A New Look at the Molecular Gas in M42 and M43: Possible Evidence for Cloud–Cloud Collision that Triggered Formation of the OB Stars in the Orion Nebula Cluster

Yasuo Fukui1, Kazufumi Torii2, Yusuke Hattori1, Atsushi Nishimura1, Akio Ohama1, Yoshito Shimajiri3, Kazuhiro Shima4, Asao Habe5, Hidetoshi Šano1, Mikito Kohno1, Hiroaki Yamamoto1, Kengo Tachihara1, and Toshikazu Onishi1

1 Department of Physics, Nagoya University, Chikusa-ku, Nagoya, Aichi 464-8601, Japan
2 Nobeyama Radio Observatory, 462-2 Nobeyama Minamimaki-mura, Minamisaku-gun, Nagano 384-1305, Japan
3 Laboratoire AIM, CEA/DSM-CNRS-Université Paris Diderot, IRFU/Service d’Astrophysique, CEA Saclay, F-91191 Gif-sur-Yvette, France
4 Faculty of Science, Department of Physics, Hokkaido University, Kita 10 Nishi 8 Kitaku, Sapporo 060-0810, Japan
5 Department of Physical Science, Graduate School of Science, Osaka Prefecture University, 1-1 Gakuen-cho, Naka-ku, Sakai, Osaka 599-8531, Japan

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Abstract

The Orion Nebula Cluster toward the H II region M42 is the most outstanding young cluster at the smallest distance (410 pc) among the rich high-mass stellar clusters. By newly analyzing the archival molecular data of the 12CO(J = 1–0) emission at 21″ resolution, we identified at least three pairs of complementary distributions between two velocity components at 8 and 13 km s−1. We present a hypothesis that the two clouds collided with each other and triggered formation of the high-mass stars, mainly toward two regions including the nearly 10 O stars in M42 and the B star, NU Ori, in M43. The timescale of the collision is estimated to be ~0.1 Myr by a ratio of the cloud size and velocity corrected for projection, which is consistent with the age of the youngest cluster members less than 0.1 Myr. The majority of the low-mass cluster members were formed prior to the collision in the last Myr. We discuss the implications of the present hypothesis and the scenario of high-mass star formation by comparing with the other eight cases of triggered O-star formation via cloud–cloud collision.

Key words: ISM: clouds – ISM: kinematics and dynamics – ISM: molecules – stars: formation

1. Introduction

High-mass stars are influential in the evolution of galaxies by injecting a large amount of energy from ultraviolet photons, stellar winds, and supernova explosions. It is of fundamental importance to understand the formation mechanism of high-mass stars in order to elucidate the structure and evolution of galaxies, and considerable efforts have been devoted to understanding the formation mechanism of high-mass stars. It has been discussed that self-gravitational massive aggregations of molecular gas or protostars are probable sites of high-mass star formation. The theories of high-mass star formation include the monolithic collapse and competitive accretion (for recent reviews, see Zinnecker & Yorke 2007; Tan et al. 2014), and massive and dense clouds including the hot cores and infrared dark clouds are studied as possible sites of such high-mass star formation (e.g., Egan et al. 1998). It is, however, puzzling that these massive objects are not commonly associated with H II regions, the most obvious signature of O/early-B star formation, and we do not yet have a convincing confrontation between the theories and observations (Tan et al. 2014).

Recently, supersonic collision between the interstellar molecular clouds was discussed as a possible triggering mechanism of high-mass star formation both observationally and theoretically. Up to now, we have eight regions of cloud–cloud collision toward the super star clusters and H II regions in the Milky Way disk and the young O stars in the Large Magellanic Cloud (LMC) (Furukawa et al. 2009; Ohama et al. 2010; Torii et al. 2011, 2015; Fukui et al. 2014, 2015, 2016; Saigo et al. 2017). These collisions take place supersonically at a velocity of 10–30 km s−1, and the high velocity indicates that the cloud motion is not governed by the cloud–cluster self-gravity. Subsequently, we find that similar cases of cloud–cloud collision triggering O/early-B star formation are still increasing in number (Miyawaki et al. 1986, 2009; Hasegawa et al. 1994; Sato et al. 2000; Okumura et al. 2001; Furukawa et al. 2009; Ohama et al. 2010; Shimoikura & Dobashi 2011; Torii et al. 2011, 2015, 2017a, 2017b, 2017c; Nakamura et al. 2012; Shimoikura et al. 2013; Dobashi et al. 2014; Fukui et al. 2014, 2015, 2016, 2017, 2018a, 2018b, 2018c; Tsuboi et al. 2015; Baug et al. 2016; Dewangan et al. 2016, 2017; Dewangan et al. 2017; S. Fujita et al. 2017, in preparation; Gong et al. 2017; Hayashi et al. 2017; Kohno et al. 2017; Ohama et al. 2017a, 2017b, 2017c; Sano et al. 2017a, 2017b; Saigo et al. 2017; Tsutsui et al. 2017; Shimoikura et al. 2018a, 2018b). It is shown by theoretical works that cloud–cloud collision increases the cloud density and effective sound speed in the shocked interface layer (Habe & Ohta 1992; Whitworth & Zinnecker 2004; Anathpindika 2010; Takahira et al. 2014). According to the recent magnetohydrodynamical numerical simulations for a head-on collision at 20 km s−1 by Inoue & Fukui (2013), the mass accretion rate is enhanced by two orders of magnitude to 10−4–10−3 M⊙ yr−1 due to the collision, as compared with the precollision state. The mass accretion rate 10−4–10−3 M⊙ yr−1 satisfies the theoretical requirement to overcome the radiation pressure feedback of the forming O star (Wolfire & Cassinelli 1986; McKee & Tan 2003). The typical collision timescale is estimated to be ~0.1 Myr from a ratio of the O-star cluster size and velocity, 1 pc/10 km s−1, and a stellar mass of 10–100 M⊙ can be accumulated at the enhanced mass accretion rate in the timescale.

Currently, a key question is if cloud–cloud collision is one of the major mechanisms of high-mass star formation. It is premature to conclude that cloud–cloud collision is common because the number of samples is yet too small. One of the difficulties in studying high-mass star formation is that the number of high-mass star-forming regions is small compared with that of low-mass star formation sites. The nearest young O-star cluster is the Orion Nebula Cluster (ONC), including M42 and M43, located 410 pc from the Sun (for reviews, see Muench et al. 2008; O’Dell et al. 2008; Peterson & Megeath
The ONC has been the best studied among the O-star clusters at various wavelengths from X-rays to radio emissions and is the primary object where theories of high-mass star formation are tested. The other known regions of high-mass star formation are located at a distance of around 2 kpc or larger.

The Orion A molecular cloud, which harbors the ONC, is an active star-forming region and includes Orion Molecular Cloud (OMC)-1, OMC-2, and OMC-3 in the M42–M43 region. A number of molecular-line observations were made toward the Orion A cloud in the last few decades, mainly in the millimeter/submillimeter CO emission lines (Kutner et al. 1977; Maddalena et al. 1986; Sugitani et al. 1986; Takata et al. 1986; Bally et al. 1987; Castets et al. 1990; Heyer et al. 1992; Tatematsu et al. 1993; Sakamoto et al. 1994; White & Sandell 1995; Nagahama et al. 1998; Plume et al. 2000; Shimajiri et al. 2011; Nakamura et al. 2012; Wilson et al. 2005; Ripple et al. 2013; Shimajiri et al. 2014; Nishimura et al. 2015). Around 100 OB stars and 2000 low-mass young stars are distributed in and around the molecular cloud having \(10^2 M_\odot\). In particular, the H II region M42 is the most active site of O-star formation that includes about 10 O/early-B stars. On a large scale, including the Orion B cloud, four OB associations named Ori OB1a, Ori OB1b, Ori OB1c, and Ori OB1d are identified (Blaauw 1991), and they may be distributed spatially in age sequence. A model of the sequential formation of the OB associations was therefore proposed, where OB stars are formed due to triggering by the ionization shock fronts (Elmegreen & Lada 1977). The Orion A cloud appears to be converging toward M42 showing a V shape pointing to the north, and a model consisting of self-gravitationally bound converging motion was presented to explain the shape and formation of the ONC (Hartmann & Burkert 2007), whereas details of the star formation remain elusive (for low-mass star formation, see also Stutz & Gould 2016).

In this paper, we present a new analysis of the archival data of the \(^{12}\text{CO}(J = 1 \rightarrow 0)\) transition obtained with large single-dish telescopes aiming to test the scenario of cloud–cloud collision as a possible mechanism of high-mass star formation. The present paper focuses on the distribution and kinematics of the cloud. In Section 2, we give a summary of observational and theoretical papers on cloud–cloud collision and present common signatures characteristic to the collision scenario. Section 3 explains an analysis of the CO data, and Section 4 presents a model of the colliding clouds, along with discussion. Section 5 gives the discussion from a broader perspective, and Section 6 concludes the paper.

### 2. Cloud–Cloud Collision: Observational and Theoretical Signatures

Evidence for triggered formation of O/early-B star(s) by cloud–cloud collision is found in the four super star clusters—Westlerlund 2, NGC 3603, RCW 38, and [DBS2003] 179 (Furukawa et al. 2009; Ohama et al. 2010; Fukui et al. 2014, 2015, 2017a, 2018), and in the single high-mass stars in the LMC, N159W-South and the Papillon Nebula YSO of N159E (Fukui et al. 2015; Saigo et al. 2017). The physical parameters of the eight objects along with the ONC are summarized in Table 1. The four super star clusters include 10–20 O stars with ages of 0.1–4.0 Myr, while the others with a single O star have ages less than 1.0 Myr. Theoretical studies of cloud–cloud collision are made by using hydrodynamical numerical simulations (Habe & Ohta 1992; Ananthpindika 2010; Inoue & Fukui 2013; Takahira et al. 2014). These studies allow us to gain insight into the observational/theoretical signatures of colliding clouds. It is also notable that synthetic observations present observable characteristics of cloud–cloud collision, including the complementary distribution at the two velocities and the bridging feature between the two colliding clouds (Haworth et al. 2015a, 2015b; Torii et al. 2017a). We shall summarize the major properties obtained by these previous studies in the following.

| Object | Molecular Mass | Molecular Column Density | Relative Velocity | Complementary Distribution | Bridging Feature | Cluster Age | Number of O Stars | Reference |
|--------|----------------|-------------------------|------------------|---------------------------|-----------------|------------|------------------|-----------|
| RCW 38 | \((2 \times 10^4, 3 \times 10^5)\) | \((1 \times 10^{21}, 1 \times 10^{25})\) | 12 | no | yes | \(-0.1\) | \(~0.1\) | \(~20\) | [1] |
| NGC 3603 | \((7 \times 10^4, 1 \times 10^5)\) | \((1 \times 10^{23}, 1 \times 10^{25})\) | 15 | no | yes | \(-2.0\) | \(~5.0\) | >10 | [2] |
| Westerlund 2 | \((9 \times 10^5, 8 \times 10^6)\) | \((2 \times 10^{23}, 2 \times 10^{25})\) | 16 | yes | yes | \(-2.0\) | 14 | [3, 4] |
| [DBS2003] 179 | \((2 \times 10^5, 2 \times 10^6)\) | \((8 \times 10^{22}, 5 \times 10^{25})\) | 20 | yes | yes | \(-5.0\) | \(~0.1\) | \(~10\) | [6] |
| ONC (M42) | \((2 \times 10^4, 3 \times 10^5)\) | \((2 \times 10^{21}, 2 \times 10^{25})\) | \(~7(a)\) | yes | no | \(-0.1\) | \(~0.1\) | \(~1\) | [7] |
| ONC (M43) | \((3 \times 10^3, 2 \times 10^4)\) | \((6 \times 10^{22}, 2 \times 10^{25})\) | \(~7(a)\) | yes | no | \(~1\) | \(~5.0\) | \(~0.6\) | [9] |
| RCW 120 | \((1 \times 10^4, 1 \times 10^5)\) | \((1 \times 10^{21}, 1 \times 10^{25})\) | 7.5 | yes | yes | \(-0.3\) | 1 | [10] |
| M20 | \((5 \times 10^4, 4 \times 10^5)\) | \((3 \times 10^{22}, 8 \times 10^{25})\) | 20 | yes | yes | \(-2.0\) | 1 | \(~0.2\) | [11] |
| N159W-South | \((9 \times 10^5, 6 \times 10^6)\) | \((1 \times 10^{21}, 1 \times 10^{25})\) | \(~8(b)\) | no | no | \(~0.6\) | 1 | \(~0.2\) | [10] |
| N159E-Papillon | \((5 \times 10^4, 7 \times 10^5, 8 \times 10^6)\) | \((4 \times 10^{22}, 4 \times 10^{25}, 6 \times 10^{27})\) | \(~9(c)\) | no | no | \(~0.2\) | 1 | [11] |

**Notes.** Column (1): name. Columns (2) and (3): molecular masses and column densities of the two/three clouds. Column (4): relative velocity between the colliding clouds. Column (5): complementary distribution toward the center cluster/O star. Column (6): bridging feature between the two clouds. Columns (7) and (8): age and number of the cluster/O star. Column (9): References: [1] Fukui et al. (2016), [2] Fukui et al. (2014), [3] Furukawa et al. (2009), [4] Ohama et al. (2010), [5] S. Kuwahara et al. (2018, in preparation), [6] the present study, [7] Torii et al. (2011), [8] Martins et al. (2010), [9] Torii et al. (2015), [10] Fukui et al. (2015), [11] Saigo et al. (2017). (a)–(c) corrected for the projection.
2.1. The Supersonic Motion

The observed cloud–cloud collision indicates that the relative velocity between the two clouds is supersonic in a range of 10–30 km s\(^{-1}\), except for a few cases where the relative velocity is apparently small, probably due to projection (N159W-South and N159E-Papillon). Such high velocity is gravitationally unbound by the typical cloud mass within a 10 pc radius of the formed O star(s), \(10^3–10^4 M_\odot\). Observational verification of heating by O stars/H\(\text{II}\) regions is used to establish the physical association of the clouds with the formed O stars in spite of their large velocity difference (e.g., Fukui et al. 2014), which is otherwise interpreted as due to different kinematic distance. The number density of the molecular clouds in the Galactic spiral arms is high enough to cause frequent cloud–cloud collisions every 8 Myr for a giant molecular cloud, as demonstrated by numerical simulations (Fujimoto et al. 2014; Dobbs et al. 2015).

The magnetohydrodynamical numerical simulations demonstrate that in the shock-compressed interface layer between the two clouds, the density increases by a factor of 10 and the turbulent velocity and Alfvén velocity increase by a factor of 5 (Inoue & Fukui 2013). This is because the shock front is deformed into disordered turbulence by density inhomogeneities of the initial clouds, and the turbulence amplifies the field strength. The mass accretion rate is proportional to the third power of the effective sound speed including the turbulent velocity and Alfvén velocity, and the supersonic motion produces a high-mass accretion rate on the order of \(10^{-4}–10^{-3} M_\odot\) yr\(^{-1}\), which is large enough to overcome the stellar radiation pressure and allow mass growth of the star(s). We note that the turbulent velocity field in the interface layer is nearly isotropic, providing a signature of the collision even when the velocity between the colliding clouds becomes small by the projection effect, as shown in the interface layer of N159W-South and N159E-Papillon (Fukui et al. 2015; Saigo et al. 2017).

We see in Table 1 that the number of forming O stars has a threshold value of molecular column density (Fukui et al. 2016). The 10–20 O-star formation takes place for a high column density around \(10^2\) cm\(^{-2}\), derived from \(^{12}\)CO (J = 1–0) line intensity by using the X\(_{CO}\) factor, whereas formation of a single O star happens for a lower column density around \(10^{2.5}\) cm\(^{-2}\). If one of the two clouds, not always both of them, satisfies these conditions, O star(s) are formed. We suggest that in the high column density case, the O-star formation takes place in a small path length of the collision, e.g., \(~0.1\) pc (see RCW 38; Fukui et al. 2016), and that in the low column density case, the path length prior to the O-star formation is longer, \(~1\) pc (see RCW 120; Torii et al. 2015).

2.2. The Cloud Dispersal by Ionization and Collisional Interaction

Molecular clouds within 1–10 pc of O-star formation will be rapidly dispersed by the ionization/winds and may not be observable at a timescale larger than \(~2\) Myr (Fukui et al. 2016), while the details will depend on the number of O stars, i.e., the ultraviolet radiation field, and the gas density distribution. Collisional interaction also converts the natal gas into the shocked interface layer and stars and dissipates the natal clouds, as discussed further in Section 2.3.

Figure 1 shows the radial distribution of the associated molecular emission in the nine regions of O-star formation in Table 1. Table 2 shows the velocity ranges of the molecular emission in these regions. The super star clusters including 10–20 O stars in a volume smaller than 1 pc often show a central cavity of 10 pc radius, as seen in Westerlund 2, NGC 3603, and [DBS2003] 179, whose ages are 2–4 Myr. Similar cavities are observed in the other super star clusters, including Arches, Quintuplet, and R 136 (e.g., De Marchi et al. 2011; Stolte et al. 2015). The only exception is RCW 38, which shows rich molecular gas at a pc scale. A close look at RCW 38 indicates a cavity of 0.5 pc radius in the molecular gas created by the ionization, and the small ionization cavity likely reflects the small age of 0.1 Myr (Fukui et al. 2016). These super star clusters suggest that the ionization propagates at a typical velocity of \(~5\) km s\(^{-1}\) (a ratio of 0.5 pc/0.1 Myr, or 10 pc/2 Myr). This velocity is consistent with theoretical values of a ionization shock front (e.g., Elmegreen & Lada 1977). We expect that the clouds within 1 pc will soon be ionized and dispersed in another 0.1 Myr, leading to termination of star formation in a few times 0.1 Myr. The age spread of the cluster members formed by triggering is therefore short, on the order of 0.1 Myr in super star clusters. Such a small age spread is consistent with that of 0.1–0.3 Myr of the young cluster members estimated by careful Very Large Telescope (VLT) and Hubble Space Telescope (HST) observations of the two super star clusters NGC 3603 and Westerlund 1 (Kudryavtseva et al. 2012).

Among the regions of single O-star formation, the three regions M20, N159W-South, and N159E-Papillon show rich molecular gas within 1 pc, and RCW 120 shows a molecular cavity of 2 pc radius. The size of the molecular cavity in single O-star formation seems to be smaller than in the super star clusters, perhaps due to less ionizing photons. M20, whose age is 0.3 Myr, is extended over 3 pc, whereas it also shows a clear cavity of neutral matter with a 0.1 pc radius centered on the O star in the HST image (ESA/Hubble & NASA, Bruno Conti). The Papillon Nebula YSO in N159E shows a molecular cavity of 0.5 pc radius whose inside is filled by the H\(\text{II}\) region, and the age of the Papillon Nebula YSO is estimated to be 0.2 Myr (Saigo et al. 2017). N159W-South has no H\(\text{II}\) region and no molecular cavity and is driving protostellar outflow with the associated accretion disk (Fukui et al. 2015). N159W-South has a small age of 0.1 Myr and is younger than the Papillon Nebula YSO. So, the molecular cavities in M20 and the Papillon Nebula are likely created by the ionization. It is suggested that the molecular cavity in RCW 120 was created by the cloud–cloud collision as first modeled by Habe & Ohta (1992), and the effect of the ionization is not dominant in forming the cavity (Torii et al. 2015; see also, for a different scenario, Zavagno et al. 2010). The single O-star-forming regions in the current sample are fairly young, and the effect of the ionization does not seem to be prevailing, whereas the cloud dispersal by ionization will become dominant later.

2.3. Complementary Distribution between the Colliding Clouds

It is often the case that colliding clouds are not of the same size as simulated by Habe & Ohta (1992), Anathpindika (2010), and Takahira et al. (2014). If one of the colliding clouds is smaller than the other, the small cloud can create a cavity in the large cloud. This produces complementary
distribution of the two clouds at different velocities, which is used to identify candidates for colliding clouds, unless the cloud dispersal by the ionization is significant.

In order to visualize the collision, we adopt the numerical simulations by Takahira et al. (2014), and Table 3 lists the simulation parameters. In Figure 2, surface density plots of the 10 km s$^{-1}$ collision model are presented, while in Figure 3, a schematic picture is shown. In the model where the two clouds are spherical, the cross section of the cavity is determined by

![Figure 1](image_url)  
**Figure 1.** CO radial distribution in nine objects, including the eight regions of cloud–cloud collision and the ONC. Radial distributions of the molecular emission in the nine regions from (a) to (i) are listed in Table 1. (a) RCW 38, (b) NGC 3603, (c) Westerlund 2, (d) [DBS2003] 179, (e) the ONC, (f) RCW 120, (g) M20, (h) N159W-South, and (i) N159E-Papillon Nebula YSO. The five regions in panel (i) have O stars over $\sim$10, and the remaining four regions in panels (ii) and (iii) have a single O star. The averaged intensity of molecular emission is calculated for circular areas at each radius from the center of the cluster or the O star. The CO transition and velocity range used are listed in Table 1. The error bar corresponds to the $\pm 1 \sigma$ fluctuations in each grid.

**Table 2.** Velocity Range of the Molecular Emission in the Eight Cases (Table 1)

| Object          | Velocity Range [km s$^{-1}$] | Reference |
|-----------------|-------------------------------|-----------|
| (1)             |                               |           |
| RCW 38          | $+3.0$ to $+34.0$              | [1]       |
| NGC 3603        | $+1.2$ to $+20.9$              | [2]       |
| Westerlund 2    | $+1.2$ to $+8.7$               | [3, 4]    |
| [DBS2003] 179   | $-104.0$ to $-81.0$            | [5]       |
| ONC             | $+4.0$ to $+14.9$              | [6]       |
| M20             | $-1.0$ to $+30.0$              | [7]       |
| RCW 120         | $-40.0$ to $+8.8$              | [8]       |
| N159W-South     | $+200.0$ to $+269.8$           | [9]       |
| N159E-Papillon  | $+200.0$ to $+269.8$           | [10]      |

**Notes.** Column (1): object name. Column (2): velocity range. Column (3): Reference.

**Table 3.** The Initial Conditions of the Numerical Simulations (Takahira et al. 2014)

| Parameter     | The Small Cloud | The Large Cloud | Note                           |
|---------------|-----------------|-----------------|--------------------------------|
| Temperature   | 120             | 240             |                                |
| Freefall time | 5.31            | 7.29            |                                |
| Radius [pc]   | 3.5             | 7.2             |                                |
| Mass [$M_e$]  | 417             | 1635            |                                |
| Velocity dispersion [km s$^{-1}$] | 1.25 | 1.71 | |
| Density [cm$^{-3}$] | 47.4 | 25.3 | Assumed a Bonner–Ebert sphere |

In order to visualize the collision, we adopt the numerical simulations by Takahira et al. (2014), and Table 3 lists the simulation parameters. In Figure 2, surface density plots of the 10 km s$^{-1}$ collision model are presented, while in Figure 3, a schematic picture is shown. In the model where the two clouds are spherical, the cross section of the cavity is determined by
the size of the small cloud and the length of the cavity by the travel distance since the initiation of the collision. The cavity is identified observationally as an intensity depression in the molecular distribution at the velocity of the large cloud. The projected distributions of the small cloud and intensity depression are complementary, and they are generally displaced with each other because the angle of the relative motion to the line of sight, \( \theta \), is not 0°.

While the real cloud shape can be more complicated, it is still worthwhile to use the simple two-sphere model to gain insight into the cloud distribution created by the collision. The relative motion of the colliding clouds generally has an inclination angle to the line of sight, and three cases of the inclination angle \( \theta = 0°, 45°, \) and 90°, are shown in the velocity-channel distributions in Figures 4–6.

For \( \theta = 0° \) (Figure 4), we see two velocity features whose distribution varies with velocity. We identify the initial two clouds at \(-5.1 \) to \(-3.1 \) km s\(^{-1} \) (panels (b)–(d) in Figure 4) and \(-1.2 \)–\(-0.7 \) km s\(^{-1} \) (panels (f)–(h) in Figure 4) and the intermediate-velocity feature mainly at \(-3.1 \) to \(-1.2 \) km s\(^{-1} \) (panels (d)–(f) in Figure 4). The small cloud fits well with the cavity created in the large cloud by collision, showing the complementary distribution between them (Figure 4(i)). For \( \theta = 45° \) (Figure 5), we see the two clouds at \(-4.1 \) to \(-2.2 \) km s\(^{-1} \) (panels (c) and (d) in Figure 5) and \(-1.2 \)–\(-0.7 \) km s\(^{-1} \) (panels (f) and (g) in Figure 5) and the intermediate-velocity feature mainly at \(-2.2 \) to \(-1.2 \) km s\(^{-1} \) (panel (e) in Figure 5). In Figure 5, we see a displacement of the complementary distribution between the cavity and the small cloud, which is a natural result of projection for \( \theta = 45° \).

The interaction between the two clouds mixes them up because of the momentum exchange and deforms the distribution of the two clouds in the intermediate-velocity ranges; these are included in \(-2.8 \) to \(-0.9 \) km s\(^{-1} \) (Figures 4(e) and (f)) and \(-2.2 \) to \(-0.2 \) km s\(^{-1} \) (Figures 5(e) and (f)). If the relative motion is vertical to the line of sight \( \theta = 90° \) (Figure 6), we do not see the two velocity components. For these three cases of \( \theta \), the position–velocity diagrams with two integration ranges in the \( Y \)-axis of \(+10 \) and \(+2 \) pc are presented in Figures 4(j) and (k), 5(j) and (k), and 6(d) and (e). In the 0° and 45° cases, the two clouds are continuously distributed in velocity due to the “bridging” feature (Section 2.4). Figures 4–6 illustrate that, even if we see only a singly peaked velocity component in the observations, the possibility of cloud–cloud collision is not excluded. Figure 7 shows another presentation of the velocity distribution in first-moment distributions for the three \( \theta \), Figures 7(a) and (b) indicate that the two clouds are clearly seen at two cloud velocities, suggesting that the first moment serves as another way to identify the two clouds, whereas the displacement at \( \theta = 45° \) is masked by averaging.
In regions of single O-star formation, the most significant complementary distribution toward an O star at a 0.1 pc scale is found in M20 (Tori et al. 2017a). In RCW 120, the dispersal of the small cloud is significant, and only the large cloud with the intensity depression, one of the complementary clouds, is seen along with the remnant of the small cloud outside the “bubble” (Tori et al. 2015). In N159, it is possible that the angular resolution of ALMA, 0.3 pc × 0.2 pc, is not high enough to resolve the complementary distribution, which is likely to be in a scale of 0.1 pc. In the super star clusters where the ionization is more significant, it is probable that the complementary distribution is dispersed more quickly. Even in the youngest cluster, RCW 38, we see that the ionization is dominant in shaping the clouds (Fukui et al. 2016). We note that the oldest cluster among the four, [DBS2003] 179, shows a large-scale complementary distribution at a scale of more than 10 pc, which is not affected much by the ionization (S. Kuwahara et al. 2018, in preparation). To summarize, the colliding clouds with small age and relatively low ionization are the most probable site to find the complementary distribution, whereas it is possible that the complementary distribution is often dispersed by the stellar feedback and collisional interaction, depending on the cloud distribution.

Another possible signature of cloud–cloud collision is seen in the optical/near-infrared extinction toward the H II region. In cloud–cloud collision, the blueshifted cloud is always on the far side of the redshifted cloud prior to the collision but moves to the near side after the collision. As a result, one may expect that only the blueshifted cloud, not the redshifted cloud, is located in front of the H II region and can create dark, heavily obscured features. Such dark lanes are in fact observed in M20, where the collision took place ∼0.3 Myr ago to form a single O star; the dark lanes toward M20 show a good correspondence with the blueshifted cloud (Tori et al. 2011, 2016). A caveat is that this may not always be the case if the collision happened very recently where the line-of-sight separation between the two clouds is still small. The super star cluster RCW 38 shows a narrow dark lane in the near-infrared as IRS 1, whereas IRS 1 is identified as part of the redshifted cloud (Fukui et al. 2016). The blueshifted cloud in RCW 38 also corresponds to the near-infrared dark features surrounding the cluster. These authors interpreted that IRS 1 remains neutral without full ionization due to the small age of the system; the O-star formation occurred only 0.1 Myr ago, and part of the redshifted cloud within 1 pc of the cluster center is still surviving in front of or inside the H II region. So, the dark lanes can arise from both clouds, depending on the age and shape of the clouds, and we need to be cautious in examining the extinction features when the collision is a very recent event.

2.4. The Bridging Features between the Two Colliding Clouds

Numerical simulations show that the two colliding clouds become connected in velocity by a bridging feature in synthetic observations if the projected velocity separation is larger than the line widths of the clouds (Haworth et al. 2015a, 2015b). The shocked interface layer appears as the bridging feature connecting the clouds in the position–velocity plots, as shown in Figures 4(j) and (k) and 5(j) and (k). The bridging features are observable in the spots of collision, although all of them are not necessarily related to O-star formation, as shown later. As discussed in the previous subsection, the intensity depression in the large cloud due to creation of the cavity is also seen in the spots of collision, and if we make a position–velocity diagram so that a colliding spot is sliced, both the bridging features and intensity depression of the large cloud are seen, resulting in a “V-shaped” gas distribution in the position–velocity diagram, as shown in Figures 4(k) and 5(k). In addition, in the θ = 45° case in Figure 5(k), the V shape becomes skewed due to inclination of the viewing angle, and the CO emission in the V shape is bright at the front side of the collision.

In Table 1, we see that only the youngest two cases, RCW 38 and M20, show the bridging feature toward the O-star formation. RCW 38 shows the bridging feature within 0.5 pc of the ∼20 O-star candidates, where the small colliding cloud is localized (Fukui et al. 2016). The connection among the three features (the bridging feature, ∼20 O stars, and the small colliding cloud) is tight (see Figure 3 in Fukui et al. 2016). M20 shows three bridging features, and one of them is found toward the O star (Tori et al. 2017a). The three super star clusters, NGC 3603, Westerlund 2, and [DBS2003] 179, show the bridging features in the outer regions of more than 10 pc radius of the cluster, where molecular gas still remains. RCW 120 also shows the bridging features outside the H II region in CO and H I (Tori et al. 2015). N159W-South and N159E-Papillon have a small projected velocity separation of a few km s⁻¹, and the bridging features are not seen.

The synthetic observations in Figures 4 and 5 show that the two velocity components are not clearly separable because of the momentum exchange in the collision, which produces intermediate-velocity features between the initial two clouds. It is therefore not correct to assume that the colliding clouds are always observable as two clearly separate clouds, and observational discrimination of cloud–cloud collision intrinsically involves some ambiguity. Figure 6 shows that collision is not discernible for θ = 90°, whereas the probability for the large inclination angle is smaller than 1.5% at θ greater than 80°, if the cloud relative motion is randomly distributed. Importantly, in spite of these obstacles, we are able to use the following three methods as dependable tools to identify cloud–cloud collision as long as the ionization is not significant.

(A) Complementary distribution between the two colliding clouds. Velocity-channel distributions are used to identify the two velocity components at the initial two velocities, and the two distributions show complementary distribution (Figures 4(i) and 5(i)). The two distributions show generally relative displacement depending on the inclination angle of the relative motion to the line of sight (Figure 5(i)). The intermediate velocity between them, which is mixed up by the interaction, is to be excluded in this comparison.

(B) Position–velocity distribution. The small cloud colliding appears as a V-shaped protrusion including the bridge in a position–velocity diagram along the projected direction of collision, providing a characteristic feature of collision.

(C) Distribution of the first moment. Distribution of the first moment serves as another tool to pick out the two components (Figure 7). This gives a similar distribution than the complementary distribution (A), whereas the displacement may be masked in the first moment due to averaging.
We note that the cloud dispersal by the ionization and the collisional merging of the clouds, in addition to the projection effect, can weaken or extinguish these signatures, and one is required to carefully examine these effects that can smear out the collision signatures. Even if a cloud collision happens, it is possible that one sees none of the signatures. In order to catch the signatures observationally, it is required that the system is young, without significant dispersal of the natal gas, and that the projection effect is small. In more than a few Myr after the O-star formation by collision, it probably becomes impossible to find any of the observable signatures—for instance, as in case of the relatively young cluster NGC 6231, with an age of 3–5 Myr (Baume et al. 1999), which has no molecular gas within 30 pc of the center (Y. Fukui et al. 2018, in preparation).

3. \(^{12}\text{CO}\) Distribution in M42 and M43

3.1. \(^{12}\text{CO}\) Data Sets

The \(^{12}\text{CO}(J = 1–0)\) distributions in the M42–M43 region obtained with the NRO 45 m telescope are presented and discussed by Shimajiri et al. (2011). The observational parameters are listed in Table 4. The paper shows that the Orion A molecular cloud is singly peaked in velocity, which is consistent with the previous CO results summarized in Section 1. The cloud properties created in cloud–cloud collisions may, however, show no obvious double component (Section 2), and it is worthwhile to make a thorough investigation of the kinematic properties in the M42–M43 region from the viewpoint of the cloud–cloud collision scenario. The numerical simulations of the cloud–cloud collision in Section 2 assumed physical parameters that do not exactly coincide with the observed properties of the present cloud. Nonetheless, it is conceivable that the basic characteristics of the colliding clouds hold for different physical parameters, and we here consider the qualitative properties presented in Section 2. In the following, we apply an \(X\text{CO}\) factor of \(2 \times 10^{20}\) (K km s\(^{-1}\))\(^{-1}\) cm\(^{-2}\) (Strong et al. 1988) to convert the \(^{12}\text{CO}(J = 1–0)\) intensity into the molecular column density.

3.2. The Possible Two Velocity Components of \(^{12}\text{CO}\)

Figure 8 shows the decl.–velocity diagram covering \(\sim 1^\circ\) in decl. integrated in an R.A. range from \(5^h34^m6\) to \(5^h35^m8\), and Figure 9 shows the velocity-channel distributions in a region of \(\sim 0^\circ5\) (R.A.) by \(\sim 1^\circ\) (decl.) centered on \(\theta^1\) Ori from Muench et al. (2008). Although most (75\%) of the CO emission is apparently seen in a velocity range of 6–13 km s\(^{-1}\) as a single component, in Figure 9, we find that the distribution of the \(^{12}\text{CO}\) emission is significantly different between the velocity ranges 5.3–9.8 km s\(^{-1}\) (panels (b)–(d)) and 11.4–14.4 km s\(^{-1}\) (panels (f) and (g)). The strongest peak of the \(^{12}\text{CO}\) emission is seen at 9 km s\(^{-1}\) toward \(\theta^1\) Ori, where the \(^{12}\text{CO}\) line width is...
enhanced from 5 to 14 km s\(^{-1}\) at a 1 K km s\(^{-1}\) level toward the ONC. This main peak, having a size of \(\sim 1 \text{ pc} \times 1 \text{ pc}\), is called the OMC-1 clump in the following. We see that the blueshifted emission at \(\sim 8 \text{ km s}^{-1}\), which constitutes the integral shape of the cloud (mainly in panel (d) of Figure 9), is extended on the northern and southern sides of the OMC-1 clump, whereas the redshifted component at \(\sim 12 \text{ km s}^{-1}\) (mainly in panel (f) of Figure 9) has a sharp intensity decrease toward the south at decl. = \(-5^\circ 30'\). We also see the trend in Figure 8. These different spatial distributions at the two velocity ranges suggest a possibility that the two clouds are overlapping, as modeled later in Section 4. The intermediate-velocity range \(10\text{–}11 \text{ km s}^{-1}\) (panel (e) of Figure 9) shows a mixed morphology of the two velocity components.

### 3.3. The Complementary Distributions

Based on the empirical signatures of cloud–cloud collision (Section 2), we searched the \(^{12}\text{CO}\) data for complementary distribution and found three possible pairs. Figure 10 shows the three complementary distributions between the blueshifted and redshifted clouds in panels (a)–(c). Figure 10(a) shows the distribution toward M42, and Figure 10(b) shows that toward M43 and OMC-2. Figure 10(c) is the distribution toward OMC-3, where no H\(^{\text{II}}\) region is associated (e.g., Peterson & Megeath 2008).

In Figure 10(a), we define the OMC-1 clump in the blueshifted cloud at the contour level of 15 K km s\(^{-1}\). We find that the U-shaped cloud in part of the redshifted cloud appears to surround the OMC-1 clump and define the cloud at the contour level of 2 K km s\(^{-1}\). The defined levels are used for calculating the cloud mass. In Figures 10(b) and (c), we find that the redshifted component shows complementary distributions to the blueshifted component, as detailed below.

In order to show the complementary distributions clearly, Figure 11 overlays the two velocity components in the three regions with appropriate displacements, as indicated by arrows in Figures 11(b) and (c), whereas no displacement is applied in Figure 11(a). In Figure 11(a), the complementary distribution is clear in the two components. The OMC-1 clump is extended by more than 1 pc only toward the northwest at an intensity level of \(\sim 7 \text{ K km s}^{-1}\) (Figure 10). It is possible that this extension forms a complementary pair with the intensity depression in the redshifted component toward (R.A., decl.) = \(5^h 34^m 30^s, -5^\circ 32'\) (panel (f) of Figure 9), although the diffuse nature of the extension makes the distribution less evident than that toward OMC-1. We note that the intensity depression in the south of the OMC-1 clump in the blueshifted component, which is extended from R.A. = \(5^h 35^m 01'\) to \(5^h 35^m 08'\) at decl. = \(-5^\circ 32'\), also shows a possible complementary distribution to the redshifted component in the same direction. Further, in the south of the OMC-1 clump, we see an intensity depression elongated east to west (R.A. = \(5^h 35^m 00^s\)–\(45^s\), decl. = \(-5^\circ 34'\)–\(-30'\)) in the blueshifted component (Figure 12(a)). This depression seems similar in shape to the southern part of the complementary distribution of the redshifted component and possibly represents another sign of complementary distribution.
The depression appears to be shifted to the south, as compared with the redshifted component. A displacement similar to Figure 11(b) may be applicable, while the large size of the OMC-1 clump at ∼1 pc tends to complicate the complementary correspondence more than in Figure 11(b).

In order to explain the estimate of the displacement in Figure 11(b), in the upper panels of Figure 12, we show the inner part of the two 12CO components toward the central part of M42 and M43 in the redshifted and blueshifted velocity ranges. Figure 12 also shows enlarged 12CO images toward M43 in the lower panels. The blueshifted cloud shows an intensity depression toward the exciting star NU Ori, which is elongated in the north–south by ∼0.5 pc with a width of ∼0.2 pc, as enclosed by a box in Figure 12(c). The eastern side of the depression is bound by a filamentary feature that corresponds to the dark lane in M43 (see also Figure 15). A corresponding emission feature to the intensity depression is seen in the redshifted component, which has a similar shape to the depression. We call the two features the "Orion keyhole" and "Orion key" in order to avoid confusion with the Keyhole Nebula in Carina. We applied the method to estimate the displacement in the complementary distribution, which is presented in the Appendix. In fitting the displacement, we restricted the area of the analysis to the region of the Orion keyhole and key, as shown in Figure 13. By inspection, we find

that the Orion key has a discontinuous "bend" in the middle at ∼0.25 pc from the southern edge, which seems to morphologically correspond to the edge of the eastern filament of the Orion keyhole (Figure 10). We then chose the direction of the displacement at a position angle of 108° so that the two

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**Table 4**

| Parameter | Value |
|-----------|-------|
| Diameter  | 45 m  |
| Date      | 2007 Dec–2008 May |
| Molecular transition | 12CO(J = 1–0; 115.271 GHz) |
| Observation mode | On-the-fly mode |
| Observation time | 40 hr |
| Mapping area | 1°2 × 1°2 |
| FWHM beam size | 7°5 |
| Spatial grid size | 15″ |
| Effective beam size | 21″ |
| Receiver | BEARS (Sunada et al. 2000; Yamaguchi et al. 2000) |
| Tsys | 250–500 K in the single-side band |
| Tarr | 0.94 K |
| Velocity resolution inside the cloud | 0.5 km s⁻¹ |
| Bandwidth | 32 MHz |

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Figure 6. Same as Figure 4, but for θ = 90° (Figure 2(c)).
features coincide spatially after the displacement. Figure 13 shows the overlapping function $H(\Delta)$ in pc$^2$ defined in the Appendix and indicates that $\Delta = 0.3$ pc gives the optimum fit. We confirmed that the present position angle adopted gives the best fit, i.e., the maximum value of $H(\Delta)$, by changing the angle in a range of $103^\circ$–$113^\circ$, and the displacement of 0.3 pc shown by the arrow in Figure 11(b) gives the fit between the Orion keyhole and key. By the displacement, we also see that the western edge of the redshifted component shows good correspondence with the eastern edge of the blueshifted component over $\sim 1$ pc in the north–south direction, which lends support for the displacement (see dashed green line in Figure 11(b)).

In Figure 11(c), while not so clear as in the other two cases, the two peaks of the blueshifted component at (R.A., decl.) = $(5^h35^m10^s, -5^\circ00')$ and $(5^h35^m15^s, -5^\circ05')$ are located toward the intensity depression of the redshifted component, forming a possible pair of complementary distribution, after a displacement of 0.1 pc (shown by an arrow). This displacement was chosen based on eye inspection because the distribution is relatively simple.

### 3.4. The Bridging Features

Figure 14 shows the position–velocity diagrams of the three regions in Figures 10(a)–(c), where the integration ranges are indicated by filled white areas in Figure 10. While in Figures 14(a) and (c), the CO velocity distributions along the R.A. are presented, the CO distribution along the X-axis defined in Figure 13(a) is shown in Figure 14(b). In Figure 14(a), which includes the U-shaped cloud in the redshifted cloud and the OMC-1 clump in the blueshifted cloud, the CO emission shows a V-shaped distribution, depicted by dashed lines. The V-shaped gas distribution in the position–velocity diagram is an observational signature of cloud–cloud collision, as discussed in Section 2.4, and the V shape in Figure 14(a) resembles the position–velocity diagram.

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**Figure 7.** First-moment maps of the cloud-cloud collision model data for the three inclination angles (a) $\theta = 0^\circ$, (b) $45^\circ$, and (c) $90^\circ$.

**Figure 8.** Decl.–velocity diagram of the $^{12}$CO($J = 1$–0) emission toward M42 and M43. Contours are plotted every 1 K from 0.25 K. The horizontal dashed line indicates the position of the Becklin–Neugebauer object at decl. = $-5^\circ$ 22m24s.
of the synthetic CO data in the $\theta = 0^\circ$ case in Figure 4(k). In Figures 14(b) and (c), toward M43 and OMC-3, respectively, the CO emission shows a V-shaped velocity distribution with skew, which is more similar to the $\theta = 45^\circ$ case in Figure 5(k) than the $\theta = 0^\circ$ case. This is consistent with the complementary distributions with displacement in Figures 11(b) and (c).

3.5. Comparisons with the Optical Image and the First Moment

Figure 15 show overlays of the two velocity components on the optical image. The most notable correspondence is seen toward M43, where the thin dark lane in the center of the nebula coincides with the CO filament in the east of the Orion keyhole (Figure 15(a)). The other blueshifted features of $\sim 0.5^\circ$ in length show a coincidence with the dark areas in the northeast of M42, and the visual extinction of this direction is high ($A_v \gtrsim 30$; Scandariato et al. 2011). This correspondence is consistent with the fact that the blueshifted component separated by 1–4 pc from the core of the O stars lies on the near side of the optical nebula. On the other hand, it is well known that the visual extinction toward the Trapezium stars is small ($A_v \lesssim 3$; Scandariato et al. 2011). Therefore, we suggest that the OMC-1 clump as a part of the blueshifted cloud is on the far side of the optical nebula. This reflects the three-dimensional distribution of the clouds (Balick et al. 1974) and is consistent with the Champaign flow model (Tenorio-Tagle 1979). The redshifted component in Figure 15(b) shows no correspondence with the optical features, suggesting that the redshifted component lies on the far side or the inside of the nebula. We remark that the Orion key has no corresponding dark lane in M43, which is consistent with the present collision.

Figure 16 shows the distribution of the first moment overlaid on the blueshifted and redshifted components in contours. Generally, the first-moment distribution shows good correspondence; the blueshifted component corresponds to the first moment at a velocity smaller than 10 km s$^{-1}$, and the redshifted component corresponds to the Orion key and the U-shaped cloud. This lends additional support to the present interpretation of the two components.

4. The Cloud–Cloud Collision Model

4.1. Model

We present a model of the two molecular clouds that are colliding to trigger the formation of the O/B stars in M42 and M43. Table 5 lists the main physical parameters of the model clouds, and Figure 17 gives a schematic of the clouds before and after the collision. The model consists of two clouds of projected velocities peaked at $\sim 8$ and $\sim 13$ km s$^{-1}$, while the actual relative velocity between the two clouds is on the order of 10 km s$^{-1}$. Both of the clouds are elongated along the Galactic plane. The mass of the blueshifted component is dominant ($\sim 80\%$) toward OMC-1, explaining the apparent
single peak, while the border velocity of 11 km s\(^{-1}\) between the two model clouds may have some uncertainty. The intermediate-velocity gas is not clearly separable in velocity because of the gas mixing in the collision (e.g., Takahira et al. 2014). It is difficult to clearly separate the compressed layer in the intermediate velocity, as shown theoretically by Figures 5 and 6 and as confirmed observationally by Figure 17. We therefore gave the velocity ranges of the two components at a representative boundary of 11 km s\(^{-1}\) in Table 5. The total mass of the two clouds, \(\sim 10^4 M_\odot\), is too small by an order of magnitude to gravitationally bind the estimated relative velocity of \(\sim 7\) km s\(^{-1}\). The model clouds have an overlap toward the OMC-1 clump at decl. = \(-5^\circ30'\) to \(-5^\circ18'\), which corresponds to the region of the enhanced velocity span in Figure 8. The enhancement is interpreted as due to the turbulence by the collisional interaction (Inoue & Fukui 2013), while the effect of the protostellar outflow may also be in part responsible for the enhancement only in the small region close to the protostar. The model offers an explanation of the complementary distribution that is found in the present clouds. The collisional interaction is at least seen in the three regions as indicated by the complementary spatial distribution; one is toward M42 and triggered formation of \(\theta^1\) Ori and \(\theta^2\) Ori (Figure 11(c)), and another is toward M43, which triggered formation of NU Ori (Figure 11(b)). The other is toward the north of M43 without an H\,\!II region (Figure 11(a)). Two more regions associated with possible complementary distribution are noted in Section 3, while no clear star formation is seen except for M42 and M43. In the present case, the half-power line widths of the two clouds are 2–3 km s\(^{-1}\), and the projected velocity separation of \(\sim 5\) km s\(^{-1}\) is too small for separating the possible bridging feature.
In the model, \( \theta^1\) Ori and \( \theta^2\) Ori, including nearly 10 O stars, were formed on the near side of the blueshifted cloud, which was collided and shock-compressed by the more extended redshifted cloud. This collision created the cavity in the redshifted cloud following the cloud–cloud collision model (Habe & Ohta 1992; Anathpindika 2010; Takahira et al. 2014). The interface layer between the two clouds became strongly compressed and highly turbulent to form O stars, as shown by Inoue & Fukui (2013). The O stars formed on the near side of the dense blueshifted cloud and ionized the near side of the cloud to form the M42 nebula as exposed to us. NU Ori was formed in the collision between the Orion key and the redshifted component having the Orion keyhole. NU Ori is a B3 star and ionized M43 (see Section 4.3 for more details). The ionization possibly has widened the size of the Orion keyhole, whereas the smaller UV photon flux of NU Ori than \( \theta^1\) Ori and \( \theta^2\) Ori is not powerful enough to dissipate the Orion keyhole at present.

4.2. Timescales and the Collision

The timescale of the collision is approximately estimated from a ratio of the cloud size and the relative velocity between the two clouds. If we assume tentatively that the relative motion between the two clouds has an angle of 45° to the line of sight, the relative velocity corrected for the projection is estimated to be \( \sim 7 \) km s\(^{-1}\), which is consistent with the enhanced \(^{13}\)CO broadening toward the ONC (Figure 8). The apparent spatial extent of the colliding clouds forming O/B stars ranges from \( \sim 0.3 \) to \( \sim 0.8 \) pc (Figure 10). The ratio between the timescale and the cloud size yields roughly
Orion key and keyhole were assumed to be a uniform value of 1.0 normal to the contour levels are the same as those in Figure 10. The X-axis was taken for the direction of the displacement of the Orion key, as explained in the text, and the Y-axis is normal to the X-axis. See also the Appendix on the upper limit for the age of the stars formed by triggering.

Figure 13. (a) Image and blue contours show the blueshifted cloud, including the Orion keyhole, and the white and red contours show the redshifted cloud, including the Orion key. The blue and red contours with white shaded regions indicate the lowest intensity limit, 5 and 9 km s\(^{-1}\), of the keyhole and key, respectively. The contour levels are the same as those in Figure 10. The X-axis was taken for the direction of the displacement of the Orion key, as explained in the text, and the Y-axis is normal to the X-axis. See the text and Appendix for more details. (b) The overlapping integral \(H(\Delta)\) for the key and keyhole in the Appendix is presented, where the Orion key and keyhole were assumed to be a uniform value of 1.0 (arbitrary unit) with a grid spacing of 0.1 pc × 0.1 pc.

0.05–0.11 Myr as the collision timescale and poses a constraint on the upper limit for the age of the stars formed by triggering.

The complementary distribution is characterized by the projected displacement between the colliding clouds (Figure 4; see also the Appendix). The displacement is small for a small collision timescale. Also, the displacement relative to the size of the small cloud becomes smaller if the size of the small cloud in the collision model is large. Figure 12 shows different displacements between the two velocity components among the three regions. We apply a detailed analysis of the timescale to the Orion key and keyhole, where a displacement is obtained on their relative location by the analysis in Section 3 thanks to the small size, ~0.2 pc, of the small cloud. The separation between the two features is estimated to be 0.3 pc at a relative velocity of 4 km s\(^{-1}\). If we assume 45° as the angle of the relative motion to the line of sight, the timescale of the collision is estimated to be 0.4 pc/5.7 km s\(^{-1}\) = 0.07 Myr if no deceleration of the relative motion is assumed. The northern region in Figure 11(c) shows a displacement of ~0.1 pc, and it may be less accurate than that in Figure 11(b). The OMC-1 clump in Figure 11(a) shows no appreciable displacement, whereas the larger clump size, ~1 pc, tends to smear out a possible displacement. The separation between the two velocity components may vary from region to region, reflecting the initial distribution of the two components and leading to different collision parameters. In summary, we conclude that the typical collision timescale is ~0.1 Myr with some regional minor variation.

4.3. The Star Formation Under Triggering

At the present epoch, the blueshifted component has a high peak column density toward the peak of the OMC-1 clump, ~2 × 10\(^{23}\) cm\(^{-2}\), while the redshifted cloud has a significantly smaller column density, ~10\(^{22}\) cm\(^{-2}\). In M43, the typical column density in the Orion key and keyhole is ~10\(^{22}\) cm\(^{-2}\). We assume that the initial conditions of the two clouds are similar to those of the present clouds, whereas it is probable that the present column densities have become somewhat lower than the initial values due to the collisional interaction and ionization by the formed stars. By comparing O-star formation in several regions, Fukui et al. (2016) argued that the number of O stars formed by collisional triggering depends on the initial column density; more than 10 O stars are formed for a threshold column density of ~10\(^{23}\) cm\(^{-2}\) and a single O star for a threshold column density of ~10\(^{22}\) cm\(^{-2}\). The difference in the O/B star formation in M42 and M43 is consistent with the suggestion.

The MHD numerical simulations by Inoue & Fukui (2013) have shown that the interface layer between the colliding clouds become denser and more turbulent with an amplified magnetic field, realizing the high mass accretion rate of ~10\(^{-4}\)–10\(^{-3}\) \(M_\odot\) yr\(^{-1}\) that satisfies the formation of the high-mass stars greater than 20 \(M_\odot\). In the present typical collision timescale of 0.1 Myr, the stellar mass that is attained by mass accretion is 10–100 \(M_\odot\). So, the present short timescale is consistent with the O-star formation.

More details of the star formation may be explored. In M42, the ionized gas has higher density in \(\theta^1\) Ori than in \(\theta^2\) Ori. There are even younger, heavily embedded high-mass protostars showing outflows, the BN/KL object and the Orion-S region (e.g., Drapatz et al. 1983), in the west of \(\theta^1\) Ori. We see an age sequence from east to west, where \(\theta^2\) Ori is the oldest and the BN/KL object and Orion-S region are the youngest. A possible scenario is that the age sequence is caused by the time sequence of the collision; i.e., the colliding two components have a spatial gradient in the sense that the western part collided first and then the collision is propagating to the west, and the most recent triggering formed the BN/KL object and Orion-S region. A similar age gradient is seen in RCW 38; the eastern part is already ionized, whereas the western part is more heavily embedded (Fukui et al. 2016).

In M43, the position of NU Ori is separated to the west by ~0.15 pc from the eastern filament of the Orion keyhole. The velocity of the interface layer generally becomes smaller by momentum conservation (e.g., Haworth et al. 2015a), which places the formed star behind the small cloud. A possible scenario is that the B-star formation took place by the collision in the eastern edge of the Orion key. This explains the location
of NU Ori, and the situation is similar to that of M20, where a single O star is formed by triggering in the eastern edges of the clouds (Torii et al. 2017a).

4.4. The Age of the ONC

The age of the ONC members ranges from less than 0.1 Myr to more than 1 Myr, while the majority are in the range 0.1–1 Myr, as estimated in the HR diagram by comparing with the theoretical stellar evolutionary tracks (Hillenbrand 1997). The collision timescale of less than 0.1 Myr corresponds to the youngest end of the age distribution. We infer that the blueshifted cloud that dominates the molecular column density in the Orion A cloud was forming low-mass stars of the ONC prior to the collision in the last Myr. The distribution of low-mass young stars of the ONC obtained by 2MASS in Figure 18 (Carpenter et al. 2001), indicates that these stars toward the OMC-1 clump are correlated well with the column density distribution of the blueshifted cloud, except for the $^{12}$CO peak including the BN/KL object, where the extinction may be large at the $K$ band (Feigelson et al. 2005). In addition, it is possible that the 2MASS variable stars are obscured by several magnitudes in the $K$ band toward the molecular peak of the OMC-1 clump (R.A. $\sim 5^h35^m3$ and decl. $\sim -5^\circ20'$ to $-5^\circ30'$), as suggested by their decrease in number by $\sim 20\%$ (Figure 18(b)). These low-mass members are spatially more extended than the O stars (Hillenbrand 1997) beyond the region of the collisional interaction. We see little molecular gas in the two regions in the north of M42, (R.A., decl.) = ($5^h35^m4$–$5^h36^m0$, $-5^\circ15'$ to $-5^\circ00'$), and the south of the M42 clump, (R.A., decl.) = ($5^h35^m0$–$5^h35^m7$, $-5^\circ28'$ to $-5^\circ32'$), whereas 2MASS stars are distributed there. The two correspond to the regions of the suggested collisional interaction, and the blueshifted gas in the regions has possibly been removed by the collision after the low-mass star formation. The redshifted cloud had a lower column density, not actively forming stars before the collision, while the northern part of the redshifted component may have been forming part of the stars, as indicated by the spatial correspondence with the stars (Figure 18). It is possible that not only O/B stars but also low-mass stars were formed by the collisional triggering (cf. Nakamura et al. 2012). The young low-mass stars in the HR diagram by Hillenbrand (1997) suggest very young low-mass stars of an age less than 0.1 Myr. Part of them might represent protostars whose accretion disk was destroyed by the UV photons of $\theta^1$ Ori and $\theta^2$ Ori before they reached $>10 M_\odot$.

4.5. Alternative Interpretations

$\text{H II}$ regions containing high-temperature ionized gas are expanding, and $\text{H II}$ expansion can be an alternative to explain the gas motion instead of cloud–cloud collision. Sugitani et al. (1986) examined $^{13}$CO($J = 1$–0) emission over the M42/M43 region in order to test the gas motion driven by the $\text{H II}$ region. These authors found it more likely that the gas motion is dominated by the preexistent motion unrelated to the $\text{H II}$ expansion. Figure 14(c) shows that the velocity span of the $^{12}$CO emission is not particularly enhanced toward the peak of the $\text{H II}$ region, where one expects the most significant acceleration if $\text{H II}$ expansion plays a role. Conversely, the span is most enhanced at the eastern edge of the molecular gas with no systematic trend. Figure 8, another position–velocity cut in decl., shows that the velocity span is nearly uniform at $\sim 8 \text{ km s}^{-1}$ at a contour level of $\sim 2 \text{ K}$ over 1 pc. This is the OMC-1 clump and is part of the blueshifted component. The clump is on the far side of the O stars, and the blueshift is in the opposite sense to the
acceleration by H II expansion. Figure 14(b), a position–velocity cut in M43, also shows that the velocity span has no enhancement toward NU Ori except for the Orion key in a small size of 0.1 pc. These current kinematic signatures are consistent with the conclusion reached by Sugitani et al. (1986).

In other H II regions, significant molecular gas motion driven by H II regions is not reported (e.g., RCW38, Fukui et al. 2016; RCW120, Torii et al. 2015; NGC6334, Fukui et al. 2017d; M20, Torii et al. 2017a; M16, Nishimura et al. 2018a; M17, Nishimura et al. 2018b). In RCW38, where two velocity components are observed, the redshifted gas is on the near side of the H II region, supporting that H II expansion does not dominate gas motion, and in RCW120, a typical Spitzer bubble, 12CO observations found no sign of expansion due to the H II region. Theoretical studies of H II expansion (e.g., Hosokawa & Inutsuka 2005) showed that the molecular gas layer accelerated by H II expansion is thin, on the order of 0.1 pc, and that the bulk of the molecular gas cannot be accelerated prior to ionization. The observations above are consistent with these theoretical works. Alternatively, H II gas may be pressurized and accelerate ambient molecular gasunionized. The molecular gas is, however, always clumpy, and it is unlikely that the H II region is totally confined by the molecular gas. This suggests that H II gas escapes easily through low-density holes without molecular acceleration. It is more likely that high-mass stars accelerate the surrounding gas via supernova explosion, as observed in molecular super shells formed by multiple supernova explosions over a larger timescale of ~20 Myr (e.g., Fukui et al. 1999; Matsunaga et al. 2001; Dawson et al. 2008). Such acceleration may explain the origin of the supersonic gas motion that leads to cloud–cloud collision over a timescale larger than 100 Myr.

5. Discussion

5.1. Theories of High-mass Star Formation Under Gravitational Binding

The monolithic collapse and competitive accretion are the two scenarios for massive cluster formation and have been discussed for more than a decade (e.g., Zinnecker & Yorke 2007). In either case, the massive gas/star system is self-gravitationally bound, and multiple sources evolve into stars of various masses by mass accretion. It is also discussed that the bound system may evolve in time and becomes unbound by gas dispersal (e.g., Kroupa et al. 2001). These two gravitationally bound scenarios have no explicit physical mechanism of realizing the high-mass accretion rate like the shock-induced turbulence in the cloud–cloud collision scenario, and it is assumed that the gas achieves the high-mass accretion rate by some gravitationally driven mechanism. The colliding clouds in the present hypothesis are not gravitationally bound by the supersonic velocity, and the collision increases the mass accretion rate to $10^{-2}$–$10^{-3} M_\odot yr^{-1}$, which is higher than in the bound scenarios, favoring the high-mass star formation (Inoue & Fukui 2013).

5.2. Evolutionary Timescales and Mass Segregation

The evolution of the monolithic mass aggregation has been tested theoretically. In the simulations of protoclusters, a single gravitationally bound N-body system is adopted as the initial condition of a cluster whose number of stars is assumed to be 800–2000 in the same order as that of the ONC (e.g., Kroupa et al. 2001; Banerjee & Kroupa 2015). The effect of stellar
feedback is also incorporated in recent simulations (e.g., Dale et al. 2013).

The typical timescale of the evolution of the N-body system is Myr, which is significantly larger than that of the cloud–cloud collision (less than 0.1 Myr). It is probable that these simulations are applicable to the precollision cluster of low-mass stars in the Orion blueshifted cloud of the present hypothesis. Some N-body simulations assume “rapid” gas dispersal by ionization due to the high-mass stars, and it is argued that such rapid dispersal is consistent with the observations (Banerjee & Kroupa 2015). The rapid dispersal is, however, still on a large timescale, close to Myr. There is increasing observational evidence for a short timescale of less than 0.1 Myr in O-star formation; observations of the ONC show that the youngest stars have ages less than 0.1 Myr, and in the two super star clusters NGC 3603 and Westerlund 1, the age spread of young clusters is short on the order of 0.1 Myr (Kudryavtseva et al. 2012). It is also becoming established that the age and mass segregation are outstanding in young massive clusters; the O stars are concentrated in the innermost part of NGC 3603, the ONC, and R 136. While the stellar mass function depends on the area for averaging the stellar properties, the innermost part tends to have a top-heavy mass function in these clusters. We need to be cautious that the ONC may consist of at least two different populations. The ONC has a usual mass function similar to the field initial mass function (IMF) having a Salpeter-like slope (Kroupa 2001). In the present model, the stars toward M42 are a superposition of two different populations; the older low-mass members formed prior to the collision are likely dominant in the blueshifted cloud, and the other youngest stars, including O/early-B stars, were formed in triggering by the collision. The preexistent low-mass stars dominate the stars of the ONC, making the steep slope of the mass function, while about a half of them may still be deeply embedded in the blueshifted cloud (Hillenbrand & Carpenter 2000; Muench et al. 2008). One may expect that the IMF has discontinuous slopes if the star formation by the two different modes is working. We suggest that the total mass of the O stars in the center of the ONC is $\sim 150 M_\odot$ (Muench et al. 2008). On the other hand, the molecular mass of the OMC-1 clump is $3.3 \times 10^3 M_\odot$. If we assume tentatively that the depth of the shock front propagated in the OMC-1 clump is 0.3 pc, one-third of the clump size, the molecular mass already shocked is estimated to be $\sim 1000 M_\odot$, large enough to form the 10 O stars of 20–30 $M_\odot$. The interface layer is included in these two components for the collisional area of $\sim 1$ pc$^2$ toward $\theta$ Ori and $\theta$ Ori and NU Ori, although the layer is not clearly

| Parameter          | The Blueshifted Cloud | The Redshifted Cloud |
|--------------------|-----------------------|----------------------|
| Velocity range [km s$^{-1}$] | 4.0–11.1 | 11.1–14.9 |
| Length [pc] | 8.9 | 4.7 |
| Width [pc] | 6.5 | 3.4 |
| Mass [$M_\odot$] | $1.5 \times 10^4$ | $3.4 \times 10^3$ |

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Table 5

The Model Parameters of the Two Clouds in M42 and M43

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separable in velocity because of the turbulent mixing by the collision. The present collision model suggests that the stars forming by triggering are located on the front side of the M42 clump, producing a nonspherically symmetric distribution of the cluster. This is a natural consequence of the collision that has a directivity, at least in the early phase, where part of the molecular gas still remains without ionization. We note that the N-body simulations result in a spherically symmetric system after Myr, which does not explain such asymmetry. The total mass of the Orion key and keyhole region is estimated to be $\sim 150 \, M_\odot$ for a size of $\sim 0.5$ pc. This is large enough to form NU Ori with $17 \, M_\odot$ (Muench et al. 2008).

The initial conditions of the present cloud–cloud collision assume a molecular cloud having a high column density of $10^{23} \, \text{cm}^{-2}$, which has been continuously forming low-mass stars. These low-mass stars are not able to ionize the cloud, and the blueshifted cloud continues to form low-mass stars until it forms high-mass stars that are capable of ionizing the cloud. The O-star formation is suddenly triggered by the impact of the supersonic collision with the redshifted cloud, which has lower column density. The epoch of O-star formation may range in a certain time span, whereas the cloud–cloud collision poses a limit on the age spread of the youngest members, including O stars, by the ratio of the cluster size divided by the collision velocity to be $\sim 0.1$ Myr. It is unlikely that the two gravitationally bound scenarios can explain the very short discontinuous history of star formation less than 0.1 Myr. We do not see any gap in the age distribution of the cluster members. This is a natural consequence of the cloud–cloud collision following Myr low-mass star formation.

6. Conclusions

We have made a new analysis of the molecular gas toward M42 and M43 and tested a hypothesis that two clouds collided about 0.1 Myr ago to form the northern part of the Orion A cloud. We have shown that the collision model offers a reasonable explanation of the observed cloud and cluster properties in the M42 and M43 region. However, we currently do not have an extensive observational basis that the cloud–cloud collision is a dominant mechanism of O-star formation in the Milky Way. The main conclusions of the present study are summarized as follows:

1. The present analysis of the high-resolution CO data shows a possibility that the Orion A cloud toward M42 and M43 consists of two velocity components, one at

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Figure 17. Panel (a) shows the two clouds before the collision, and panel (b) shows them after the collision projected in the sky. The lower left panels show rectangular solid model clouds before the collision (c1) for the key and keyhole and (c2) for the M42 clump and the U-shaped cloud, and the lower right panels shows these after the collision (d1) for the key and keyhole and (d2) for the M42 clump and the U-shaped cloud.
4.0–11.1 km s\(^{-1}\) and the other at 11.1–14.9 km s\(^{-1}\). The mass of the blueshifted component is 1.5 \(\times 10^4 M_\odot\) with a velocity range of 4.0–11.1 km s\(^{-1}\), and the redshifted component is 3.4 \(\times 10^3 M_\odot\) with a velocity range of 11.1–14.9 km s\(^{-1}\) having a size of 4 pc–7 pc in R.A. and decl. The interface layer having \(~1000 M_\odot\) is included in

Figure 18. Comparisons between the \(^{12}\text{CO}(J = 1 \rightarrow 0)\) distribution of the blueshifted cloud and 2MASS variable stars (Carpenter et al. 2001). (a) The image and contours indicate the blueshifted cloud at 8.8 km s\(^{-1}\), and the red crosses indicate variable stars. (b) The image indicates the blueshifted cloud, and the contours indicate density distributions of the 2MASS stars. Panels (c) and (d) are the same as panels (a) and (b) but for the redshifted cloud at 12.9–14.9 km s\(^{-1}\). The contour levels are from 2.3 \(\times 10^2\) stars pc\(^{-2}\) to 2.8 \(\times 10^3\) stars pc\(^{-2}\) every 2.9 \(\times 10^2\) stars pc\(^{-2}\).
these two components for the collisional area of $\sim 1 \text{ pc}^2$ toward $\theta^1$ Ori and $\theta^2$ Ori and NU Ori, although the layer is not clearly separable in velocity because of the turbulent mixing by the collision.

2. We find at least three pairs of complementary distributions between the two clouds having scale sizes of 0.1–1 pc. These complementary distributions of molecular gas are an observational characteristic of cloud–cloud collision according to the hydrodynamical numerical simulations at the early phase of O-star formation. The major complementary distribution is found toward $\theta^1$ Ori and $\theta^2$ Ori, where the blueshifted component of $\sim 0.5 \text{ pc}$ radius, the OMC-1 clump, is surrounded by the redshifted component, the U-shaped cloud, which is extended with a radius of $\sim 1 \text{ pc}$. The secondary complementary distribution is seen toward M43, named the Orion key and keyhole, where a spatial displacement of 0.3 pc is seen between the two complementary distributions.

3. We frame a hypothesis that the two velocity components collided with each other to trigger formation of the nearly $\sim 0.5 \text{ pc}$ angle to the line of sight. By assuming the angle to be 45°, the relative velocity and separation between the clouds is estimated to be $\sim 6 \text{ km s}^{-1}$ and $\sim 0.5 \text{ pc}$, respectively, after correction for the projection, and the typical collision timescale is calculated to be $\sim 0.1 \text{ Myr}$.

4. Although the collision is extended over an area of 4 pc x 7 pc in R.A. and decl., the triggering of the O/B star formation is seen only toward the localized regions with OB stars. We suggest that this trend is consistent with the threshold for O-star formation in cloud–cloud collision suggested by Fukui et al. (2016); multiple O-star formation is possible for a column density of $\sim 10^{23} \text{ cm}^{-2}$, while the single O/B star formation is for $\sim 10^{22} \text{ cm}^{-2}$. The high segregation of the high-mass cloud members to the cluster center is explained as a reflection of the initial column density distribution prior to the collision.

5. The stellar contents of the ONC have been best studied among the rich clusters thanks to its unrivaled small distance to the Sun, although the cluster is not overwhelmingly rich in high-mass stars. The OB stars in the ONC are minor members in terms of stellar mass, and the IMF is not significantly influenced by the formation of the OB stars. The youngest members, including the O/early-B stars, are formed by the collision within 0.1 Myr, and the large age spread of the cluster, from a few 0.01 to a few times 1.0 Myr, is understood by a combination of low-mass star formation in the blueshifted cloud prior to the collision and the recent O/B star formation by the collisional triggering. Formation of O stars may still be continuing toward the western edge of the M42 clump, where the BN object and OMC-1-S are located along the north–south direction.

In the present study, we have shown that cloud–cloud collision offers a possible consistent interpretation of the formation of the O/B stars in M42 and M43. Since the immediate vicinity of $\theta^1$ Ori and $\theta^2$ Ori is significantly ionized, we are not allowed to directly witness the triggering, as in the case of RCW 38. We note that the BN/KL object can be such a candidate, as discussed in Section 5, and suggest that future more careful scrutiny of the region and its surroundings at higher resolutions with ALMA, etc. will offer further insight into the possible role of the collisional interaction.

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Appendix

Estimate of the Displacement in the Complementary Distribution

We describe the method for a simple case of the complementary distribution in the $X-Y$ plane (Figure 19), where the small cloud and intensity depression are assumed to be circles of the same radius $\alpha$ with an initial displacement of $x_0$ along the $X$-axis in the sky. By shifting the small cloud by $\Delta$ in the direction of the intensity depression along the $X$-axis, we calculate the overlapping product between the two circles represented as $f(x, y)$ and $g(x, y)$ by assuming that they have a uniform intensity of 1.0 in an arbitrary unit inside the circle and 0.0 outside the circle. By taking a product of the circle and the intensity depression at $\Delta$, the overlapping between the two circles is given by $h(x - \Delta, y)$, the product of $f(x - \Delta, y)$ and $g(x - x_0, y)$. Here $h(x - \Delta)$ is integrated in the $X-Y$ plane and expressed by $H(\Delta)$. The displacement of the two circles is then estimated to be $\Delta = x_0$ at the peak of $H(\Delta)$ (Figure 19).

The method is applied to the synthetic observations in Figures 19(b)–(d). In Figures 19(b) and (c), the distributions of the small cloud and intensity depression are taken from Figure 5. Grid spacing is given as 0.1 pc x 0.1 pc in the $X-Y$ plane according to the numerical simulations (Takahira et al., 2014), and we assign a numerical value to be 1.0 for each pixel inside both components and zero outside of them, as above (Figures 19(i) and (j)). Here $H(\Delta)$ is calculated in the same manner as above, with an incremental step of 0.1 pc in $\Delta$, and is shown in Figure 19(d). The peak position of $H(\Delta)$
gives the displacement to be \( \sim 2 \) pc. By correcting for the projection effect, the displacement corresponds to the length of the cavity, \( \sim 3 \) pc, where the size of the small cloud is taken into account. We find that the value is roughly consistent with the length of the cavity in the large cloud, \( \sim 4 \) pc, at 1.6 Myr in the numerical simulations. In Section 3, we applied the method to estimate the displacement between the Orion key and keyhole.

**Figure 19.** Simple model of the small cloud and intensity depression. Both are assumed to be a circle of radius \( a \), where we take \( a = 1 \) pc. In order to calculate the overlapping integral \( H(\Delta) \), the shift of the small cloud \( \Delta \) is swept along the \( X \)-axis, as shown in panels (a)–(e), where panel (a) is the initial state. In panel (i), the equations are summarized, and in panel (j), \( H(\Delta) \) is shown. The peak of \( H(\Delta) \) gives the initial displacement \( x_0 \) of the two circles.

\[
\begin{align*}
\text{The small cloud: } f(x,y) \\
\text{The intensity depression: } g(x,y) \\
f(x,y) &= g(x,y) = 1; x^2 + y^2 \leq a^2 \text{ (a radius)} \\
0; x^2 + y^2 > a^2 \\
\text{The center of the small cloud; } \\
\text{The initial position: } (x,y) = (0,0) \\
\text{After shift: } (x,y) = (\Delta,0) \\
\text{The center of the intensity depression; } \\
(x,y) = (x_0,0) \\
\text{The product of } f(x,y) \text{ and } g(x,y): h(x,y) \\
h(x-\Delta,y) = f(x-\Delta,y) \ast g(x-x_0,y) \\
\text{The integral of } h(x,y): H(\Delta) \\
H(\Delta) = \iint h(x-\Delta,y) \, dx \, dy
\end{align*}
\]
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Toshikazu Onishi

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Fukui et al.