Rapid and efficient mass collection by a supersonic cloud-cloud collision as a major mechanism of high-mass star formation

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Abstract

A supersonic cloud-cloud collision produces a shock-compressed layer which leads to formation of high-mass stars via gravitational instability. We carried out a detailed analysis of the layer by using the numerical simulations of magneto-hydrodynamics which deal with colliding molecular flows at a relative velocity of 20 km s⁻¹ (Inoue & Fukui 2013). Maximum density in the layer increases from 1000 cm⁻³ to more than 10⁵ cm⁻³ within 0.3 Myrs by compression, and the turbulence and the magnetic field in the layer are amplified by a factor of ~5, increasing the mass accretion rate by two orders of magnitude to more than 10⁻⁴ M⊙ yr⁻¹. The layer becomes highly filamentary due to gas flows along the magnetic field lines, and dense cores are formed in the filaments. The massive dense cores have size and mass of 0.01 – 0.1 pc and 10 – 100 M⊙ and they are usually gravitationally unstable. The mass function of the dense cores is significantly top-heavy as compared with the universal IMF, indicating that the cloud-cloud collision triggers preferentially the formation of O and early B stars. We argue that the cloud-cloud collision is a versatile mechanism which creates a variety of stellar clusters from a
single O star like RCW120 and M20 to tens of O stars of a super star cluster like RCW38 and a mini-starburst W43. The core mass function predicted by the present model is consistent with the massive dense cores obtained by recent ALMA observations in RCW38 (Torii et al. 2019) and W43 (Motte et al. 2018) considering the increasing evidence for collision-triggered high-mass star formation, we argue that cloud-cloud collision is a major mechanism of high mass star formation.

Key words: xxxx: xxxx — ......

1 Introduction

Formation of high-mass stars has been an issue of compelling interest in the last two decades because the influence of high-mass stars in galactic evolution is overwhelming and profound. Considerable efforts have been paid toward understanding high mass star formation by a number of papers (see for a review Tan et al. 2014; Krumholz et al. 2009).

Three scenarios have been considered until now in the literature. They are (1) stellar collisions in a rich stellar cluster (Bonnell et al. 1998), (2) the competitive accretion in a massive self-gravitating system (Bonnell et al. 2001), and (3) the monolithic collapse of a dense cloud (McKee & Tan 2002; Krumholz et al. 2009). If the stellar density is high enough for frequent collision between stars, collisional merging of low-mass stars may work as a possible mechanism. Later, it was proved that the stellar density has to be uncomfortably large for such collisions to be efficient, and stellar collisions is no more considered as a viable mechanism of high mass star formation (Moeckel & Clarke 2011). The other two mechanisms remain to be confronted by observations, and it is not yet settled how high-mass stars are forming (see for a review Tan et al. 2014). A possible argument unfavorable to the competitive accretion is an isolated O star such as the exciting star of M20 and RCW120, which does not belong to a massive cluster (Torii et al. 2011; Torii et al. 2015; see also Ascenso 2018). The numerical simulations of the monolithic collapse by Krumholz et al. (2009) showed the formation of O stars from molecular gas of 100 \( M_\odot \) confined within 0.1 pc, which was adopted from observations of a protostar candidate IRAS 05358+3543 in the S233 – 235 high-mass star forming region and other typical regions of high-mass star formation (Beuther et al. 2007; see also McKee & Tan 2002). A recent analysis of molecular gas by Kohno et al. (in prep.) showed that IRAS 05358+3543 was possibly formed by an external trigger of a cloud-cloud collision, an ad-hoc situation externally
driven, raising caution on the initial condition adopted by Krumholz et al. (2009).

High-mass star formation requires accumulating large cloud mass into a small volume. Suppose that the initial condition is a massive low-density cloud and the final phase is a small dense cloud of the same mass which rapidly forms high-mass star(s). This scenario requires an intermediate phase when cloud density is high enough to form low-mass stars unless the phase has a time scale much shorter than the free-fall time scale. During the phase star formation has to be strongly suppressed. Otherwise, the cloud loses mass by star formation before being collected into the small volume and high-mass star(s) cannot be formed. Such a naive thought may be useful to shed light on the essence of the high-mass star formation as suggested in a review article by Zinnecker & Yorke (2007), while no further pursuits are found in the literature:

“Rapid external shock compression (i.e., supersonic gas motions) generating high column densities in less than a local free-fall time rather than slow quasistatic build-up of massive cores may be the recipe to set up the initial conditions for local and global bursts of massive star formation.” (in Section 9 of Zinnecker & Yorke 2007)

Cloud-cloud collision is another promising mechanism of the high-mass star formation as shown by recent theoretical and observational works, and has become a possible alternative to the previous scenarios of high-mass star formation above, (2) and (3). Habe & Ohta (1992) showed that, in a supersonic collision between small and large molecular clouds, the small cloud creates a cavity in the large cloud, and the layer between the two clouds are strongly compressed to higher density, where a condition favorable for high-mass star formation is realized (Habe & Ohta 1992; Anathpindika 2010; Takahira et al. 2014). After the onset of the collision, the two clouds show complementary distribution between the cavity and the small cloud, and the interface layer shows a broad bridge feature connecting the two cloud in velocity. Recent observations show that in more than 50 regions of high-mass star formation these observational signatures of collision are identified and typical cloud properties are derived such as density and mass of the colliding clouds. These objects includes HII regions and super star clusters in the Milky Way and the Local Group (e.g., M42/M43 Fukui et al. 2018a; M17 Nishimura et al. 2018; NGC6334 and NGC6357 Fukui et al. 2018b; RCW120 Torii et al. 2015; RCW38 Fukui et al. 2016; Wd2 Furukawa et al. 2009; Ohama et al. 2010; and NGC3603 Fukui et al. 2014).

It is important to understand the detailed properties of the forming stars under a trigger of a cloud-cloud collision, and theoretical understanding of the physical properties of the colliding clouds is crucial. Magneto-hydrodynamic (MHD) numerical simulations were made for molecular gas flows colliding supersonically in a plane-parallel configuration by Inoue &
Fukui (2013), and showed that dense cores around $100 M_\odot$, precursors of high-mass stars, are formed. These simulations showed that the layer is characterized by enhanced turbulence and magnetic field where the effective sound velocity is increased by several times depending on the collision velocity. As a result, a mass accretion rate, which is proportional to the third power of the effective sound speed, becomes as high as $10^{-4} - 10^{-3} M_\odot \text{yr}^{-1}$, which satisfies a value high enough to overcome the stellar radiation feedback (Wolfire & Cassinelli 1987). Since the simulations include more details of the compressed layer such as the mass function of the dense cores, which were not presented by Inoue & Fukui (2013), it is worthwhile to explore further the molecular gas properties in the simulations. Such a study will shed light on the time evolution in a cloud-cloud collision and help us to obtain an insight into the triggered high-mass star formation.

The aim of the present paper is to analyze the simulation data of Inoue & Fukui (2013) and to explore the details of the gas dynamics. In particular, we aim to derive a core mass function in a cloud-cloud collision and their detailed physical properties, which will allow us to make a comparison between the theory and the observations, and deepen our understanding of the role of cloud-cloud collision. This paper is organized as follows. Section 2 describes the model of Inoue & Fukui (2013) and Section 3 the outcomes of the simulations. Section 4 gives the dense core properties including the distribution of the cores and the core mass function. Confrontations with the observations are given in Section 5. Section 6 compare the present results with the other theoretical scenarios, and Section 7 gives conclusions.

2 The model

Figure 1 shows a three-dimensional view of the shock compressed layer in a volume rendering map at an epoch of 0.6 Myrs, where the three axes $x$, $y$ and $z$ are shown in a simulation box, which has a size of 8 pc in each axis and the pixel size is $8 \text{pc}/512 = 0.015 \text{pc}$ or 3000 AU. Two colliding molecular flows along the $x$ axis at $10 \text{km s}^{-1}$ in the box frame create the shock compressed layer in the central $y$-$z$ plane of the box. The simulations were made in the ideal MHD with self-gravity. The molecular cooling time scale is less than $10^4 \text{yrs}$ and the gas is approximated to be isothermal at 12K, corresponding to a sound speed of $0.2 \text{km s}^{-1}$. The initial magnetic field is taken to be $20 \mu \text{G}$ and the field direction is chosen to be perpendicular to the collision velocity. The assumption does not substantially affect the final outcome because the colliding flows strongly compress the magnetic field lines in a direction perpendicular to the collision velocity. The initial gas density is $300 \text{cm}^{-3}$ with a density fluctuation of $\sim 30\%$. The
model setup is summarized in Table 1 and more details are given in Inoue & Fukui (2013). The calculations are made up to 0.7 Myrs and the numerical results are recorded every 0.1 Myrs.

3 Structure of the shock compressed layer and the formation of the dense cores

3.1 The shock compressed layer

The colliding gas has inhomogeneous density and velocity distribution. The flows create the compressed layer between them, which becomes denser and decelerated. Figure 2(a) shows the velocity vectors in an x-y plane on the negative-x side, and Figure 2(b) shows a close up in the velocity transition zone at an epoch of 0.7 Myr. The velocity does not change from the initial value at \( x < -1.0 \), and quickly becomes small and completely randomized in angle at \( x = -1.0 - 0.6 \). This change is due to the shock dissipation and momentum exchange between the colliding flows. The behavior is similar on the positive x side. Figures 2(c) – (f) show the averaged velocity, the angle between the velocity vector and the x axis, the gas density and pressure respectively, as a function of x, and show that the velocity decreases to \( \sim 2 \text{ km s}^{-1} \) from \( 12 \text{ km s}^{-1} \) and is randomized in direction. In Figures 2(a) and (b) velocity is larger than the initial value 10 \( \text{ km s}^{-1} \) because of the gravitational acceleration by the shock compressed layer.

The time evolution of the layer is shown as a density distribution along the x-axis at each epoch in Figure 3. In 0.3 Myr the maximum density becomes more than \( 10^5 \text{ cm}^{-3} \) and the fraction of the dense gas increases in time. Table 2 shows the gas mass in the compressed layer above \( 10^4 \text{ cm}^{-3} \). The full thickness of the compressed dense layer above \( 10^4 \text{ cm}^{-3} \) is \( \sim 1.5 \text{ pc} \) in the x direction. After 0.4 Myr we find sharp narrow spikes which indicate formation of filaments and dense cores in the layer as detailed later. The fraction of the dense gas above \( 10^5 \text{ cm}^{-3} \) is 10% – 17% of the total gas mass of density above \( 10^4 \text{ cm}^{-3} \). Figure 4 shows a probability distribution function of density, where \( t = 0.0 \text{ Myr} \) shows the initial condition. The collision creates the higher density tail above \( 10^4 \text{ cm}^{-3} \) as well as the low-density tail below the initial density distribution produced by turbulence. The high-density tail characterizes the compression as expressed by a power law with an index of \( -3.0 - -2.0 \), which becomes flatter in time.

3.2 Dense cores in the filaments

The density distribution in the three-dimensional space is characterized by filaments which include dense cores. Figure 5(a) shows the distribution of filamentary distribution identified as
connected region with $n > 10^5 \text{ cm}^{-3}$, where different filaments are indicated by different arbitrary colors. In each filament we define dense cores by using CLUMPFIND algorithm (Williams et al. 1994). The algorithm is designed to be applied to spectral line datasets, $T(x,y,V)$ data cubes, but here we use it to find cores in $n(x,y,z)$ datasets.

Inoue & Fukui (2013) explained that the distorted field lines guide the gas flow into dense cores in a filamentary shape (see their Figure 1). The created filaments are generally oriented perpendicular direction to the magnetic field. Filament formation is a common feature in a collision-compressed layer as shown in the other simulations of cloud-cloud collision (Inoue et al. 2018). In this particular simulation by Inoue & Fukui (2013), because the colliding two gas flows have different magnetic field orientations (perpendicular to each other), the directions of the resulting filaments are often crossing at 90 degrees. This crossing feature disappears if the magnetic field orientations are similar between the colliding clouds. Note that the crossing feature does not affect the mass distribution of the dense cores. We look into more details in Figure 6, where the magnetic field lines and the velocity vector are shown in two typical regions with filaments. In Figures 6 we find that the filaments are well aligned in a direction perpendicular to the field line. This is a common feature around the filamentary distributions. The velocity vectors in Figures 6(a), on the other hand, do not show a very systematic trend and are not always aligned with the field lines. This suggests that the gas motion has both parallel and perpendicular components near the filaments, whereas the time average produces the net gas flow into the filaments. We also notice that the line mass in a filament tends to increase if the velocity vectors and field lines are in a similar direction as suggested in Figure 6(b), which shows that the growth of a filament is achieved by the flow along the field lines.

Each filament contains dense cores. Formation of similar dense cores is observed in the non-MHD numerical simulations of a cloud-cloud collision by Takahira et al. (2014), which is due to cloud self-gravity. In order to characterize the cores we applied the clump-find algorithm to the filaments at $n_{\text{threshold}}$, and identified 777 cores in total in 0.7 Myr as shown in Figure 5(b). In each epoch the physical parameters including mass, size, average density of the dense cores are derived for density above $10^5 \text{ cm}^{-3}$. The mass of a core is a sum of all of the pixels, and the size of a core is calculated as a geometrical mean of three major axes, which are derived by fitting a spheroid with three semi-major axes $a$, $b$, and $c$. Figure 7(a) shows a scatter plot between mass and size of the dense cores, Figure 7(b) a size histogram, and Figure 7(c) a scatter plot between the axial ratios, $a/b$ and $b/c$. Mass of a core is in a range $0.1 - 100 M_\odot$ with size in a range of $0.01 - 0.1 \text{ pc}$. The maximum mass of a core attained is close to $100 M_\odot$ with size of $0.1 \text{ pc}$ at density above $10^5 \text{ cm}^{-3}$, while it depends on the threshold density adopted. The
aspect ratios $a/b$ and $b/c$ are mostly a range of $1 - 3$ with an average of $1.9 - 2.5$, indicating that they are not spherical: 15% of the cores are spherical, 35% prolate and 50% oblate. For the prolate and oblate cores we made histograms of an angle between the major axis and the field lines in Figure 8(a) and the minor axes and the field lines in Figure 8(b). We find that the prolate cores are aligned within 40 degrees to the field lines, while the oblate cores have minor axes with an angle to the field lines in a broad range of $10 - 70$ degrees. The former seems to be a natural result of the prolate core formation in a filament, while the oblate cores form more randomly.

3.3 A core mass function

Figure 9 shows a core mass function for five epochs, and the ratio of the core mass $M_{\text{core}}$ to the effective jeans mass $M_{\text{eff}}$, which counts the turbulent and magnetic pressure in addition to the thermal pressure, and to the jeans mass $M_{\text{j}}$, which counts only the thermal pressure, as a function of the core mass at five epochs. The cores grow by the collisional compression. We find an increase of the cores in a mass range $0.1 - 10 M_\odot$ and the highest mass above $10^5 \, \text{cm}^{-3}$ reaches $\sim 60 M_\odot$ at 0.7 Myr. We see a clear signature of a top-heavy mass function extending beyond $10 M_\odot$ in Figure 9. The ratio between the core mass and the effective jeans mass shows that most of the cores with mass more than $10 M_\odot$ are gravitationally bound and will become high-mass protostars as shown by Inoue & Fukui (2013). Dense cores with mass less than $10 M_\odot$ are more weakly gravitationally bound. They may form low-mass stars if the core mass is greater than the jeans mass depending on the details of the gas dynamics. In this sense, the number density of the cores whose mass lies between $0.3 M_\odot$ and $10 M_\odot$ in Figure 9 gives an upper limit for the number density of the low-mass protostars. It is unlikely that cores less massive than the jeans mass form stars, while the less massive cores may grow into a more massive ones by mass accretion and coagulation, depending on the time scale before dissipation by ionization by the forming O stars.

4 Properties of the dense cores and O stars

The present results on dense cores allow us to obtain an insight into the O star formation by cloud-cloud collision. We first describe the formation of individual O stars in dense cores, and, second, present the predicted mass function and spatial distribution of multiple O stars.
4.1 O star formation and subsequent evolution in the shock compressed layer

In the shock-compressed layer, dense cores smaller than 0.1 pc with maximum mass close to $100 M_\odot$ are created (Inoue & Fukui 2013). These cores have density more than $10^5$ cm$^{-3}$ and become gravitationally unstable. Inoue & Fukui (2013) showed that the mass accretion rate in the shock-compressed layer is greater than $\sim 10^{-4} M_\odot$ yr$^{-1}$ due to the enhanced effective sound speed, which is large enough to overcome the radiation pressure to form high-mass stars (Wolfire & Cassinelli 1987). The formation time scale of a $15 M_\odot$ O star is estimated to be $15 M_\odot / 10^{-4} M_\odot$ yr$^{-1} = 0.15$ Myrs if a constant mass accretion rate is assumed. In this mass accretion phase, we expect molecular outflow is generated as driven by the accretion disk in a dynamical timescale of $\sim 10^4$ yr (e.g., Machida et al. 2008). When the star becomes as massive as $15 M_\odot$, its surface temperature reaches 30000 K (Cox 2000), which is high enough to emit significant ionizing photons to its surroundings. The ionization then proceeds at a typical speed of more than a few km s$^{-1}$ (e.g., Hosokawa & Inutsuka 2005), and in a few times 0.1 Myrs a radius of $\sim 1$ pc will be ionized, while a significant portion of the neutral gas generally remains unionized outside of the radius.

The O star formation is a natural outcome of cloud-cloud collision, a rapid process which converts the low-density molecular gas to dense gas in 0.1 Myrs. It is essential that the compression is done not by self-gravity but by the magnetic-field guided supersonic flow. This rapidness is the key to collect large mass of $100 M_\odot$ into a 0.1 pc volume. If the collect process is slow in the order of the free fall time ($\sim$ Myr for density 1000 cm$^{-3}$), it is likely that the gas is consumed by formation of low-mass stars before being collected in the volume.

4.2 Cluster formation in the collision-compressed layer

4.2.1 Formation of filaments and O stars in the compressed layer

A cloud-cloud collision produces the filamentary morphology of the compressed layer and the dense-core distribution confined to the filaments as shown in Figure 10. The O stars formed will not move by more than 0.2 pc within 0.1 Myrs, the typical timescale of the O star formation, for an average velocity of dense cores of $\sim 1$ km s$^{-1}$ (Figure 2). This indicates that the O star distribution is determined by the collision-formed filamentary distribution until gravitational relaxation becomes effective later, in more than Myr. The evolution of the stellar system in this phase is essentially similar to that given by $N$-body simulations (e.g., Fujii & Portegies Zwart 2015). The filaments will be destroyed in the order of 0.1 Myrs by the ionization once the stars become as massive as $15 M_\odot$, and the final mass of the formed stars, i.e., the O
stars and their neighbors, are determined by the mass of the dense cores and the duration of the mass accretion until full ionization. In the following we assume for simplicity that the mass of the gravitationally unstable dense cores is converted into the stellar mass, while the conversion efficiency may be somewhat less than 1.0. In the present simulations no ionization is incorporated. In Figure 10 we draw a circle of the ionization front for each “O star” by assuming for simplicity that the ionization front proceeds at a uniform speed of $3 \text{ km s}^{-1}$ after a dense core of $10 M_\odot$ having density $10^5 \text{ cm}^{-3}$ appears. This allows us to have a rough idea on the dispersal of the filaments by ionization.

We obtain a further insight into the O star formation by inspecting column density in the filaments. Figure 11 shows the column density distribution in space for 8 regions of $1.5 \text{ pc} \times 1.5 \text{ pc}$ in the $y$-$z$ plane selected by the number of O stars and the distribution function of column density in each box, and indicates that O stars can be formed in isolation and/or in a cluster depending on the resultant column density. In the distribution function of column density in Figure 8, the typical column density peaks are found at around $10^{22} \text{ cm}^{-2}$. Formation of nearly ten O stars occurs in a filament with high column density tails beyond $10^{23} \text{ cm}^{-2}$ (Regions (2), (3), (4), and (6)). On the other hand, in a region of a single or no O star formation column density distribution is not beyond $10^{23} \text{ cm}^{-2}$.

Figure 12 shows a histogram of the separation between dense cores with mass more than $5 M_\odot$ in the $y$-$z$ plane. The separation is peaked at $0.1 \text{ pc}$ and is extended up to a few pc. The cores more massive than $10 M_\odot$ show two peaks at $\sim 0.1 \text{ pc}$ and $\sim 1 \text{ pc}$, where the small value reflects the core distribution within a filament and the large one the core distribution between filaments. The distribution provides a test tool for a comparison with observations.

Figure 13 shows another comparison of the core mass function in the collision compressed layer taken from Figure 9. The core mass function in cloud-cloud collision is top-heavy with a negligible contribution of dense cores less than $1 M_\odot$, which makes a contrast with the initial mass function (IMF) of field stars which is shifted to lower mass by more than an order of magnitude as compared with that in cloud-cloud collision (e.g., Kroupa 2001; Chabrier 2005). We therefore conclude that cloud-cloud collision is a mechanism which preferentially forms high-mass stars.

### 4.2.2 Cluster formation scenario

A cloud-cloud collision creates massive dense cores, precursors of an O star, which are clustered in a filament. In order to illuminate the whole process of a cluster formation, we present a formation scenario of an O-star cluster as a two-step process, i.e., (i) pre-collision phase, and
(ii) post-collision phase, in the following. Similar discussion is given for two individual objects RCW38 and the ONC, from an observational point of view (Fukui et al. 2016; Fukui et al. 2018a).

In the pre-collision phase, the two clouds independently form only low-mass stars from low-mass cores without mutual interaction if they are dense enough: a typical observed case is the Taurus cloud complex forming \( \sim 20 \) low mass stars in a cloud having mass of \( \sim 1000 M_\odot \), size of \( \sim 5 \) pc and column density \((1-10) \times 10^{21} \) cm\(^{-2}\) (Mizuno et al. 1995; Onishi et al. 1996; Onishi et al. 1998; Onishi et al. 2002). The timescale of this phase can be as long as several Myrs, forming low-mass stars at a mass accretion rate of \( 10^{-6} M_\odot \) yr\(^{-1}\) in the non-shocked condition as long as the cloud dispersal by outflows/winds is not substantial. The core mass function is shown in Onishi et al. (2002), which indicates that the dense core of density \( 10^5 \) cm\(^{-3}\) have mass range from 1 to 10 \( M_\odot \), which can be roughly converted to a stellar mass range from 0.1 to 1 \( M_\odot \).

Suppose an accidental collision between such two clouds happens at a supersonic velocity in the order of \( 10 \) km s\(^{-1}\), the collision rapidly creates the collision-compressed layer in \( \sim 0.1 \) Myrs to form massive dense cores (the post-collision phase). The moment of the collision is subject to a stochastic process among the clouds in the Galactic disk with a typical mean free time of less than 10 Myrs depending on the cloud number density as shown by numerical simulations (e.g., Kobayashi et al. 2018; see also Fujimoto et al. 2014; Dobbs et al. 2014). The number of O star(s) depends on the cloud column density. Based on the previous observations of cloud-cloud collisions, Fukui et al. (2018a) showed that a single O star can be formed for total column density of \( 10^{22} \) cm\(^{-2}\), and that formation of nearly ten O stars requires total column density as high as \( 10^{23} \) cm\(^{-2}\) at a 1-pc scale. Clouds with column density below \( 10^{22} \) cm\(^{-2}\) will grow in mass by collision without O star formation.

Subsequently, the massive dense cores form O stars which ionize the clouds and suppress subsequent star formation, details of which depends on the number of the O stars, and density and size of the clouds. In the end of this phase a cluster becomes exposed by ionization, and the emerging cluster consists of old low-mass stars extended over the clouds and young O star(s) localized within the colliding area. Consequently, the age of the low-mass members can be distributed from 1 Myr to several Myrs as determined by the collision mean free time, and the age of the O stars is peaked just after the collision with a short duration in the order of 0.1 Myrs. Such a short time duration is supported by the detailed observations of stellar ages in two clusters NGC3603 and Westerlund1 (Kudryavtseva et al. 2012). In \( \sim 1 \) Myr after the O star formation the ambient gas will be fully ionized and dispersed as seen in NGC3603 and
Westerlund1. After the ionization, gravitational relaxation will redistribute the filamentary O stars into a more centrally concentrated stellar cluster in a few Myr, as is modeled by the N-body numerical simulations (e.g., Fujii & Portegies Zwart 2015).

For example, the ONC and RCW38 correspond to the earliest post-collision phase of 0.1 Myr after collision, and NGC3603 is of 2 Myrs after the ionization. The pre-collision phase is not easily recognized observationally at a usually distance of O stars more than 1 kpc because a pre-collision cluster without O stars is not obvious in the Galactic plane due to extinction and contamination.

5 Comparison with observations of O stars triggered by a cloud-cloud collision

Recent studies show that cloud-cloud collision is an essential process in high-mass star formation. Observationally, cloud-cloud collision is found in many high-mass stars associated with molecular clouds which are not fully ionized. In the literature more than 50 such objects formed by cloud-cloud collision are presented as compiled by Enokiya et al. submitted to PASJ, lending support for the cloud-cloud collision as a major mechanism of high-mass star formation. Theoretically, numerical simulations of the hydrodynamics of cloud-cloud collision show that cloud-cloud collision plays a role in triggering high-mass star formation (Habe & Ohta 1992; Inoue & Fukui 2013; Takahira et al. 2014; Inoue et al. 2018; Shima et al. 2018).

Here we compare the present theoretical results with observations of cloud-cloud collisions in the youngest phase of \(\sim 0.1\) Myrs, where we are able to find the O star distribution just after their formation without ionization or gravitational relaxation. The key features of the O star formation derived in the present work and Inoue & Fukui (2013) are summarized as follows;

a. Cloud-cloud collision is a mechanism of rapid formation of massive dense cores with density of \(10^5\) cm\(^{-3}\) up to \(\sim 60\, M_\odot\) in 0.1 Myr, which is characterized by a top-heavy mass function. The massive dense cores are gravitationally unstable and lead to O star formation under the high-mass accretion rate which satisfies the criterion to overcome radiation pressure. Cloud-cloud collision is therefore a mechanism of O star formation. Less massive dense cores are also formed more in number than the massive dense cores in the collision compressed layer, while a small fraction of them perhaps becomes gravitationally unstable to form low-mass stars.

b. The colliding gas flow of 10 km s\(^{-1}\) is quickly decelerated to around 1.5 km s\(^{-1}\) in the collisional-shocked layer, where the velocity vector becomes randomized. The collision-compressed layer of \(\sim 1\) pc thickness becomes filamentary with 0.1-pc width, where the gas flow...
is guided to a filament by the magnetic field lines. The formation of the filament is not due to the self-gravity and is, therefore, more rapid in $\sim 0.1$ Myr than the free fall time, $\sim 1$ Myr for $1000 \, \text{cm}^{-3}$, which is essential in O star formation. Once a filament is formed, the filament grows in mass by the incoming flow. In the filament the massive dense cores are formed by self-gravity in a $0.1$ pc scale in free-fall time of $0.1$ Myr for density above $10^5 \, \text{cm}^{-3}$.

c. The massive dense cores form O stars which are confined in the filament, and the O star distribution is filamentary having the same velocity field with the collisional shocked layer. When a mature O star of more than $15 \, M_\odot$ forms, the ionization by the O star becomes effective to disperse the gas and quenches star formation within a few pc of the O star(s). The ionization removes gas and the O star distribution evolves by gravitational relaxation in a Myr timescale.

5.1 Triggered formation of a single O star; a comparison in RCW120 and M20

O star formation takes place in a region with high column density above $10^{23} \, \text{cm}^{-2}$ (Figure 11). In the following, we compare the present results with RCW120 and M20 as a typical region of single O star formation triggered by cloud-cloud collision (Torii et al. 2011; Torii et al. 2015; Torii et al. 2017). The comparison shows that the synthesized distribution of an O star and low-mass stars formed by the trigger match the observed properties of the stars.

5.1.1 RCW120

RCW120 is a typical Spitzer bubble with a single O star within a dust cavity and has been studied extensively at various wavelengths (e.g., Deharveng et al. 2009). The O star is located inside the cavity enclosed by a curved wall of $\sim 1$ pc thickness, and the cavity wall includes $\sim 140$ low mass stars, at least $\sim 50\%$ of which are likely YSOs, as shown in Figure 14 (Deharveng et al. 2009). A conventional scenario on the bubble is a collect collapse scenario driven by a HII region, where the exciting star is assumed to form the bubble as simulated by Hosokawa & Inutsuka (2005). Alternatively, based on observations of two dissimilar molecular clouds of $20 \, \text{km} \, \text{s}^{-1}$ velocity separation, Torii et al. (2015) presented a scenario that the two dissimilar clouds collided with each other and the O star was formed in the collision-compressed layer $\sim 0.4$ Myrs ago. According to Torii et al. (2015), RCW120 currently corresponds to the last phase of the Habe-Ohta type cloud-cloud collision and the small cloud is already dissipated into the compressed layer (see Figure 3 of Habe & Ohta 1992). The collision time scale needs consideration on the deceleration, which is not taken into account in the present continuous two-flow model. Density of the flow in the real process decreases in time due to the limited
length of the small cloud, and the collision velocity becomes smaller than the uniform flow (c.f., Haworth et al. 2014). Torii et al. (2015) therefore estimated the collision time scale to be 0.4 Myr instead of a simple ratio $4 \text{pc}/30 \text{km s}^{-1} = 0.13 \text{Myr}$ for no deceleration, and the present discussion assumes the timescale.

In the scenario the small cloud entered from the northeast of the large cloud, where the cavity has currently an opening as created by the small cloud. After travelling over $\sim 4 \text{ pc}$ from the northeast to the southwest, the small cloud is fully dissipated into the cavity wall at present. The O star and $\sim 20$ YSOs concentrated near/in the southwest of the cavity wall having $\sim 1\text{-pc}$ thickness lend support for the collisional compression from the northeast (Figure 14). We interpret that these young stars are the products of the trigger in the common compressed layer of pc-scale thickness. There are more than ten YSOs clustered along the wall at a length of 1 pc, which possibly correspond to filamentary distribution as predicted by the cloud-cloud collision. For the $\sim 20$ YSOs separations between the YSOs are compared with the present results in Figure 12(b). The separations in RCW120 are peaked around 0.1 pc and are consistent with those predicted by the cloud-cloud collision. The other YSOs distributed in the east and west of the cavity in Figure 14 may have been triggered by the oblique shock between the small cloud and the cavity along the path of the small cloud.

We present a possible scenario that the first massive dense core is formed, leading to the O star formation, and then several dense cores in the nearby filaments form YSOs (e.g., in Region (2) of Figure 11). This process is qualitatively consistent with the O star and $\sim 20$ YSOs in RCW120, about ten of which seems filamentary. When the O star was formed, the ionization starts, and the compressed layer is ionized at a radius around 1 pc in $\sim 0.1 \text{ Myrs}$. A possible half-circular boundary is marked for this HII region having $\sim 1\text{-pc}$ radius in Figure 14. The ionized mass by the O star is estimated to be $200 M_\odot$ (Torii et al. 2015), and is consistent with the initial molecular mass within a semi-circular HII region of 1-pc radius. Most of the inner surface of the cavity wall is irradiated by the O star and is being ionized slowly at distance larger than 1 pc from the O star.

In order to understand the collision more quantitatively, we explore the physical parameters. For the sake of discussion, we approximate the cavity of RCW120 by a cylinder of 1.5 pc radius and 4 pc length as shown in Figure 14, while the model ignores the curved shape of the cavity for simplicity. At an end of the cylinder, the collision-compressed layer of the same radius lies with a 1-pc thickness. The related physical parameters, density, mass etc., are summarized in Table 3. The average density of the two clouds is taken to be 300 cm$^{-3}$ initially and it increases to 3000 cm$^{-3}$ in the compressed layer. The observed parameters match the model.
parameters in Table 3. The total cloud mass within the cavity prior to the collision is $500 \, M_\odot$ and the final total mass of the collision compressed layer is $1000 \, M_\odot$. The collision-compressed layer consists of the pre-existent large cloud merged with the compressed layer. The column density of the layer is estimated to be $\sim 10^{22} \, \text{cm}^{-2}$ from CO observations (Torii et al. 2015), which is consistent with the present results. Part of the collision compressed layer in RCW120 is converted to the O9 star having $15 \, M_\odot$ in addition to around 20 low mass stars in the bottom of the cavity wall. The stellar mass formed by the trigger is then roughly estimated to be around $40 \, M_\odot$ ($15 \, M_\odot + 20 \times 1 \, M_\odot$), and a ratio of the stellar mass to the total mass of the stars and gas becomes $40 \, M_\odot / 3040 \, M_\odot \sim 1\%$.

For RCW120 a conventional model is the collect collapse scenario which is driven by the ionizing star (Zavagno et al. 2007; Deharveng et al. 2009). As discussed above, however, the cloud-cloud collision offers a better explanation of the observed properties of RCW120. One of the important observed properties is that the bubble is not circular symmetric as opposed to the conventional picture of “complete bubble” (e.g., Zavagno et al. 2007). Figure 14 shows that the bubble is broken on the northeast and open to the outside. This shape is consistent with the collision path of the small cloud from the northeast as modeled by Habe & Ohta (1992). The star formation takes place mostly near the cavity bottom in a highly asymmetric way, which is consistent with the present model that predicts star formation in the compressed layer. It is also important that the O star formation is of the same generation with the other YSOs under a single trigger in the present model, whereas the collect-collapse scenario has no explanation on the origin of the O star. We are able to apply a similar cloud-cloud collision scenario to the other bubbles, which include regions of single O star (N4 ?, and S44 Kohno et al. 2018), the bubble complexes (S166 – 168 Fukui et al. 2018b, RCW166 Ohama et al. 2018), multiple O stars (RCW79 Ohama et al. 2018, N35 Torii et al. 2018) in the Milky Way.

5.1.2 M20

M20 is another object where single O star and several lower-mass stars are formed by a collisional trigger (Torii et al. 2011; Torii et al. 2017). Collision happened nearly along the line of sight 0.3 Myrs ago as evidenced by the bridge features associated. Figure 2(b) in Torii et al. (2017) reproduces a HST image (Yusef-Zadeh et al. 2005) which shows a small cluster with a O star and several lower mass stars as shown in Figure 15. We see an ionized cavity of 0.3 pc centered on the O star. These stars including O7.5V(III), A2Ia, B6V, Be, F3V, and a few more are aligned in a filamentary distribution of $\sim 0.2 \, \text{pc}$ length with a few stars more scattered within an area of $0.5 \, \text{pc} \times 0.5 \, \text{pc}$. The molecular mass toward the cluster is roughly estimated
to be $100 \, M_\odot$ for $0.5 \, \text{pc} \times 0.5 \, \text{pc}$ for column density of $3 \times 10^{22} \, \text{cm}^{-2}$ and the total stellar mass is $40 \, M_\odot$. Separations between these stars as listed by Rho et al. (2008) are shown in Figure 12(c), and seem to be consistent with the prediction of the present results. The M20 cluster is different from the isolated O star in RCW120, where the O star has no known nearby low-mass stars. In both M20 and RCW120 a core mass function is not available yet.

5.2 Formation of the very young super star cluster RCW38 and a mini-starburst W43

Super star clusters in the Milky Way include $10 - 20$ O stars in a pc scale in addition to $\sim 10^4$ low mass stars more extended (see for a review Portegies Zwart et al. 2010; Ascenso 2018). Among them the very rich clusters including O stars as young as 0.1 Myr are the primary site to test the collision signatures, separations between dense cores (or O stars) and a core mass function, which will be rapidly lost by ionization in Myr.

5.2.1 RCW38

As the best cluster for comparison we focus on RCW38 the youngest super star cluster where O star formation was triggered by a cloud-cloud collision according to Fukui et al. (2016). Most recently, Torii et al. (2019) mapped the CO clouds with ALMA at high resolution of $\sim 2''$ in C$^{18}$O $J = 2-1$ emission (P.I.: Fukui, Y., #2015.1.01134.S), and resolved 21 dense cores larger than 0.01 pc with a mass detection limit of $\sim 6 \, M_\odot$. Table 4, a reproduction from Torii et al. (2019), shows that the density of these cores is rather high in the order of $10^{7} \, \text{cm}^{-3}$, while lower density cores may be excluded. Figure 16 shows the spatial distributions of dense cores and O-star candidates in RCW38, which seems to well match the present results. The O star candidates are distributed in filamentary distribution of $\sim 1$ pc length (Wolk et al. 2006; Winston et al. 2011) toward the collisional area of a 0.5-pc radius as shown in Figure 16. Both of the stars and cores seem to show filamentary distribution in the SW-NE direction or the SE-NW direction. The number density of O stars and the massive dense cores is $\sim 100 \, \text{pc}^{-2}$. Figure 12(d) shows that separations between the dense cores/O stars are consistent with the present results. In Figure 13 the core mass function is compared, showing also good correspondence in a mass range of $6 - 60 \, M_\odot$. The top-heavy core mass function in RCW38 is consistent with the collisional compression, and also the separations of the massive dense cores and the O stars.

We test the physical parameters of the clouds into more detail. The total number of the massive dense cores and O star candidates in RCW38 is $\sim 40$ for an area of $\sim 0.5 \, \text{pc} \times 0.5 \, \text{pc}$ (Table 4), and the projected density of cores/O stars is $\sim 160 \, \text{pc}^{-2}$, ten times higher than in Region (6) of the present synthetic observations. The age of RCW38 is in the order of 0.1 Myrs,
which is significantly shorter than 0.7 Myrs of the present model. These suggest that the initial
density of the parent cloud of RCW38 may be significantly higher than the present initial
density 300 cm\(^{-3}\). Inoue & Fukui (2013) showed a case of the initial density 1000 cm\(^{-3}\), three
times higher than the present model (Model No. 4 in Inoue & Fukui 2013) which indicates
more rapid dense core formation and higher column density in the compressed layer. A rough
estimate indicates that the initial density more than 10\(^4\) cm\(^{-3}\) may be appropriate to explain
these differences, which needs to be confirmed by further MHD simulations. We may need more
objects to be tested, whereas most of the other massive clusters in the Milky Way studied so
far into detail are not so young as RCW38. The only possible exception is the ONC, which is
worth testing by a uniform survey for dense cores with ALMA over the collisional area. The
collisional age of the O stars in the ONC is 0.1 Myrs (Fukui et al. 2018a) and such observations
will shed new light on the issue.

### 5.2.2 W43

W43 is a remarkable mini-starburst in the Milky Way which attracted keen interest in understand-
high mass star formation, and considerable efforts have been devoted to resolve star
formation there (Motte et al. 2018 and references therein). Recently, Kohno et al. (in prep.)
made a detailed analysis of the molecular clouds in W43 and found evidence for multiple cloud-
cloud collisions in triggering high-mass star formation. So, W43 is another region where we are
able to test the signatures of cloud-cloud collision. In one of the proto clusters in W43 main
new ALMA observations were used to resolve dense cores with unprecedented details by Motte
et al. (2018). These authors obtained a core mass function of 130 dense cores with density
\(\sim 10^7\) – \(10^{10}\) cm\(^{-3}\) covering a mass range 1 – 100 \(M_\odot\) in dust continuum emission with a mass
detection limit of 1.6 \(M_\odot\), whereas linewidths and other kinematic information are not available
at present. Figure 17 shows the dust image (Motte et al. 2018) where we find highly filamentary
dust distribution with a number of dense cores. The filaments have \(\sim 0.1\)-pc width and \(\sim 0.5\)-pc
length and the mass of the dense cores are derived by the authors. The separations between the
dense cores as shown in Figure 12(e) have a peak at \(\sim 0.4\) pc, which is similar but somewhat
smaller than in RCW38. The core mass function is plotted from Motte et al. (2018) in Figure
13 and shows that the core mass function is consistent with the present one in particular at the
high-mass end of the present function in a range 6 – 60 \(M_\odot\). The formation of filaments and
dense cores by a cloud-cloud collision is a plausible mechanism applicable to W43.
5.3 Dependence on the model parameters

The present results depend on the parameters adopted in the simulations by Inoue & Fukui (2013). The model is idealized as compared with the real cloud-cloud collision, whereas no fine tuning of the parameters is made. We discuss possible changes of the model parameters for a future more-refined model construction.

The size of the collision area $8 \text{pc} \times 8 \text{pc}$ is larger than the typical area of $1 \text{pc}^2$ in the cloud-cloud collisions in the Milky Way. This difference perhaps causes higher gas peak column density in the present results than a smaller area by collecting mass in directions perpendicular to the collision. The size of the model cloud length, which is assumed to be as long as $7 \text{pc}$ by setting the final epoch to be $0.7 \text{Myr}$, is also longer than the typical real clouds. The small length can lead to a decrease of collision density of one of the clouds, and thus needs a non-steady simulation where one of the flows decreases in density in time. In RCW120 such time dependence may facilitate a more realistic picture of triggered star formation which has a size of the small cloud $\sim 4 \text{pc}$.

The other effect which can be significant is the stellar feedback, in particular, ionization which is not incorporated numerically in the present model. Such inclusion of ionization was undertaken by Shima et al. (2018) in a two cloud collision case, and will be made separately from the present paper as a future work. This will allow us to have a more realistic picture of the formed cluster.

Another concern is density and velocity adopted as the initial condition. RCW120 and M20 seem to be relatively well fit by the present parameters, whereas the more active star formation in RCW38 and W43 may suggest higher initial density than the present model as shown by the shorter timescale less than $0.1 \text{Myr}$ of O star formation in RCW38 and the numerous O star candidates in W43. We will need therefore test density dependence of the star formation. These wider ranges of the model parameters will help to gain an insight into the outcomes in cloud-cloud collision.

Finally, the relationship between the dense cores and the stellar mass is to be better quantified, while in the present work we simply assume that the core mass at density higher than $10^5 \text{cm}^{-3}$ corresponds to the stellar mass. It is possible that the conversion is incomplete and a fraction of the core mass becomes a star. Such an attempt is found in Motte et al. (2018). We will explore this issue along with the above tasks in future modeling.
6 Comparison with the other mechanisms of high-mass star formation

We compare the cloud-cloud collision as the mechanism of high-mass star formation with the other mechanisms, the competitive accretion and the monolithic collapse.

The competitive accretion is a mechanism of formation of a massive cluster having $\sim 2000 M_\odot$ like the ONC. The initial state is a massive aggregation which is self-gravitating and evolves by self-gravity in a timescale of a few Myrs (Bonnell et al. 2001). In the early phase low-mass stars are mainly formed under the low-density condition and in time the dense gas segregate into the central part. In the final phase, the central gas becomes dense enough to form high mass stars, and forms centrally condensed high-mass stars in a cluster like the ONC. The scenario is therefore able to explain the basic observed properties of such massive clusters. A weakness of the competitive accretion is that there are many isolated O stars and small clusters with a single O star, which include M20, RCW120, GM24, RCW79, etc. and a number of single/several O stars with a small mass less than 1000 $M_\odot$ (section 5.1, see also the papers in the special issue on cloud-cloud collision of PASJ in 2018). In the competitive accretion in order to form O stars, the total system mass needs to be large. A usual scenario to explain isolated O stars is a gravitational sling shot (e.g., Leonard & Duncan 1988), which requires a large bound cluster nearby. It is however not often the case, and cannot be a common mechanism to explain O stars in isolation (e.g., Harada et al. 2019).

The cloud-cloud collision scenario for cluster formation is described in section 3.3. The ONC-type cluster is formed by low-mass star formation in a massive pre-collision cloud and the O star formation after the collision toward dense gas in the center of the pre-collision cloud. Since a large range of the cloud mass is allowed, a wide range of the cluster mass from $\sim 100 M_\odot$ to a few 1000 $M_\odot$ is explicable in this scenario. Another difference of the cloud-cloud collision from the competitive accretion is that the O stars are formed not in the cluster center but on one side of the central dense gas being collided. In fact, in the ONC the O stars show little extinction toward us indicating that the O stars are on the near side of the cloud core but not in the cluster center. This location is consistent with the collision scenario for the ONC (Fukui et al. 2018a), but is not readily explained by the competitive accretion.

The monolithic collapse is a scenario which explains O star formation by a self-gravitating massive cloud without a trigger. McKee & Tan (2002) and McKee & Tan (2003) presented the scenario and Krumholz et al. (2009) presented numerical simulations of O star formation by assuming the initial condition, 100 $M_\odot$ molecular mass within 0.1 pc radius, and showed that the cloud undergoes rapid collapse to form O stars in $10^4$ yrs. These authors concluded
that O stars can be formed by self-gravity without an external trigger. We pay attention to the initial condition which is dense and massive, favoring O star formation. The condition was adopted from observations toward O star forming regions like the ONC, W3(OH) and a protostar candidate IRAS 05358+3543 in an HII region S235 (Beuther et al. 2007). Recent papers show that the initial conditions are mostly taken in the region of cloud-cloud collision; the ONC was studied by Fukui et al. (2018a) and a cloud-cloud collision was discovered as the trigger. W3(OH) and S235 are analyzed by Sakasai et al. (in prep.) and Konho et al. (in prep.) and cloud-cloud collision is found as a trigger. These suggest that the massive dense cores adopted as the initial condition for high-mass star formation but are rather the outcome of cloud-cloud collision. It is thus possible that the monolithic collapse is considered as the evolution of dense massive cores which are formed in the collision-compressed layer.

7 Conclusions

In order to obtain a better insight into the star formation triggered by cloud-cloud collision, we analyzed the simulation data of colliding molecular flows made by Inoue & Fukui (2013). The main conclusions of the present study are summarized below.

1. The two supersonic molecular flows in head-on collision at a relative velocity of 20 km s\(^{-1}\) create a shock compressed layer of 1-pc thickness. In the layer, velocity is decelerated rapidly and gas density becomes higher by two orders of magnitude. The gas distribution is characterized by filamentary distribution at pc scale, which is elongated perpendicular to the field direction. The gas flow along the field increases the filamentary mass, and dense cores are formed in the filaments. The dense cores have size and mass of 0.01 – 0.1 pc and 1 – 100 \(M_\odot\), respectively. The most massive cores reach \(\sim 60 M_\odot\) at density above \(10^5 \text{ cm}^{-3}\) within a radius of 0.1 pc and the cores more massive than \(10 M_\odot\) become gravitationally unstable. They are plausible precursors of high-mass protostars.

2. The present results provide a comprehensive scenario as an alternative to the two conventional scenarios of high-mass star formation, i.e., the competitive accretion and the monolithic collapse. Cloud-cloud collision realizes high-mass accretion rate of \(10^{-4} - 10^{-3} M_\odot \text{ yr}^{-1}\) and offers a condition suitable to high-mass star formation in the collision compressed-layer. It is shown that cloud-cloud collision provides a versatile scenario which accommodates various O star distribution for a wide mass range of the parent clouds. Observations show that single O star formation is possible for merged column density of \(\sim 10^{22} \text{ cm}^{-2}\) and cloud mass of around \(100 M_\odot\). It is also possible that tens of O stars are formed for column density
distribution extending above $10^{23}$ cm$^{-2}$ even for small colliding cloud mass less than $10^3 \, M_\odot$. This offers an explanation on the origin of numerous isolated O stars and massive O star clusters observed in the Milky Way in terms of cloud-cloud collision.

3. We compare the distribution and mass function of dense cores in two O star clusters, RCW38 and W43, obtained with ALMA with the present results. The separation between O stars formed is typically $0.03 – 0.1$ pc as determined by the dense core distribution in the collision-compressed layer. The separation becomes smaller for the massive dense cores in the youngest super star cluster RCW38 is consistent with the top-heavy distribution predicted by the cloud-cloud collision scenario. The $\sim 130$ dense cores observed in W43 also show a mass function consistent with the predicted core mass function for a wider mass range than RCW38. In addition, we showed that single O star formation in RCW120 and M20 is well explained by cloud-cloud collision for a collisional area of $\sim 1$ pc$^2$ where the spatial distribution of the low-mass stars is consistent with the filamentary shape as predicted by cloud-cloud collision. These results lend support for cloud-cloud collision as a universal mechanism to form single O stars and O star clusters.

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Fig. 1. Volume rendering map of density at $t = 0.6$ Myr (reproduced from Inoue & Fukui 2013).

Fig. 2. (a) Projected velocity vectors (arrows) overlaid on distribution of mean density (image) in $|z| < 0.08$ pc at $t = 0.7$ Myr. (b) Close up view of (a). (c) Distribution of size of velocity vector ($|V|$), (d) angle between velocity vector and the $x$-axis, (e) density $n$ and (f) dynamic pressure for each pixel. The contours in panels (c) – (f) contain 30, 60, and 90% of data points but excluding gas with initial condition ($|V| > 12$ km s$^{-1}$ and angle $\sim 0^\circ$).
Fig. 3. (a) Distribution of dense molecular gas along the $x$-axis at $t = 0.2$ Myr. (b) – (f) Same as (a) but for $t = 0.3$–0.7 Myr. Gray, thin-black and thick-black lines in each panel show $n > 10^4$ cm$^{-3}$, $n > 10^5$ cm$^{-3}$ and $n > 10^6$ cm$^{-3}$, respectively.
Fig. 4. (a) Histogram of H$_2$ density for each pixel in a range of $-1.5\,\text{pc} < x < +1.5\,\text{pc}$ at $t = 0.1\,\text{Myr}$. Histogram at $t = 0$ is also shown by red dashed-line.

(b) – (e) Same as (a) but for $t = 0.1, 0.3, 0.5$ and $0.7\,\text{Myr}$. Vertical dashed line in each panel shows $n = 10^5\,\text{cm}^{-3}$. 
Fig. 5. The distribution of (a) filamentary distribution, identified as connected region with $n > 10^5 \text{ cm}^{-3}$ and (b) dense cores defined by using CLUMPFIND algorithm (Williams et al. 1994). Different filaments/cores in panels (a) and (b) are indicated by different arbitrary colors.
Fig. 6. (a) Projected magnetic field vector ((a)-1) and velocity vector ((a)-2) shown in a typical region with filaments. The magnetic field vector and velocity vector are given as $\mathbf{B} = \sum_{\text{filament}} \left[ B(x) n(x) \Delta x \right] / \sum_{\text{filament}} \left[ n(x) \Delta x \right]$ and $\mathbf{V} = \sum_{\text{filament}} \left[ V(x) n(x) \Delta x \right] / \sum_{\text{filament}} \left[ n(x) \Delta x \right]$, respectively, where the summation is along the $x$-axis. (b) Same as (a) but for another sample.

Fig. 7. (a) Mass-size diagram and (b) size histogram for the identified cores at $t = 0.7$ Myr. The sizes are derived as geometric mean of the major-axis length $a$, second-major-axis length $b$ and minor-axis length $c$. The vertical dashed lines in panels (a) and (b) show the pixel size ($1.6 \times 10^{-2}$ pc). (c) Scatter plot between $b/c$ vs $a/b$. The red crosses are the cores with $M_{\text{core}} > 10 M_\odot$ and $M_{\text{core}} > M_{\text{eff}}$. The vertical solid- and dashed-lines show mean and standard deviation of $a/b$ and the horizontal ones show those of $b/c$. 

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Fig. 8. (a) Histogram of angle between magnetic field vector and major-axis for prolate \((a/b > 2 \text{ and } b/c < 2)\), gray shaded, and ribbon-like morphology cores \((a/b > 2 \text{ and } b/c > 2)\). (b) Histogram of angle between magnetic field vector and minor-axis for oblate cores with \(a/b < 2 \text{ and } b/c > 2\).
Fig. 9. upper panels: Core mass function (CMF) for (a) $t = 0.3$ Myr, (b) 0.4 Myr, (c) 0.5 Myr, (d) 0.6 Myr, and (e) 0.7 Myr. Light- and dark-gray show CMF for $M_{\text{core}} > M_j$ and $M_{\text{core}} > M_{\text{eff}}$, respectively.

lower panel: $M_{\text{core}}/M_j$ and $M_{\text{core}}/M_{\text{eff}}$ ratios plotted against $M_{\text{core}}$. The horizontal dashed lines show $M_{\text{core}} = M_j$ ($M_{\text{core}} = M_{\text{eff}}$).
Fig. 10. Column density map of H$_2$ (low density gas with $<10^4$ cm$^{-3}$ is excluded) in the $y$-$z$ plane at (a) $T = 0.4$ Myr, (b) 0.5 Myr, (c) 0.6 Myr and (d) 0.7 Myr. The crosses show the positions of massive cores with $M_{\text{core}} > 10 M_\odot$ and $M_{\text{core}} > 10 M_j$, and the dots show intermediate mass cores with $M_{\text{core}} = 5 - 10 M_\odot$. Circles show ionization front in “HII regions” which proceeds at a uniform speed of $X$ km s$^{-1}$ after dense cores with $M_{\text{core}} > 10 M_\odot$ and $M_{\text{core}} > 10 M_j$ appear.
Fig. 11. Column density map of H$_2$ (low density gas with $< 10^4$ cm$^{-3}$ is excluded) in the $y$-$z$ plane at $t = 0.7$ Myr (top-left panel) and column density histogram in the 8 regions of 1.5 pc $\times$ 1.5 pc (panels (1) – (8)). The crosses in the top-left panel show the positions of massive cores with $M_{\text{core}} > 10$ $M_{\odot}$ and $M_{\text{core}} > 10$ $M_{\text{eff}}$, and the dots show intermediate mass cores with $M_{\text{core}} = 5 - 10$ $M_{\odot}$.
Fig. 12. (a) Histogram of core-to-core separation for $M_{\text{core}} > 5 M_\odot$ at $t = 0.7$ Myr and those for $M_{\text{core}} > 10 M_\odot$ (gray shaded). Here, the separations are given as edge-lengths of two-dimensional (projected along the $x$-axis) minimum-spanning-trees (MSTs) of cores. (b) – (e) Same as (a) but for (b) 870 µm dust condensations (gray shaded) and Class I/flat-spectrum YSOs (dashed lines) associated with RCW120 (Deharveng et al. 2009), (c) M20 (stars and IR sources in HD164492 complex, taken from Table 1 of Rho et al. 2008), (d) RCW38 dense condensations (Torii et al. 2019) and OB-star candidates (Wolk et al. 2006), and (e) W43 cores (Motte et al. 2018).
Fig. 13. CMF at $t = 0.7$ Myr (identical to Figure 9(e)-1). Those for RCW38 cores (Torii et al. 2019) and W43 cores (Motte et al. 2018) are superimposed. The error bars correspond to $\sqrt{N}$ statistical uncertainties. The dashed line shows the single-star IMF of Kroupa (2001) and the solid curve shows the system IMF by Chabrier (2005).
Fig. 14. (a) Spatial distribution of the exciting star of RCW120 (large cross), Class I or flat-spectrum YSOs (circles, Deharveng et al. 2009) and cold dust condensations identified at 870 µm (small crosses, Deharveng et al. 2009). The background is a color composite image of RCW 120; green: Spitzer/IRAC 8 µm (Benjamin et al. 2003), blue: Spitzer/MIPS 24 µm (Carey et al. 2009), red: Herschel/SPIRE 250 µm (Zavagno et al. 2010). The dashed-line curve show the southern edge of the HII region. This figure is reproduced and modified from Torii et al. (2015). (b) A schematic picture of RCW120. A single O star (the star symbol) is within a cavity, according to the cloud-cloud collision scenario, created by a small cloud which drives into a larger cloud and streams into the compressed layer (the shaded part).
Fig. 15. (a) Optical image of M20 (credit: NOAO). The exciting O7.5 star (HD 164492 A) is depicted by a cross, while Class I/0 and Class II young stars identified by Rho et al. (2008) are plotted with filled red circles and filled white circles, respectively. (b) The HST image of the central region of M20 (Yusef-Zadeh et al. 2005). The HD 164492 components are indicated by arrows. Both (a) and (b) are reproduced and modified from Torii et al. (2017).
Fig. 16. Spatial distribution of dense cores (circles), RCW38 IRS2 (large cross) and O star candidates (small crosses, Wolk et al. 2006; Winston et al. 2011) in RCW38, overlaid on a C$^1$8O integrated intensity map in a velocity range from $-2$ to $+12$ km s$^{-1}$ (reproduced and modified from Torii et al. 2019).
Fig. 17. 1.3 mm dust continuum emission image of W43-MM1 cloud (reproduced from Motte et al. 2018). The ellipses outline core boundaries identified by the authors.
Table 1. Model parameters

| Parameter     | Value            |
|---------------|------------------|
| $\langle n \rangle_0$ | 300 cm$^{-3}$ |
| $\Delta n / \langle n \rangle_0$ | 0.33 |
| $B_0$         | 20 $\mu$G        |
| $V_{\text{coll}}$ | 10 km s$^{-1}$ |
| Resolution    | (8.0/512) pc     |

Table 2. Mass of dense gas

| $t$  | Mass ($M_\odot$) |
|------|------------------|
|      | $n > 10^4$ cm$^{-3}$ | $n > 10^5$ cm$^{-3}$ | $n > 10^6$ cm$^{-3}$ |
| 0.2  | 5.6 $\times$ 10$^4$ | —                  | —                  |
| 0.3  | 8.1 $\times$ 10$^4$ | 6.2 $\times$ 10$^2$ | —                  |
| 0.4  | 1.1 $\times$ 10$^5$ | 6.2 $\times$ 10$^3$ | 1.1 $\times$ 10$^2$ |
| 0.5  | 1.9 $\times$ 10$^5$ | 1.9 $\times$ 10$^4$ | 5.6 $\times$ 10$^1$ |
| 0.6  | 2.6 $\times$ 10$^5$ | 3.7 $\times$ 10$^4$ | 7.7 $\times$ 10$^2$ |
| 0.7  | 3.7 $\times$ 10$^5$ | 5.8 $\times$ 10$^4$ | 2.7 $\times$ 10$^4$ |

Table 3. Physical properties of RCW120

| Cavity          | Radius | Length | Initial mass* | Average* | Typical* |
|-----------------|--------|--------|---------------|----------|----------|
|                 | density | column density |
| Cavity          | Radius | Length | Initial mass* | Average* | Typical* |
| Collision       | Thickness | Current | Average | Typical |
| Collision       | radius | mass | density | column density |
| compressed layer |         |       |        |             |
|                 | 1.5 pc | 4 pc  | 500 $M_\odot$ | 300 cm$^{-3}$ | 1 $\times$ 10$^{21}$ cm$^{-2}$ |
| Collision       | 1 pc   | 1000 $M_\odot$ | 3000 cm$^{-3}$ | 1 $\times$ 10$^{22}$ cm$^{-2}$ |

* Physical parameters of the molecular gas in the cavity prior to the collision.
Table 4. Physical properties of the C$^{18}$O condensations (reproduced from Torii et al. 2019)

| #  | R.A. (J2000)  | Dec. (J2000)  | $r_{\text{C}^{18}\text{O}}$ | $dv$ | $n_{\text{H}_2}$ | $M_{\text{vir}}$ |
|----|---------------|---------------|-----------------|------|---------------|----------------|
|    | (h m s)       | (° ′ ″)       | ($10^{-2}$ pc)  | (km s$^{-1}$) | ($10^7$ cm$^{-3}$) | ($M_\odot$)    |
| 1  | 8 59 06.598   | −47 29 27.749 | 2.1             | 1.1           | 2.4 – 3.3       | 28             |
| 2  | 8 59 06.129   | −47 29 37.749 | 1.9             | 1.2           | 2.2 – 3.1       | 33             |
| 3  | 8 59 04.699   | −47 29 58.250 | 1.5             | 0.8           | 3.2 – 4.2       | 11             |
| 4  | 8 59 08.350   | −47 30 12.996 | 0.6             | 0.8           | 6.7 – 8.7       | 4              |
| 5  | 8 59 01.417   | −47 30 12.997 | 1.4             | 1.0           | 1.3 – 1.8       | 16             |
| 6  | 8 59 02.330   | −47 30 19.499 | 1.9             | 1.6           | 2.5 – 3.5       | 60             |
| 7  | 8 59 03.194   | −47 30 22.999 | 2.0             | 1.1           | 2.5 – 3.4       | 30             |
| 8  | 8 59 01.343   | −47 30 29.747 | 1.7             | 0.9           | 3.0 – 3.9       | 17             |
| 9  | 8 59 01.540   | −47 30 37.997 | 2.4             | 1.0           | 2.8 – 3.6       | 30             |
| 10 | 8 59 02.577   | −47 30 41.499 | 1.6             | 1.3           | 3.4 – 4.5       | 30             |
| 11 | 8 58 59.862   | −47 30 41.744 | 1.9             | 1.3           | 2.1 – 2.8       | 36             |
| 12 | 8 59 02.897   | −47 30 44.249 | 1.4             | 1.0           | 5.6 – 6.7       | 14             |
| 13 | 8 59 03.687   | −47 30 44.750 | 1.5             | 1.6           | 6.2 – 8.7       | 44             |
| 14 | 8 59 02.478   | −47 30 47.749 | 1.2             | 0.7           | 4.0 – 5.1       | 6              |
| 15 | 8 59 00.553   | −47 30 53.246 | 1.8             | 1.2           | 3.0 – 4.0       | 30             |
| 16 | 8 58 59.961   | −47 30 56.994 | 1.3             | 1.4           | 5.1 – 6.5       | 29             |
| 17 | 8 59 01.293   | −47 30 57.247 | 1.2             | 0.8           | 3.9 – 5.0       | 8              |
| 18 | 8 59 00.084   | −47 30 59.994 | 1.1             | 1.3           | 6.7 – 10.6      | 21             |
| 19 | 8 59 00.627   | −47 31 00.746 | 1.1             | 0.9           | 6.2 – 7.8       | 11             |
| 20 | 8 59 01.120   | −47 31 02.497 | 1.0             | 0.8           | 5.9 – 9.0       | 7              |
| 21 | 8 59 00.405   | −47 31 05.995 | 1.0             | 1.4           | 5.1 – 10.6      | 22             |

(a) $n_{\text{H}_2}$ was calculated from $M_{\text{H}_2}$ assuming a sphere with a radius of $r$.  

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