Triggered O Star Formation in M20 via Cloud–Cloud Collision: Comparisons between High-resolution CO Observations and Simulations

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Abstract

Understanding high-mass star formation is one of the top-priority issues in astrophysics. Recent observational studies have revealed that cloud–cloud collisions may play a role in high-mass star formation in several places in the Milky Way and the Large Magellanic Cloud. The Trifid Nebula M20 is a well-known Galactic H II region ionized by a single O7.5 star. In 2011, based on the CO observations with NANTEN2, we reported that the O star was formed by the collision between two molecular clouds ~0.3 Myr ago. Those observations identified two molecular clouds toward M20, traveling at a relative velocity of 7.5 km s⁻¹. This velocity separation implies that the clouds cannot be gravitationally bound to M20, but since the clouds show signs of heating by the stars there must be spatially coincident with it. A collision is therefore highly possible. In this paper we present the new CO J = 1–0 and J = 3–2 observations of the colliding clouds in M20 performed with the Mopra and ASTE telescopes. The high-resolution observations revealed that the two molecular clouds have peculiar spatial and velocity structures, i.e., a spatially complementary distribution between the two clouds and a bridge feature that connects the two clouds in velocity space. Based on a new comparison with numerical models, we find that this complementary distribution is an expected outcome of cloud–cloud collisions, and that the bridge feature can be interpreted as the turbulent gas excited at the interface of the collision. Our results reinforce the cloud–cloud collision scenario in M20.

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

1. Introduction

There is increasing evidence that cloud–cloud collision plays an important role in high-mass star formation. Based on CO observations with the NANTEN2 4 m telescope, Furukawa et al. (2009) and Ohama et al. (2010) revealed that two giant molecular clouds with a velocity separation of 20 km s⁻¹ are both associated with the H II region RCW 49, which is excited by the massive star cluster Westerlund 2. The large velocity separation cannot be interpreted either as gravitational binding or as an expansion driven by stellar feedback. An alternative proposed by the authors is a scenario in which the massive cluster was formed by a supersonic collision between the two clouds, where the observed velocity separation can be deemed to be the projection of the colliding velocity. Following its discovery in Westerlund 2, the association of two clouds of significantly different velocities with O stars has been reported in several high-mass star-forming regions in the Milky Way, and the formation of O stars triggered by cloud–cloud collision was discussed as a plausible interpretation: see, e.g., Torii et al. (2011, hereafter Paper I) and Torii et al. (2015) for the Galactic H II regions M20 and RCW 120, and Fukui et al. (2014, 2016) for the massive star clusters NGC 3603 and RCW 38. In the Large Magellanic Cloud, ALMA observations led to the discoveries of a 36 M☉ star in N159 West and a 40 M☉ star in N159 East, likely triggered by collisions between filamentary clouds (Fukui et al. 2015; Saigo et al. 2016). Most recently, Y. Fukui et al. (2016, in preparation) proposed a scenario in which the Orion Nebula Cluster (ONC) was formed by a collision between two molecular clouds. These results suggest that cloud–cloud collisions can trigger the formation of O stars for a wide mass range. M20 and RCW 120 are H II regions dominated by a single O star, while Westerlund 2, NGC 3603, RCW 38, and the ONC are massive star clusters that harbor several or more than 10 O stars. Fukui et al. (2016) discussed how the H₂ column density of the clouds is a critical parameter in determining the number of O stars and that 10²³ cm⁻² is required to form a massive star cluster.

A pioneering study of the numerical calculations of cloud–cloud collisions was performed by Habe & Ohta (1992), followed by Anathpindika (2010) and Takahira et al. (2014). These authors simulated head-on collisions between two molecular clouds of different sizes. Figure 1 shows a schematic picture of high-mass star formation resulting from a collision between two dissimilar clouds, although the connection between cloud–cloud collision and high-mass star formation was not discussed in depth in the aforementioned simulations. These authors indicate that cloud–cloud collision can induce the formation of dense self-gravitating clumps inside the dense gas layer formed at the interface of the collision. The formation of massive clumps in the collisionally compressed layer was also discussed in depth in the recent magnetohydrodynamical (MHD) simulations by Inoue & Fukui (2013). In their simulations, supersonic collisions amplify the magnetic field and the turbulent velocity of the gas, leading to a mass...
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accretion rate of $10^{-4} - 10^{-3} \, M_\odot yr^{-1}$, two orders of magnitude higher than that in the case of low-mass star formation. Such a high mass accretion rate satisfies the conditions for high-mass star formation as postulated in theoretical works (e.g., McKee & Tan 2003; Hosokawa et al. 2010). One interesting signature of the collision between two dissimilar clouds is the cavity created on the surface of the large cloud. The size of the cavity corresponds to the diameter of the small cloud, and its depth is determined by the timescale of the collision and the balance of the momenta between the two colliding clouds.

Observational support for the cavity creation and the subsequent O star formation predicted in the cloud–cloud collision model was first given by Torii et al. (2015) in the H II region RCW 120. The authors identified two molecular clouds with a velocity separation of $\sim 20 \, \text{km} \, \text{s}^{-1}$ and discussed how the exciting O star inside RCW 120’s bright mid-infrared ring was formed through the collision of the two clouds. RCW 120’s beautiful ring is usually considered to be formed by the expansion of the H II region. Torii et al. (2015), however, found no evidence for the expanding motion and suggested that the observed ring emission can be interpreted as the cavity created through the cloud–cloud collision.

Another observational signature of cloud–cloud collision is the “bridge feature” seen in a position–velocity diagram. Using the model data on cloud–cloud collisions calculated by Takahira et al. (2014), Haworth et al. (2015a, 2015b) conducted synthetic CO line observations and found a broad intermediate velocity feature that bridges between two colliding clouds in the position–velocity diagram. The bridge feature probes the turbulent motion of the gas enhanced by the collision. The bridge feature was observationally confirmed in the young massive star cluster RCW 38 by Fukui et al. (2016). It was identified at a spot very near the O stars in RCW 38, suggesting that the cloud–cloud collision in RCW 38 is still continuing.

Among the previously studied cloud–cloud collision regions, M20, also known as the Trifid Nebula, is the youngest object along with RCW 38 (see the review by Rho et al. 2008). It was formed only 0.3 Myr ago (Cernicharo et al. 1998). M20 has outstanding obscuring dust lanes that trisect a nebula of gas ionized by an O7.5 star (HD 164492 A), which dominates the excitation of M20 (Figure 2). The distance to M20 estimated in the previous studies ranges from 1.7 kpc in the Sagittarius arm (Lynds et al. 1985) to 2.7 kpc in the Scutum arm (Cambrésy et al. 2011). In this paper we tentatively assume the distance of 1.7 kpc to make our analysis and discussion consistent. As shown in Figure 2(b) and Table 1, HD 164492 A is accompanied by several early-type stars, forming a small stellar group within the central $\sim 0.1$ pc (Kohoutek et al. 1999). The total stellar mass within $\sim 3 \, \text{pc}$ of HD 164492 A is about $500 \, M_\odot$ (Ogura & Ishida 1975; Rho et al. 2001; Broos et al. 2013), two orders of magnitude less than in the massive star clusters like Westerlund 2.

Low-mass stars at different stages of star formation have been detected throughout the nebula at various wavelengths, i.e., optical jets (Cernicharo et al. 1998; Hester et al. 2004), mid- and far-infrared young stellar objects (YSOs) (Rho et al. 2006), infrared and X-ray YSOs (LeFlohch et al. 2001; Rho et al. 2001, 2004; Feigelson et al. 2013), and H$\alpha$ emission stars (Herbig 1957; Yusef-Zadeh et al. 2005). Rho et al. (2001) identified 85 T-Tauri stars in the nebula. Rho et al. (2006) cataloged $\sim 160$ YSOs based on the Spitzer observations and

Figure 1. Schematics of the collision between two dissimilar clouds simulated by Habe & Ohta (1992).

Figure 2. (a) Optical image of M20, trisected by three dark dust lanes (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 the Spitzer color–color diagram (Rho et al. 2006) are plotted with filled red circles and filled white circles, respectively. White solid lines show the target region of the present work. (b) The HST image of the central region of M20 (Yusef-Zadeh et al. 2005). The HD 164492 components listed in Table 1 are indicated by arrows.
classified them into different evolutionary stages. Recently, the MYStIX project utilized near-infrared and X-ray observations to identify more than 500 YSOs in M20 (Broos et al. 2013; Feigelson et al. 2013; Kuhn et al. 2013). In Figure 2(a) the class 0/I YSOs (red circles) and the class II YSOs (white circles) identified by Rho et al. (2006) are plotted on the optical image of M20. Leech et al. (2008) made comparisons between the YSOs of Rho et al. (2006) and submillimeter dust continuum emission, indicating that many of the class 0/I YSOs are embedded within dense molecular clumps. On the other hand, the ISO-CAM observations by Leech et al. (2001) unveiled four point-like infrared sources (dubbed IRS2, IRS3, IRS6, and IRS7) with bright emission in the 9.7 μm silicate band, which provide direct evidence of the evaporating disk phase “proplyd”, a later evolutionary phase of the star formation (Table 1). IRS3, IRS6, and IRS7 are also identified in the YSO catalog of Rho et al. (2006) (see Figure 2(a)).

Thanks to the youth of M20, the natal molecular clouds have been less dissipated by the UV radiation, providing a unique opportunity to investigate the formation mechanism of the O star. In Paper I we made CO J = 1–0 and J = 2–1 observations with NANTEN and NANTEN2 toward a large area of M20 at spatial resolutions of 90′′ and 156′′, revealing that two molecular clouds with ~10^4 M⊙ and a velocity separation of ~7 km s\(^{-1}\) are both physically associated with the H II region in M20. The two clouds both have peaks just to the west of HD 164492 A and have high 12CO (J = 2–1)/ (J = 1–0) line intensity ratios of ~1.0, which corresponds to a kinetic temperature of ~30 K, indicating heating of the two clouds by HD 164492 A. The large velocity separation can be explained neither by gravitational binding by the total mass included in M20 nor by the expanding motion driven by the feedback from HD 164492 A, and Paper I concluded that the two molecular clouds collided with each other ~0.3 Myr ago and triggered the formation of the central O star.

Although the association of the two clouds with M20 was firmly indicated by the increase in temperature toward the exciting O star, the spatial resolutions of the NANTEN and NANTEN2 data set used in Paper I were much coarser than those of the optical and infrared images obtained toward M20, and the detailed distributions and dynamics of the two colliding clouds have not been studied. In this paper we present the results of our new observations of 12CO J = 1–0 and J = 3–2 at high angular resolutions of 22″–35″. The new data set allows us to investigate the detailed evolutionary scenario of M20 through the cloud–cloud collision. Section 2 describes observations and Section 3 observational results of the two colliding clouds in M20. Section 4 makes a new analysis of the model data of the cloud–cloud collision in Haworth et al. (2015a, 2015b) and discusses comparisons with the observations. Section 5 concludes the paper. The equinox of the celestial coordinates used in this paper is J2000.0.

2. Observations

2.1. Mopra CO J = 1–0 Observations

The Mopra 22 m telescope in Australia was used for the observations of the CO J = 1–0 emission during 2011 October. The backend system “MOPS” enabled us to obtain the three CO J = 1–0 isotopes—12CO J = 1–0, 13CO J = 1–0, and C^{18}O J = 1–0—simultaneously, providing a velocity coverage of 360 km s\(^{-1}\) and a velocity resolution of 0.08 km s\(^{-1}\). The OTF (on-the-fly) mode was used with a unit field of 4′ × 4′ toward an 8′ × 8′ area of the M20 region. The observed spectra were smoothed along the velocity axis to a resolution of 0.44 km s\(^{-1}\). The pointing accuracy was kept within 7″ by observing 86 GHz SiO masers every 1 hr. For the absolute intensity calibrations, Orion-KL (R.A., decl.) = (−5°35′44″5, −5°22′29″6) was observed and compared with the CO spectrum obtained by Ladd et al. (2005), which was calibrated with an “extended” beam efficiency. The typical rms noise fluctuations in the 12CO, 13CO, and C^{18}O J = 1–0 emission are 0.6 K, 0.4 K, and 0.4 K, respectively, with a typical system noise temperature of 400–600 K in the SSB (single sideband).

2.2. ASTE CO J = 3–2 Observations

Observations of the 12CO J = 3–2 transition were performed with the ASTE 10 m telescope located in Chile in 2014 June (Ezawa et al. 2004, 2008; Inoue et al. 2011). The waveguide-type sideband-separating SIS mixer receiver “CATS345” and the digital spectrometer “MAC” were used at a frequency coverage of 128 MHz and a frequency resolution of 0.125 MHz (Sorai et al. 2000), which corresponds to a velocity coverage of 111 km s\(^{-1}\) and a velocity separation of 0.11 km s\(^{-1}\), at 345 GHz . The beam size was 22″ at 345 GHz, and the observations were made with the OTF mode toward the same area as the Mopra observations at a grid spacing of 7′.5. The pointing accuracy was checked every ~1.5 hr to keep within 5″ by observing W Aql (R.A., decl.) = (19°15′23″35, −7°02′50″3). The absolute intensity calibration was made with observations of W28 (R.A., decl.) = (18°00′30″4, −24°03′58″5). The day-to-day fluctuations of the peak intensity were within 10%. The typical system temperature was ~250 K in the SSB and the final rms noise fluctuations are typically 0.2 K at the output velocity resolution of 0.44 km s\(^{-1}\).

3. Results

3.1. CO Distributions

Figure 3 shows the CO J = 1–0 and J = 3–2 integrated intensity distributions of the two colliding clouds in M20. The blueshifted cloud is pronounced at ~1–5 km s\(^{-1}\), while the redshifted cloud is distributed at 7–12 km s\(^{-1}\). The two clouds are separated by ~7 km s\(^{-1}\). Following Paper I, we hereafter refer to the blueshifted cloud as the “2 km s\(^{-1}\) cloud” and the redshifted cloud as the “9 km s\(^{-1}\) cloud.” The 2 km s\(^{-1}\) cloud

Table 1

| Object | Position (J2000) | Type | Comments |
|--------|-----------------|------|----------|
| A      | 18:02:23.5, −23:01:51 | O7.5V(III) | the exciting star |
| B      | 18:02:23.7, −23:01:45 | A2Va |          |
| C (IRS1) | 18:02:21.1, −23:02:01 | B6Ve | hard X-rays |
| D (IRS2) | 18:02:22.9, −23:02:00 | Be, LkHα 123 | proplyd |
| E      | 18:02:23.1, −23:02:06 | F3Ve |          |
| F      | 18:02:25.1, −23:01:57 | ... | optical source |
| G (IRS4) | 18:02:22.3, −23:02:30 | ... | optical source |
| IRS3 (HST 1) | 18:02:23.3, −23:01:35 | late-F to mid-G | proplyd |
| IRS5 | 18:02:21.1, −23:01:04 | ... | IR source |
| IRS6 | 18:02:14.1, −23:01:44 | ... | IR source, proplyd |
| IRS7 | 18:02:16.8, −23:00:52 | ... | IR source, proplyd |
has an elongated distribution that stretches along the east–west direction, and as presented later in Figure 6, it coincides with the dark lanes that lie in front of the M20 nebula. Our new CO observations resolve the inner structures of the $-2$ km s$^{-1}$ cloud into several clumpy structures with sizes of 0.2–0.8 pc.

Compared with $^{12}$CO J = 1–0 observations, $^{12}$CO J = 3–2 highlights these clumpy structures and is not sensitive to the diffuse CO emission that is widely distributed in the $^{12}$CO J = 1–0 maps.

The $-9$ km s$^{-1}$ cloud consists of several spatially separated clouds as discussed in Paper I, and two of them are included in the present observed region. The cloud colliding with the $2$ km s$^{-1}$ cloud is just to the very west of HD 164492 A, (R.A., decl.) $\sim (18^h2^m18^s, -23^\circ2')$, and is referred to as “cloud C” in Paper I, while the other one, “cloud S,” is located at (R.A., decl.) $\sim (18^h2^m25^s, -23^\circ5')$. Cloud S is not directly related to the collision (Paper I), and in this study we do not focus on this cloud, although it has been gaining attention because the optical jet HH 399 is protruding from the protostellar core TC2 embedded within the northern tip of cloud S (Cernicharo et al. 1998). While 2 km s$^{-1}$ cloud has overall similar distributions for $^{12}$CO J = 1–0 and $^{12}$CO J = 3–2, cloud C has different distributions. It has only one peak in the $^{12}$CO J = 1–0 map (Figure 3(b)) but has four local peaks in the $^{12}$CO J = 3–2 map (Figure 3(d)).

In order to investigate the physical interactions between the $2$ km s$^{-1}$ cloud and cloud C, in Figures 4 and 5 we present the $^{12}$CO J = 1–0 and $^{12}$CO J = 3–2 velocity channel maps over the entire velocity range of the two colliding clouds. The $^{12}$CO J = 1–0 emission in the intermediate velocity range of the two clouds ($5$–$6.5$ km s$^{-1}$) is dominated by relatively weak, diffuse emission widely distributed above a declination of $\sim -23^\circ3'$, and small-scale structures are hardly seen with significant detections. The $^{12}$CO J = 3–2, on the other hand, shows some clumpy components in the intermediate velocity range free from the diffuse emission.

Comparisons of the two colliding clouds and the intermediate velocity gas are shown in Figure 6, where the contour maps of the $2$ km s$^{-1}$ cloud (blue contours) and $9$ km s$^{-1}$ cloud (red contours) are superimposed on the optical image, and the intermediate velocity features are shown only in the $^{12}$CO J = 3–2 map (Figure 6(b)) by green contours. The distribution...
of the 2 km s$^{-1}$ cloud is consistent with the dark lanes observable against the bright nebular background in the optical. On the other hand, cloud C has no correspondence with the optical image and is likely located in the rear of the nebula. It is interesting to note that the 2 km s$^{-1}$ cloud and cloud C have complementary distributions; cloud C is sandwiched between...
the eastern and western components of the 2 km s\(^{-1}\) cloud. The clumpy structures in the intermediate velocity range basically trace the gas distribution of the 2 km s\(^{-1}\) cloud. We find that three of the clumpy structures, dubbed BR1, BR2, and BR3 in Figure 6(b), can be identified as bridge features that connect the 2 km s\(^{-1}\) cloud and cloud C in velocity space. This can be seen in the \(^{12}\)CO \(J = 3–2\) declination–velocity diagrams in Figure 7.

Figure 6. Contour maps of the two colliding clouds are shown superimposed on the optical image of M20, where the \(^{13}\)CO \(J = 1–0\) emission is shown in (a) and \(^{12}\)CO \(J = 3–2\) in (b). The 2 km s\(^{-1}\) cloud and cloud C are plotted in blue contours and red contours, respectively. In (b) the bridge features BR1, BR2, and BR3 are added with green contours. The velocity range and the contour levels are shown in the bottom right of each panel. Dashed lines plotted in (b) indicate the integration ranges of the declination–velocity diagrams in Figure 7.

Figure 7. Declination–velocity diagrams of the \(^{12}\)CO \(J = 3–2\) emission integrated over the ranges shown in Figure 6(b) with dashed lines. The dotted line in part (C) shows the declination of HD 164492 A.

\(^{12}\)CO \(J = 3–2\) distribution. The two colliding clouds and the intermediate velocity gas have high \(R_{3–2/1–0}\), above 1.0 and up to over 2.0, throughout the present target region. That both the 2 km s\(^{-1}\) and 9 km s\(^{-1}\) clouds (cloud C and cloud S) are highly excited was already discussed in Paper I by taking ratios of \(^{12}\)CO \((J = 2–1)/(J = 1–0) (R_{3–1/1–0})\) at a larger angular resolution of 4′. The analysis of the large velocity gradient in Paper I indicates that these high \(R_{2–1/1–0}\) values of the gas are attributed to its high kinetic temperature, such as over 20 K, which is significantly higher than the typical gas temperature of
10 K in the Galactic disk without heating. Following the discussion in Paper I, the high \(R_{32}/R_{1-0}\) in clouds in M20 can also be interpreted as a high gas temperature of over 20 K. It is reasonable to presume that such a high kinetic temperature is due to heating by HD 164492 A, illumination by strong UV radiation, and/or physical interaction with the ionized gas in the H II region.

The disruptive feedback effects become more efficient in the neighborhood of HD 164492 A, and indeed the gas in the central few parsecs of HD 164492 A has been completely dissipated as seen in Figure 2(b), where the central stellar group including HD 164492 A is clear of gas and dust, and is surrounded by a curved dark lane with a radius of 0.2–0.3 pc. The northern part of the surrounding dark lane has a bright rim on its southern border, indicating illumination by strong UV radiation from HD 164492 A. A molecular counterpart of the dark lane is seen in the \(v = \pm 2\) km s\(^{-1}\) cloud at 0.5–3.5 km s\(^{-1}\) as shown in Figure 9(a). In addition, we found another hole in cloud C at 8.5–12.5 km s\(^{-1}\) as seen in Figure 9(b). Unlike the (incomplete) hole in the 2 km s\(^{-1}\) cloud, the hole in cloud C is closed with a radius of \(\sim 0.3\) pc, consistent with the radius of the hole in 2 km s\(^{-1}\) cloud. Although its center does not coincide with HD 164492 A (it is shifted toward the southwest from HD 164492 A by \(\sim 0.1\) pc), it is reasonable to suppose that

![Figure 8](image1.png)

**Figure 8.** Velocity channel map of the \(^{12}\)CO \((J = 3–2)/(J = 1–0)\) intensity ratio. Contours show the \(^{12}\)CO \(J = 3–2\) emission, which was spatially smoothed to be 3\(^{\prime}\). Plotted symbols are the same as in Figure 3.

![Figure 9](image2.png)

**Figure 9.** The two hole structures surrounding the central stars of M20 are presented in \(^{12}\)CO \(J = 3–2\). The large cross indicates HD 164492 A, and black circles and white circles depict the class I/0 and class II YSOs (Rho et al. 2006), respectively. Small crosses indicate the optical and infrared sources listed in Table 1.
the second hole was also made by feedback from HD 164492 A. This offers further support for the coexistence of the 2 km s\(^{-1}\) cloud and cloud C within the M20 nebula.

3.2. Comparisons with Infrared Sources

Associations of the infrared sources with the molecular clouds are investigated with the velocity channel maps in Figures 4, 5, and 8. We found five infrared sources that show coincidence with the \(^{12}\)CO \(J = 3-2\) clumps (see arrows in Figure 5). Three of them are the YSOs toward the dense dust cores TC1, TC2, and TC8, and associations of the class 0/I YSOs with these cores were discussed in Lefloch et al. (2008). TC1 and TC8 are seen in the 2 km s\(^{-1}\) cloud, and TC2 is in cloud S in the 9 km s\(^{-1}\) cloud. Note that TC2 corresponds to the bridge feature BR3 as seen in Figure 6. On the other hand, associations of the compact CO emission toward the remaining two sources, which correspond to IRS6 and IRS7, were not found in the dust continuum observations in Lefloch et al. (2008). These authors considered that IRS6 and IRS7 are in the latest stages of early stellar evolution when the parental envelope of the newly born stars has been almost fully photoevaporated, and hence the enhancement of the \(^{12}\)CO envelope of the newly born stars has been almost fully created by the collision. At this time, the small cloud has completely streamed into the dense shell at the interface of the collision, which corresponds to stage 2 of Figure 1.

4.1. New Analysis of the Numerical Calculations of the Cloud–Cloud Collision

In order to interpret these observational signatures, we here make comparisons with the theoretical works on cloud–cloud collision. Takahira et al. (2014) calculated collisions between two Bonnor–Ebert spheres of different size, seeded with turbulence. The surface density plots of the collision model with a colliding velocity of 10 km s\(^{-1}\) are shown in Figures 10(a) and (b). The velocity separation of the two colliding clouds in M20 is measured as \(\sim 7\) km s\(^{-1}\). Considering the viewing angle of the collision, 10 km s\(^{-1}\) is a reasonable assumption for the colliding velocity in M20. Figure 10(a) shows a snapshot prior to the collision with a viewing angle perpendicular to the collision axis, where the large cloud is at rest and the small cloud is moving rightward at 10 km s\(^{-1}\). Figure 10(b) shows a snapshot at the time when the maximum number of self-gravitating cores are formed. A cavity being created by the collision is seen in the large cloud. At this time, the small cloud has completely streamed into the dense shell at the interface of the collision, which corresponds to stage 2 of Figure 1.

Haworth et al. (2015b) carried out synthetic CO observations with the 10 km s\(^{-1}\) collision model of Takahira et al. The authors postprocessed the data shown in Figure 10(b) with the TORUS radiation transport and hydrodynamics code and produced synthetic \(^{12}\)CO \(J = 1-0\) cube data with \((x, y, v)\) axes (see Haworth et al. 2015b for the detailed setups). The output data have a spatial resolution of 0.2 pc and a velocity resolution of 0.04 km s\(^{-1}\). Figure 10(c) shows a position–velocity diagram of the resulting \(^{12}\)CO \(J = 1-0\) data. The viewing angle of the synthetic observations was set to be along the collision axis such that the clouds are coincident along the line of sight, and the position–velocity map was made by integrating along the entire X-axis. The two clouds seen in the position–velocity map are separated by \(\sim 4\) km s\(^{-1}\), which indicates the reduction in the colliding velocity, and the bridge features that connect the two clouds are seen in the intermediate velocity range (\(-3\) to \(-1\) km s\(^{-1}\)).
In Figure 11 we break down the surface density plot shown in Figure 10 into three velocity components, i.e., the large cloud at \( v_z \geq 1 \) km s\(^{-1}\) is shown in red, the small cloud at \( v_z < -3 \) km s\(^{-1}\) is in blue, and the bridge features at \(-3 \leq v_z < 1\) km s\(^{-1}\) in green. It is seen that the bridge feature is the turbulent gas that is excited at the thin boundary between the small cloud (a dense layer inside the cavity) and the large cloud. Inoue & Fukui (2013) discussed that the turbulence as well as the magnetic field can increase the effective Jeans mass to orders of magnitude above the thermal Jeans mass, leading to mass accretion rates high enough to form massive stars. Although the calculations by Takahira et al. (2014) did not include the magnetic fields, the thin turbulent layer at the interface of the two colliding clouds may provide sites of high-mass star formation.

Figure 12 shows the intensity distributions of the synthetic CO data on the \( x-y \) plane integrated over the velocity ranges of the small cloud (a), the bridge feature (b), and the large cloud (c). The large cloud overall has a ring-like distribution, which is due to the cavity created by the collision as seen in Figure 10(b). The small cloud, which corresponds to the dense compressed layer that is penetrating the large cloud, is compact and bright in the CO emission. The bridge feature, or the thin turbulent layer at the interface of the collision, consists of several filamentary structures having widths ranging from 0.2 to 1 pc. For comparisons, a three-color composite image of the small cloud (blue), the bridge feature (green), and the large cloud (red) is presented in Figure 12(d). Interestingly, the small cloud coincides with the inside of the ring of the large cloud, showing complementary distribution between the two colliding clouds. The full extent of the bridge feature is slightly larger than that of the small cloud, and hence it appears as a thin layer surrounding the small cloud.

Figure 13 shows the typical CO spectra of the synthetic \(^{12}\)CO \( J = 1-0 \) cube, where the two points marked by crosses in Figure 12(c) are selected. In the spectrum at point A, it is difficult to uniquely identify the bridge feature due to contamination of the broadened emission from the small cloud. At point B, on the other hand, the bridge feature can be distinguished as a flattened profile from the emission of the two colliding clouds.

### 4.2. Comparisons between Observations and Model

These characteristic features seen in the numerical calculations of cloud–cloud collision, i.e., the complementary distribution of the two colliding clouds, the bridge feature in the intermediate velocity range, and its flattened CO spectrum, can be seen in the present CO \( J = 1-0 \) and \( J = 3-2 \) observations. The complementary distribution between the two colliding clouds is presented in Figure 6, where cloud C is sandwiched between the eastern and western components of the 2 km s\(^{-1}\) cloud. The three bridge features BR1–BR3 identified in the \(^{12}\)CO \( J = 3-2 \) data (Figure 6(b)) are distributed on the rim of or just outside cloud C. The CO spectra of the three bridge features are shown in Figure 14. The profiles of the BR1 and BR2 spectra are similar to the model profile at point B in Figure 13, which is flattened in the intermediate velocity range, while the profile in BR3 looks similar to that at point A. All of these observed signatures lend strong support to the cloud–cloud collision scenario in M20.

We note that the numerical calculations by Takahira et al. (2014) do not include magnetic fields. Inoue & Fukui (2013) pointed out that the magnetic field plays a critical role in forming the dense cores in the turbulent layer at the interface of the collision. Future numerical calculations of the cloud–cloud collision including the magnetic field are necessary to fully understand the morphological structures and kinematics of the turbulent layer (i.e., the bridge features) between the colliding clouds. In addition, the present spatial resolutions of the ASTE and Mopra data are not high enough to resolve the bridge features in M20 in order to investigate the filamentary inner structures as seen in the model data (Figure 12(b)). However, it is interesting to note that the dark dust lanes seen in the optical image in Figure 2 show entangled filamentary structures toward the complementary distribution between the 2 km s\(^{-1}\) cloud and cloud C. Future ALMA observations will allow us to investigate the inner structures of the colliding regions and to make detailed comparisons with the theoretical works to reproduce the dense clumps, the precursors of the O stars.

### 4.3. Cloud–Cloud Collision in M20

In Table 2 we summarize the physical parameters of the cloud–cloud collisions measured in the previous studies and in this study. The masses of the 2 km s\(^{-1}\) cloud and cloud C in M20 are each estimated to be \( 10^3 M_\odot \) for an assumed distance of 1.7 kpc, where we assume an X-factor, the empirical conversion factor from the integrated intensity of \(^{12}\)CO \( J = 1-0 \) to the \( N(H_2) \) column density, of \( 2 \times 10^{20} \text{cm}^{-2} (\text{K km s}^{-1})^{-1} \) (Strong et al. 1988). These figures are consistent with the estimate in Paper I. The \( N(H_2) \) column density is measured to be \( 10^{22} \text{cm}^{-2} \) for both clouds. Fukui et al. (2016) considered that the \( N(H_2) \) column density is the critical parameter in the cloud–cloud collision scenario and determines the difference between the formation of a single O star and massive star clusters, and \( 10^{22} \text{cm}^{-2} \) is the threshold for forming massive star clusters such as RCW 38 via cloud–cloud collision. Our results for M20, which harbors one single O star, are consistent with the discussion by Fukui et al. (2016). The masses and column densities of the colliding clouds in M20 are smaller than those in any of the other regions listed in Table 2, although the classification of the formed O star is earlier than the O8V or O9V star in RCW 120.
The timescale of the cloud–cloud collision in M20 can be calculated from the physical separation and the relative velocity of the two colliding clouds. Since the 2 km s\(^{-1}\) cloud and cloud C are both embedded within the H\(\text{II}\) region of M20, the distance between the two is limited to within 3–4 pc, which is the size of the nebula in M20. If we tentatively assume that the

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**Figure 12.** Spatial distributions of the synthetic CO \(J = 1-0\) data of the collision model in Figure 10(b) are shown in (a)–(c) for three different velocity ranges. The velocity components of the small cloud and the large cloud are shown in (a) and (c), respectively, while the components at intermediate velocities between those of the two clouds are in (b). The two crosses in (b) indicate the positions of points A and B, whose spectra are shown in Figure 13. (d) Three-color composite image of the three velocity components in (a)–(c). Red: (a), green: (b), blue: (c).

**Figure 13.** Example spectra of the synthetic CO \(J = 1-0\) data toward the crosses in Figure 12(c). The velocity ranges of the small and large clouds are shaded in blue and red, respectively. The bridge features in the intermediate velocity range have flattened profiles and can be distinguished from the components of the small and large clouds.
viewing angle of the collision in M20 is 45° and that the relative velocity of the two colliding clouds is ~10 km s⁻¹, then the timescale of the collision is estimated to be less than 0.3–0.4 Myr, which is consistent with the age of M20 measured from the size of the H II region by Cernicharo et al. (1998).

The formation of low-mass stars is another intriguing topic in M20 (Lefloch et al. 2002, 2008; Rho et al. 2006). Lefloch et al. (2008) argued that the filaments that trisect the optical nebula in M20 were probably self-gravitating too before the birth of M20, and that the fragmentation of the filament that may lead to the YSO formation can be accounted for by MHD-driven instabilities, not by the shock interactions with the expanding H II region. The growth timescale of the MHD instabilities is estimated to be as large as 1 Myr, suggesting that the fragmentation would have started before the onset of photonization. However, it may well be that the fragmentation occurred at an early evolutionary stage of the cloud–cloud collision. This hypothesis raises the possibility that the cloud–cloud collision that triggered the formation of HD 164492 A might accelerate the subsequent formation and evolution of the cores in the fragments. It is interesting to note a speculation that this is the case in the cold dust core TC1 in the eastern lane of the filaments, which harbors a class 0/I YSO (Lefloch et al. 2008). Our results indicate that the bridge feature BR3 is spatially well correlated with TC1 as shown in Figure 6. The existence of the bridge feature indicates the existence of turbulent gas excited by the cloud–cloud collision, suggesting the possibility that the TC2 core evolved in conditions affected by the cloud–cloud collision, although we cannot exclude the idea that the central object of TC2 was already well evolved before the collision.

### 5. Summary

The conclusions of the present study are summarized as follows:

1. We performed high-resolution CO $J = 1−0$ and CO $J = 3−2$ observations toward the two colliding molecular clouds in the Galactic H II region M20 with Mopra and ASTE. The two clouds are resolved into details, allowing us to make direct comparisons with the optical image of M20.
2. We identified two peculiar molecular gas structures in the two colliding clouds, the 2 km s⁻¹ cloud and cloud C. One is the spatially complementary distribution. Cloud C coincides with the gap in the center of the 2 km s⁻¹ cloud and appears to be sandwiched between its eastern and western components. The other is the bridge feature that

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**Table 2**

Comparisons between Cloud–Cloud Collision Regions

| Name          | Cloud Mass $(x 10^3 M_\odot)$ | Molecular Column Density $(x 10^{22}$ cm⁻²) | Relative Velocity (km s⁻¹) | Complementary Distribution | Bridge Feature | Cluster Age | # of O Stars | References |
|---------------|--------------------------------|---------------------------------------------|---------------------------|----------------------------|----------------|-------------|--------------|------------|
| RCW 38        | (20, 3)                        | (10, 1)                                    | 12                        | no                         | yes            | ~0.1        | ~20          | 1          |
| NGC 3603      | (70, 10)                       | (10, 10)                                   | 15                        | yes                        | yes            | ~2          | ~30          | 2          |
| Westerlund 2  | (90, 80)                       | (20, 2)                                    | 16                        | yes                        | yes            | ~2          | 14           | 3, 4       |
| [DBS2003]179  | (200, 200)                     | (8, 5)                                     | 20                        | yes                        | yes            | ~5          | >10          | 5          |
| ONC (M42)     | (20, 3)                        | (20, 1)                                    | $\sim 7^a$                | yes                        | no             | <1          | ~10          | 6          |
| ONC (M43)     | (0.3, 0.2)                     | (6, 2)                                     | ...                       | yes                        | no             | ...         | 1           | ...        |
| RCW 120       | (50, 4)                        | (3, 0.8)                                   | 20                        | yes                        | yes            | ~0.2        | 1            | 7          |
| N159W-South   | (9, 6)                         | (10, 10)                                   | $\sim 8^b$                | no                         | no             | ~0.06       | 1            | 8          |
| N159E-Papillon| (5, 7, 8)                      | (4, 4, 6)                                  | $\sim 9^c$                | no                         | no             | ~0.2        | 1            | 9          |
| M20           | (1, 1)                         | (1, 1)                                     | 7.5                       | yes                        | yes            | ~0.3        | 1            | This study, 10 |

Note. Columns: (1) Name, (2, 3) Molecular masses and column densities of the two/three colliding clouds, (4) Relative velocity between the colliding clouds, (7, 8) Age and the number of O stars.

$^a$ Corrected for the projection.

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. (2016, in preparation); (6) Y. Fukui et al. (2016, in preparation); (7) Torii et al. (2015); (8) Fukui et al. (2015); (9) Saigo et al. (2016); (10) Torii et al. (2011).
connects the two clouds in velocity space. We identified three bridge features BR1–BR3. They are located around the sides of cloud C. These structures strongly indicate that, although they are separated by \( \sim 7 \text{ km s}^{-1} \), the two colliding clouds are physically associated with each other.

3. In order to interpret these observed structures, we make a new analysis of the model CO \( J = 1 \rightarrow 0 \) data generated by Haworth et al. (2015b) with the 10 km s\(^{-1}\) collision model calculated in Takahira et al. (2014). As a result, we reproduce similar gas structures to those found in the present observations such as the complementary distribution and the bridge features, where the complementary distribution can be accounted for by the cavity created by the collision between two dissimilar clouds, and the bridge feature by the turbulent gas excited in the thin layer at the interface of the collision. Our new results lend support to the cloud–cloud collision scenario in M20.

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