 deg of the relative motion to the line of sight. We assume that the two most massive early B–type stars in the cloud, illuminating stars of the two reflection nebulae, were formed by the collisional triggering at the interfaces between the two clouds. Along with the other young high-mass star forming regions, M42, M43, and NGC2024 (Fukui et al. 2017b; Ohama et al. 2018), it seems possible that collisional triggering is independently working to form O–type and early B–type stars in Orion in the last Myr over a projected distance of $\sim 80$ pc.

**Key words:** High-mass star formation, Cloud-cloud collision, NGC2068, NGC2071

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1 Introduction

1.1 Background

High mass stars are so influential to excite motions of the interstellar medium (ISM) and to enrich metals in the ISM. It is therefore of crucial importance to better understand the mechanism of high mass star formation in order to elucidate galaxy evolution. The Orion region includes various types of star formation and has been a best test bench for theories on high mass star formation mechanisms at the nearest distance to the sun around 400 pc. The region hosts young star formation including HII regions, reflection nebulae and massive star clusters, e.g., M42, M43, NGC2023, NGC2024, NGC2068, and NGC2071, and also more evolved stars in OB associations without molecular gas (see Bally 2008 for a review and references therein). The stellar age ranges from less than 1 Myr to 10 Myrs. It was recognized that the OB associations show an age sequence in space, in the sense that the Ori OB1a in the north is the oldest and Ori OB1d the youngest toward M42 (Blaauw 1991). It was speculated that some common mechanism may be working to form OB associations at a semi regular separation of 25 pc. In 1970’s, a star formation scenario was proposed to explain the distribution of OB associations. Elmegreen & Lada (1977) presented a model of sequential formation of OB associations based on a shock compressed layer driven by an ionization-shock front of HII regions. The model explained formation of the quasi-regularly spaced OB associations with an age sequence in a large giant molecular cloud as a mass reservoir which is extended along the Galactic plane. This
scenario was later developed as a collect-and-collapse scenario in smaller HII regions including the Spitzer bubbles, and a number of works were made on second generation star formation triggered by O–type star(s) in the bubbles (e.g., Deharveng et al. 2006). It seems however that these scenarios need more elaboration by confrontation between theories and observations; e.g., it remains unexplained if the first generation O–type star(s) were formed either by a spontaneous process or some triggered process, and details of triggering of second generation stars are not yet worked out theoretically.

1.2 Observed cloud–cloud collisions

Observations of molecular clouds were analyzed and interpreted under an assumption that an apparently single-peaked cloud is a single component which is governed by the cloud self-gravity. This is a natural thought because a molecular cloud seems often self-gravitating with a single velocity component. Averaged kinetic properties like velocity dispersion was studied into depth in numerous papers to test the virial theorem by using the Larson’s law (Larson 1981). Detailed velocity distributions of molecular clouds were not paid much attention to as an important ingredient of star formation, and dust emission with no velocity information was often used to probe cloud properties. In the meantime, in super star clusters, two velocity clouds whose velocity separation is supersonic at 10 km s\(^{-1}\) – 15 km s\(^{-1}\) or more were found in Westerlund2, NGC3603, RCW38, and R136; these clusters are all associated with nebulosity with intense dust emission, whereas the rest of the super star clusters in the Milky Way have no associated nebulosity, suggesting that the four are youngest among the super star clusters (Portegies Zwart et al. 2010; Fukui et al. 2016; 2017a; Kuwahara et al. 2018 in preparation). The results were interpreted that cloud–cloud collision took place and triggered formation of a cluster in the collisional shock-compressed layer (Inoue & Fukui 2013). The large velocity separation cannot be gravitationally bound by cloud gravity and chance collision between two giant molecular clouds (GMCs) is a plausible scenario. All the four clusters with nebulosity among the ten super star clusters in the list by Portegies Zwart et al. (2010) and RCW38 suggest that cloud–cloud collision may be an important process to form massive super star clusters, because the super star clusters with no nebulosity have little possibility for detecting parent clouds due to cloud dispersal by stellar feedback. If two clouds are clearly seen separated in velocity and are connected by bridge features, collision is well confirmed. Such a rare example is found in RCW38 having two components with 12 km s\(^{-1}\) velocity separation, which are connected by a bridge feature within 1 pc of the cluster center (Fukui et al. 2016). A clear case like RCW38 is, however, not often seen because its age 10\(^5\) yrs is considerably shorter than the typical age of clusters more than 2 Myrs.

Subsequently, formation of a single O–type star was found to be triggered by cloud–cloud
collision in other places; e.g., M20, RCW120, N159W and N159E (Torii et al. 2011; Torii et al. 2015; Fukui et al. 2015; Saigo et al. 2017; the papers in this special issue); these show a variety of velocity separation from $2 \text{ km s}^{-1}$ to $20 \text{ km s}^{-1}$, in particular, in the latter two cases the velocity separation in projection is only a few km s$^{-1}$. It is shown that the two colliding clouds physically merge with each other by collision and are often observed as a single cloud in particular if one of the clouds is dominant in column density. This possibility, two-colliding clouds which are apparently single-peaked, is illustrated by synthetic observations of colliding clouds by Fukui et al. (2017b) based on numerical simulations by Takahira et al. (2014). Such two clouds may not be separable in observed velocity, even when supersonic cloud–cloud collision is taking place. Since the supersonic collision can influence significantly cloud physical states and star formation via shock compression (Inoue and Fukui 2013), a careful investigation of cloud kinematics is required in order to capture collision signatures and to gain an insight into the collision physics.

Theoretical simulations over a Galaxy scale show that collisions between molecular clouds are frequent in the Galactic disk (Fujimoto et al. 2014; Dobbs et al. 2015). An important question is if cloud–cloud collision is a common process of O–type star formation or an adhoc scenario which happens rarely. In the light of the extreme importance of O–type star formation in astrophysics, it is an urgent issue to explore quantitatively the role of cloud–cloud collision in high-mass star formation.

1.3 Theories of collision

Cloud–cloud collision is able to offer an alternative to the ionization driven shock compression in O–type star formation as shown by numerical simulations. Numerical hydrodynamical simulations by Takahira et al. (2014) showed a simple case of collision that a small cloud collides with a large cloud to produce a cavity in a large cloud (see also Habe and Ohta 1992; Anathpindika 2010). Note that collision between similar sized clouds is rarer than between dissimilar clouds. The results were used to synthesize observations on a cloud scale and it was derived that complementary distribution between the two clouds is a common observable signature as long as ionization by the formed star is not destructing the clouds (Fukui et al. 2017b). It was also shown that two colliding clouds merge into a single peak and are not seen usually as two distinct components due to gas in the intermediate velocity range between the two components.

On a microscopic scale, the magnetohydrodynamical simulations by Inoue and Fukui (2013) showed that the interface layer between the two clouds becomes strongly compressed. The particles in the interface layer have large velocity difference and the collisional interaction causes a large velocity dispersion in a magnitude similar to the actual velocity difference of the two clouds. The layer has to
be highly inhomogeneous with clumps, because the initial density distribution prior to the collision is highly inhomogeneous, which is a general ISM property. The clumps amplify turbulence and magnetic field by deflection of shock fronts, and realize a high mass accretion rate of $10^{-4}$ to $10^{-3}$ $M_\odot$/yr which is required to form high mass stars (Inoue and Fukui 2013).

1.4 NGC2068 & NGC2071

Large-scale molecular observations covering the Orion star forming region were made by a number of authors mainly in CO emission and have been used to address star formation process (e.g., Sakamoto et al. 1994; Wilson et al. 2005; Nishimura et al. 2015). A number of works focusing on the infrared sources in NGC2068 and NGC2071 in the north of L1630 were made at various wavelengths, and showed active formation sites of early B–type star and clusters (see for the early work e.g., Lada and Lada 2003 and references is herein). Most recent near infrared observations selected 186 candidates for young stellar objects in the region, which show good spatial correlation with optical extinction (Spezzi et al. 2015). The region was not observed so intensively in the molecular emission as the M42 region, and there were a limited number of molecular observations which covered the molecular gas on a degree scale (e.g., Aoyama et al. 2001; Ikeda et al. 2009; Buckle et al. 2010). For a review of the NGC2068 and NGC2071 region see Gibb (2008) and references therein.

1.5 Aims of the present paper

In the present paper we analyze new $^{13}$CO($J = 2 – 1$) data with a particular attention to the velocity distribution in NGC2068 and NGC2071. Our aim is to test if cloud–cloud collision is a viable scenario in this region by using the analysis applied to M42, M43, NGC2024, and other regions of high-mass star formation. We will put an emphasis on utilization of the recently developed methods on cloud–cloud collision based on hydrodynamical numerical simulations, as well as the empirical signatures acquired in the studies of cloud–cloud collision (e.g., Fukui et al. 2017b). The paper is organized as follows; Section 2 describes details of observations with the NANTEN2, Section 3 presents observed properties of colliding clouds, and Section 4 results of the present observations and analysis. Section 5 gives discussion on the results and their implications on high-mass star formation and Section 6 concludes the paper.

2 observations

We carried out observations of an area of $1 \times 1 \text{ deg}^2$ in $^{12}$CO($J = 2 – 1$) and $^{13}$CO($J = 2 – 1$) emissions toward NGC2068 and NGC2071 by using the NANTEN2 4-m milimeter/sub-milimeter telescope in
Atacama, Chile (4850 m) in December 2016. The beam size and the velocity resolutions are 90″ and 0.08 km s\(^{-1}\) at 230 GHz, respectively. These observations were made with the on-the-fly (OTF) mapping technique (Sawada et al. 2008). The backend backend was the a digital-fourier transform spectrometer (DFS) with 16384 channels of 1 GHz bandwidth. After the baseline subtraction, we created the FITS image with a spatial and a velocity resolutions of 30″ and 0.08 km s\(^{-1}\), respectively.

The typical system noise temperature which includes the atmospheric noise is 265 K – 336 K including the atmosphere forward the zenith, and the typical r.s.m. noise levels of the spectral data are 0.6 K and 0.7 K (T\(_{\text{mb}}\)) for \(^{12}\)CO\((J = 2 – 1)\) and \(^{13}\)CO\((J = 2 – 1)\), respectively. The pointing accuracy was better than 10″. We used the CO\((J = 2 – 1)\) data of the Orion B obtained by the Osaka Prefecture University 1.85–m telescope (Nishimura et al. 2015), as a standard source to calibrate the intensities. We use the Galactic coordinate in the present paper.

3 Observed properties of colliding clouds; complementary distribution with a displacement

We describe the physical states and distributions of colliding clouds and their observable signatures based on the numerical simulations by Takahira et al. (2014). The simulations deal with head-on collision between a small cloud and a large cloud, which are both spherically symmetric. The radius of the small cloud is 3.5 pc and that of the large cloud 7.2 pc. The two are colliding at 7 km s\(^{-1}\) at an epoch of 1.6 Myrs after the onset of the collision and have internal turbulence in the order of 1 – 2 km s\(^{-1}\) with highly inhomogeneous density distribution. Physical parameters of the collision are listed in Table 1. For more details see Takahira et al. (2014).

Figure 1 shows a schematic view of the collision seen from the perpendicular direction to the cloud relative motion, although the figure does not present the inhomogeneity and turbulence. The small cloud is producing a cavity in the large cloud by the collisional interaction at an epoch of 1.6 Myr from the onset of the collision. Figure 2 shows simulated velocity channel distributions at 1.6 Myrs. This is a representative epoch which illustrates cloud signatures produced by collision. The clouds are divided into three sections A, B and C (Figure 1), and the sections are observed as indicated in Figure 2i. We see the small cloud, the cavity and the large cloud mainly at \(-4.1 – -2.2\) km s\(^{-1}\) (Figures 2c and 2d), \(-1.2 – 0.7\) km s\(^{-1}\) (Figures 2e, 2f and 2g) and at \(-1.2 – 0.7\) km s\(^{-1}\) (Figures 2f and 2g), respectively. We see the cavity created in the large cloud by the small cloud most clearly in Figure 2g; the cavity and the small cloud show usually some displacement reflecting an inclination angle of the relative motion to the line of sight (Figure 2i), which is assumed to be 45 degrees in Figure 2. The projected displacement gives a measure of collision timescale as shown by Fukui et al. (2017b), and the displacement is estimated by the H-function, the degree of overlapping between
the cavity and the small cloud, which is defined in Fukui et al. (2017b). Note that we do not see a displacement if the cloud motion is parallel to the line of sight, and that two clouds are not found if the cloud motion is vertical to the line of sight.

4 Results

Because the $^{12}\text{CO}$ emission is heavily saturated with self-absorption, we mainly used the $^{13}\text{CO}$ data in the present analysis. Figure 3 shows the integrated intensity distribution of the $^{13}\text{CO}$ emission. The molecular distributions are divided into three components. NGC2068, NGC2071 and NGC2071-north, where the former two are dominant. The exciting stars, B–type star HD 38563 and HD 290861, of NGC2068 are located close to a $^{13}\text{CO}$ peak at $(l, b) = (205.38, -14.32)$ and that of NGC2071, B–type star HD290862, near a $^{13}\text{CO}$ peak at $(l, b) = (205.11, -14.11)$ (Strom et al. (1975)). Two infrared sources (LBS17 and LBS8) (Gibb & Heaton 1993) were discovered to have protostellar outflows by using $^{12}\text{CO}(J = 2 - 1)$ data. Iwata et al. (1988) discovered CO outflow at $(l, b) = (204.868, -13.866)$ in a molecular clump NGC2071–north which seems to be connected with the NGC2071 cloud in the north of the present region (Figure 3). 186 Young Stellar Object candidates (YSOc) (Spezzi et al. 2015) are found toward ridges of elevated $^{13}\text{CO}(J = 2 - 1)$ intensity; in the blue-shifted cloud the main molecular ridge of 0.4 deg length elongated in the east-west direction in the equatorial coordinate is associated with $\sim 50$ YSOc, and in the red-shifted cloud the main ridge extending by 0.4 deg elongated in the north-south direction is also associated with $\sim 50$ YSOc (Figure 3).

Figure 4b shows a position-velocity diagram along a Y-axis in Figure 4a where $(X, Y)=(0.0, 0.0)$ corresponds to $(l, b) = (205.26, -14.19)$. We find the clouds are clearly separated in position at $Y \approx 0.05$ degree in Figure 4a, where the clouds show a jump in Figure 4b. We denominate hereafter the northern cloud, the blue-shifted cloud, and the southern cloud, the red-shifted cloud. The average velocity of the blue-shifted cloud is 8.25 km s$^{-1}$ and that of the red-shifted cloud is 11.5 km s$^{-1}$.

In order to see more details Figure 5 shows velocity-channel distributions of $^{13}\text{CO}(J = 2 - 1)$ every 1.25 km s$^{-1}$. The cloud is blue-shifted in the northwest and red-shifted in the southeast, while, seemingly, the cloud is shifting in velocity in latitude continuously. By considering Figure 5 we selected two images of the blue-shifted cloud (7.0 – 9.5 km s$^{-1}$) and the red-shifted cloud (10.5 – 12.5 km s$^{-1}$) for a detailed comparison, since they show complementary distribution typical to two colliding clouds. The intermediate velocity images from 9.5 km s$^{-1}$ to 10.5 km s$^{-1}$ include the both components. Figure 6a shows the distributions of the two velocity components found to be spatially correlated. In Figure 6b a displacement of 0.6 pc shown by an arrow produces a good complementary fit, supporting physical association between the two components; the displacement
is estimated by optimizing the overlap of the intensity enhancement and depression according to the method given by Fukui et al. (2017b). Compared to the model clouds in Figure 2, the present clouds have less density inhomogeneity apparently. In Figure 6b at \((l, b) = (205.35, -14.3)\) the blue-shifted clump coincides with the two B-type stars, and at \((l, b) = (205.27, -14.2)\) the B star is located in the interface between the two velocity components. By using the \(^{13}\)CO\((J = 2 - 1)\) emission and an assumption of LTE, the cloud mass and the peak column density are calculated to be \(1 \times 10^3 \, M_\odot\) and \(2 \times 10^{22} \, \text{cm}^{-2}\), respectively, for the blue-shifted cloud within the integrated intensity 13.5 K km s\(^{-1}\), respectively. Those of the red-shifted cloud are estimated to be \(2 \times 10^3 \, M_\odot\) and \(6 \times 10^{22} \, \text{cm}^{-2}\) within the integrated intensity 10 K km s\(^{-1}\). The excitation temperature \(T_{\text{ex}}\) is 15 K and 30 K for the blue-shifted cloud and red-shifted cloud as derived from the peak brightness temperature of the \(^{12}\)CO emission. We assumed \([^{13}\text{CO}]/[\text{H}_2 = 2 \times 10^{-6}]\) for estimate of the molecular column density (e.g., Dickman 1978; Frerking et al. 1982)

### 5 Discussion

By analyzing the \(^{13}\)CO\((J = 2 - 1)\) data we investigated detailed kinematical properties of the star forming molecular gas whose column density is in a range from \(10^{22}\) to \(10^{23} \, \text{cm}^{-3}\). The two clouds, the blue-shifted cloud and the red-shifted cloud, are spatially separated by a typical gap of 1 pc in the sky. The northern cloud has an average velocity of 8.25 km s\(^{-1}\) and is associated with the reflection nebula NGC2071. The southern cloud has an average velocity of 11.5 km s\(^{-1}\) and is associated with the reflection nebula NGC2068. The two clouds are associated with an/two early B star(s), a protostellar outflow driven by young high mass protostars, and several tens of YSOc.

### 5.1 A cloud–cloud collision scenario

We found that the two components show complementary distribution with each other (Figure 6). A displacement of 0.6 pc produces a good complementary fit between the blue-shifted cloud at \(7.0 - 9.5\) km s\(^{-1}\) and the red-shifted cloud at \(10.5 - 12.5\) km s\(^{-1}\). The origin of the displacement is explained in Section 3. The blue-shifted cloud fits well the northern edge of the red-shifted cloud. The coincidence in their two-dimensional complementary distributions is not understood as a chance fit. B–type stars tend to be located near the projected interface of the two clouds, and are possibly formed by collisional trigger.

Based on the complementary distribution, we hypothesize that the two clouds collided with each other \(2 \times 10^5 \, (\approx 0.9 \, \text{pc}/4 \, \text{km s}^{-1})\) yrs ago on a tentative assumption that the relative motion makes an angle of 45 deg to the line of sight. This collision likely triggered formation of the three
B–type stars and, possibly, the driving sources of the outflow as well as some of the YSOs near the interface regions of the two clouds. The stars far from the interface were possibly formed prior to the collision. The two B–type stars in NGC2068 are located toward \((l, b) = (205.33, -14.31)\), where a small CO clump overlaps after the displacement (Figure 4 (b)). The typical column density toward the collision spots is \(10^{22} \text{ cm}^{-2}\) in the both components and is similar to that found in the other regions of single high-mass star formation by cloud–cloud collision (Fukui et al. 2017b). The B–type star in NGC2071 is located at \((l, b) = (205.17, -14.13)\), where the blue-shifted cloud is dense and the red-shifted one is less dense as seen in Figure 6. A possible scenario is that the collision happens between two uneven clouds having column densities of \(10^{22} \text{ cm}^{-3}\) and \(10^{21} \text{ cm}^{-3}\) as found in NGC6334 and NGC6357 (Fukui et al. 2018a) The boundary of the collisional area is not clearly specified toward the periphery of the clouds because part of the colliding cloud may be already dispersed by the collisional interaction. Ionization is perhaps not so important by considering the present low ultraviolet radiation of the B–type stars compared with O–type stars. We also note that the directions of the outflow driving sources are possibly toward the regions of cloud–cloud collision.

5.2 Large scale star formation in Orion

In the Orion region the ionization shock front driven by the HII regions were discussed as a mechanism to form OB associations. It is however difficult to understand the distribution of high-mass stars, O–type stars and early B–type stars, lined up in Orion A and Orion B regions, which are distributed apart with separations of \(\sim 25 \text{ pc}\). These large separations suggest that the high-mass star formation is taking place independently and without mutual influence. The present work showed that cloud–cloud collision provides a scenario to explain the high-mass star formation in the NGC2068 – NGC2071 region. The process is similar to what were presented in the M42–M43 region and the NGC2024 region. In hydrodynamic simulations of isolated galaxies, the typical cloud–cloud collision timescale for a giant molecular cloud is several Myrs (Fujimoto et al. 2014; Dobbs et al. 2015). This is longer than that inferred for the three collisions in Orion within 1 Myr. The three regions show displacements of \(0.3 – 1.0 \text{ pc}\) between the two components. A global study connecting the individual regions is a future challenge to link the individual star formation with the galaxy scale gas motion.

6 Conclusions

We made new \(^{13}\text{CO}(J = 2 – 1)\) observations of the molecular cloud associated with two early B–type star forming regions NGC2068 and NGC2071 in the L1630 dark cloud complex. By analyzing the \(^{13}\text{CO}\) data we made detailed investigation of kinematical properties of the star forming gas.
Conclusions are summarized as follows;

The northern cloud has an average velocity of 8.25 km s\(^{-1}\) and the southern cloud an average velocity of 11.5 km s\(^{-1}\). The two clouds are associated with early B–type star(s), protostellar outflow and several tens of YSOc, respectively. We found a hint that the B–type stars illuminating the reflection nebulae are partially disrupting the ambient gas, whereas the protostellar outflows are still embedded in the molecular gas. The other YSOc are lined up along the molecular ridges. We found that the two components show complementary distribution with each other; CO images of the blue-shifted and red-shifted clouds for a velocity interval of 1.5 – 2.0 km s\(^{-1}\) produce a good complementary fit after a displacement of 0.6 pc. Based on this complementary distribution, we hypothesize that the two clouds collided with each other 2 \(\times\) 10\(^5\) yr ago on a tentative assumption that the relative motion makes an angle of 45 deg to the line of sight. This collision likely triggered formation of the three B–type stars and the driving sources of the outflow as well as part of the YSOc. The typical column density toward the collision spots is 10\(^{22}\) cm\(^{-2}\), and the variation of density in the initial clouds may control the stellar mass forming. It is possible that part of YSOc were formed prior to the collision over a timescale of a Myr. In the Orion region including M42, M43, NGC2024, NGC2068, and NGC2071, most of the O/early stars are shown to be explained by the formation triggered by cloud–cloud collision by the recent works including the present paper. This offers a step forward to better understand high-mass star formation mechanisms and the role of cloud–cloud collision.

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Table 1. The initial conditions of the numerical simulations (Takahira et al. 2014)

| Parameter                  | The small cloud | The large cloud | note                               |
|----------------------------|-----------------|-----------------|-----------------------------------|
| Box size [pc]              | 30 × 30 × 30    |                 |                                   |
| Resolution [pc]            | 0.06            |                 |                                   |
| Collision velocity [km s\(^{-1}\)] | 10 (7)\(^\dagger\) |                 |                                   |
| Temperature [K]            | 120             | 240             |                                   |
| Free-fall time [Myr]       | 5.31            | 7.29            |                                   |
| Radius [pc]                | 3.5             | 7.2             |                                   |
| Mass [M\(_\odot\)]        | 417             | 1635            |                                   |
| Velocity dispersion [km s\(^{-1}\)] | 1.25           | 1.71            |                                   |
| Density [cm \(^{-3}\)]    | 47.4            | 25.3            | Assumed a Bonner-Ebert sphere     |

Note. \(^\dagger\) The initial relative velocity between the two clouds is set to 10 km s\(^{-1}\), whereas the collisional interaction decelerates the relative velocity to about 7 km s\(^{-1}\) in 1.6 Myrs after the onset of the collision. The present synthetic observations are made for a relative velocity 7 km s\(^{-1}\) at 1.6 Myrs.

Fig. 1. Schematic of the top-view of the collision; [A] the cavity, [B] the cavity and the small cloud, and [C] the large cloud.
Fig. 2. Systematic observations of $^{12}$CO ($J = 2 - 1$) emission based on the numerical simulations by Takahira et al. (2014) observed at an angle of the relative motion to the line of sight $\theta = 45$ deg. (a - h) show the velocity channel distributions every 0.96 km s$^{-1}$ map simulation model. The parameters of the model are shown in Table 1. (i) shows a complementary distributions between the large cloud, the image in (g), and the small cloud with the contour of (d) at 1.3 K km s$^{-1}$. 

Y [pc]  
-10 0 10  
X [pc]  
-10 0 10  
K km/s  
0 4 8  
Cont. : 1.3 K km/s  
(a) -6.0 - -5.1 km/s  
(b) -5.1 - -4.1 km/s  
(c) -4.1 - -3.1 km/s  
(d) -3.1 - -2.2 km/s  
(e) -2.2 - -1.2 km/s  
(f) -1.2 - -0.2 km/s  
(g) -0.2 - 0.7 km/s  
(h) 0.7 - 1.7 km/s  
(i) image : -0.2 - 0.7 km/s contour : -3.1 - -2.2 km/s
Fig. 3. The integrated intensity map of $^{13}$CO ($J = 2 - 1$) toward NGC2068 and NGC2071 integrated between 5 – 15 km s$^{-1}$. The black crosses and black squares show B-type stars and infrared sources, respectively. The black and white circles represent Class I – Flat and Class II – III YSOc, respectively, listed in (Spezzi et al. 2015).
Fig. 4. (a) The rotated integrated intensity map of $^{13}$CO ($J = 2 - 1$) toward NGC2068 and NGC2071 integrated between 5 – 15 km s$^{-1}$ (same as figure 1) with a Y-axis in a position angle of 135 degrees in Figure 3 and an X-axis orthogonal to the Y-axis, where (X,Y)=(0.0, 0.0) corresponds to ([l,b])=(205.26, -14.19). The contour levels are from 5, 10, 15, 20 and 25 K km s$^{-1}$. The two dashed line indicate the integration range of figure 2b. (b) The position velocity diagram of the $^{13}$CO ($J = 2 - 1$) emission toward NGC2068 and NGC2071. The contour levels are from 0.50, 0.75, 1.00, 1.25, 1.50 and 1.75 K degree. The blue and red dashed lines indicate the integration range of blue-shifted and red-shifted cloud presented in Figure 6.
Fig. 5. Channel maps of the $^{13}$CO ($J = 2 - 1$) emission in 0.75 km s$^{-1}$ intervals over the velocity range from 6.00 to 12.75 km s$^{-1}$. The lowest contour levels and the step are 1.0 K km s$^{-1}$ and 2.0 K km s$^{-1}$, respectively. The range of the integration is indicated in the topleft corner of each panel. The crosses represent the positions of B-type stars.
Fig. 6. (a) The gas distribution of the two colliding clouds. The gray scale shows the $^{13}$CO ($J = 2 - 1$) intensity integrated over the velocity range of 10.5 km s$^{-1}$ to 12.5 km s$^{-1}$. The blue and red contours show the intensity integrated over the velocity range of 7.0 – 9.5 km s$^{-1}$ (blue), 10.5 – 12.5 km s$^{-1}$ (red). The symbols are the same as in Figure 3. The YSO candidates within the blue and red contours are colored in blue and red. (b) Same as (a), but the blue contours and blue YSO candidate are displaced 0.6 pc as shown the arrow.