ALMA CO Observations of a Giant Molecular Cloud in M33: Evidence for High-Mass Star Formation Triggered by Cloud-Cloud Collisions

Hidetoshi SANO1,2, Kisetsu TSUGE2, Kazuki TOKUDA3,4, Kazuyuki MURAOKA4, Kengo TACHIHARA2, Yumiko YAMANE2, Mikito KOKNO2, Shinji FUJITA2, Rei ENOKIYA2, Gavin ROWELL5, Nigel MAXTED6, Miroslav D. FILIPOVIC7, Jonathan KNIES8, Manami SASAKI8, Toshikazu ONISHI4, Paul P. PLUCINSKY9 and Yasuo FUKUI1,2

1Institute for Advanced Research, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8601, Japan
2Department of Physics, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8601, Japan
3National Astronomical Observatory of Japan, Mitaka, Tokyo 181-8588, Japan
4Department of Physical Science, Graduate School of Science, Osaka Prefecture University, 1-1 Gakuen-cho, Naka-ku, Sakai, Osaka 599-8531, Japan
5School of Physical Sciences, The University of Adelaide, North Terrace, Adelaide, SA 5005, Australia
6School of Science, University of New South Wales, Australian Defence Force Academy, Canberra ACT 2600, Australia
7Dr. Karl Remeis-Sternwarte, Erlangen Centre for Astroparticle Physics, Friedrich-Alexander-Universität Erlangen-Nürnberg, Sternwartstraße 7, D-96049 Bamberg, Germany
8Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA 02138, USA

E-mail: sano@a.phys.nagoya-u.ac.jp

Received; Accepted

Abstract

We report the first evidence for high-mass star formation triggered by collisions of molecular clouds in M33. Using the Atacama Large Millimeter/submillimeter Array, we spatially resolved filamentary structures of giant molecular cloud 37 in M33 using 12CO(J = 2–1), 13CO(J = 2–1), and C18O(J = 2–1) line emission at a spatial resolution of ~ 2 pc. There are two individual molecular clouds with a systematic velocity difference of ~ 6 km s−1. Three continuum sources representing up to ~ 10 high-mass stars with the spectral types of B0V–O7.5V are embedded within the densest parts of molecular clouds bright in the C18O(J = 2–1) line emission. The two molecular clouds show a complementary spatial distribution with a spatial displacement of ~ 3.5 pc, and show a V-shaped structure in the position-velocity diagram. These observational features traced by CO and its isotopes are consistent with those in high-mass star-forming regions created by cloud-cloud collisions in the Galactic and Magellanic Cloud Hα regions. Our new finding in M33 indicates that the cloud-cloud collision is a promising process to trigger high-mass star formation in the Local Group.
**Key words:** ISM: H\textsc{i} regions—Stars: formation—ISM: individual objects (M33, M33GMC 37)

1 Introduction

It is a long-standing question how high-mass stars are formed in galaxies. Three different hypothesis are thought to be mechanisms of the high-mass star formation: the monolithic collapse, competitive accretion, and the stellar mergers (e.g., Zinnecker, & Yorke 2007 and references therein). However, these theoretical models have remained controversial due to lacking conclusive observational evidence.

Recently, an alternative idea of high-mass star formation triggered by “cloud-cloud collisions” has received much attention since the discovery of 50 or more pieces of observational evidence (e.g., Y. Fukui et al. 2019 in preparation and references therein). The colliding clouds have a supersonic velocity difference with an intermediate velocity component—bridging feature—created by the collisional deceleration. The complementary spatial distribution of two clouds is one of the important signatures of collisions because one of the colliding clouds can create a hollowed-out structure in the other cloud. Furthermore, a V-shaped structure can be seen in the position-velocity diagram due to the deceleration and hollowed-out structure. Theoretical studies also support these observational signatures, and predict that cloud-cloud collision increases the effective Jeans mass so high-mass stars can form the high-mass stars in the shock-compressed layer (e.g., Habe & Ohta 1992; Anathpindika 2010; Inoue & Fukui 2013; Takahira et al. 2014; Shima et al. 2018; Inoue et al. 2018).

Investigating the universality of the cloud-cloud collision scenario, we need further observational examples under various environments and their scales. In the individual Galactic star-forming regions such as Orion and Vela, the high-mass star formation can be understood by at least five cloud-cloud collisions on \(\sim 1-100\) pc scales (Fukui et al. 2016, 2018a; Tsutsumi et al. 2017; Sano et al. 2018; Hayashi et al. 2018; Enokiya et al. 2018). It is remarkable that collisions of molecular clouds are seen not only in our Milky Way, but also in the Magellanic Clouds (e.g., Fukui et al. 2015; Saigo et al. 2017). Furthermore, the tidally driven galactic-scale (a few kpc scales!) collisions of \(\text{H}^\text{i}\) clouds are found in the Magellanic and M31–M33 systems (Fukui et al. 2017, 2018b; Tsuge et al. 2019; Tachihara et al. 2018; Tokuda et al. 2018a). We can therefore reveal sites of cloud-cloud collisions even in external galaxies if the spatial resolution of CO/\(\text{H}^\text{i}\) data is high enough (e.g., a few pc scales).

Here, we report the first evidence for the high-mass star formation triggered by collisions of molecular clouds in M33. Sections 2 and 3 describe observations and data reduction of the ALMA CO and continuum datasets and their results. Section 4.1 gives properties of high-mass stars in the region; Section 4.2 presents a possible scenario of cloud-cloud collision as the formation mechanism of high-mass stars. A summary and conclusions are provided in Section 5.

2 Observations and Data Reduction

We carried out ALMA Band 6 (211–275 GHz) observations toward M33GMC 37 in Cycle 6 as part of the CO survey toward the SNRs in M33 (PI: H. Sano, #2018.1.00378.S). We used the single-pointing observation mode with 45–49 antennas of the 12-m arrays. The center position of the pointing is \((\alpha_{2000}, \delta_{2000}) \sim (01^\text{h}33^\text{m}35^\text{s}9, 30^\circ36'27'\text{''}5)\). There were two spectral windows including the \(^{12}\text{CO}(J = 2–1), ^{13}\text{CO}(J = 2–1),\) and \(^{18}\text{O}(J = 2–1)\) line emission with a bandwidth of 117.19 MHz. The frequency resolution was 70.6 kHz for \(^{12}\text{CO}(J = 2–1)\) and 141.1 kHz for \(^{13}\text{CO}(J = 2–1)\) and \(^{18}\text{O}(J = 2–1)\). We also observed two spectral windows as continuum bands, of which frequency ranges are 231.0–233.0 GHz and 216.3–218.2 GHz. Although these continuum bands contain line emission of H(30\iota) and SiO(\(J = 5–4)\), we could not detect the two lines significantly.

The data reduction was performed using the Common Astronomy Software Application (CASA; McMullin et al. 2007) package version 5.5.0. We used the “multiscale CLEAN” algorithm implemented in the CASA package (Cornwell 2008). The synthesized beam of final dataset is \(0.''59 \times 0.''42\) with a position angle (P.A.) of \(0.''4\) for \(^{12}\text{CO}(J = 2–1)\), \(0.''62 \times 0.''44\) with a P.A. of \(0.''1\) for \(^{13}\text{CO}(J = 2–1)\), \(0.''63 \times 0.''44\) with a P.A. of \(1.''1\) for \(^{18}\text{O}(J = 2–1)\), and \(0.''59 \times 0.''43\) with a P.A. of \(-1.''4\) for the 1.3 mm continuum. The typical spatial resolution is \(\sim 2\) pc at the distance of M33 (817 \pm 59 kpc, Freedman et al. 2001). The typical noise fluctuations of the line emission and continuum are \(\sim 0.15\) K at the velocity resolution of 1 km s\(^{-1}\) and 0.017 mJy beam\(^{-1}\), respectively. To estimate the missing flux density, we used the \(^{12}\text{CO}(J = 2–1)\) dataset obtained with the IRAM 30-m radio telescope (Gratier et al. 2010; Druard et al. 2014). Following the methods of Druard et al. (2014), we applied a forward efficiency of
0.92 and a main beam efficiency of 0.56 to convert the main beam temperature scale. We compared the integrated intensities of IRAM and ALMA CO data that are smoothed to match the FWHM resolution of 12″. As a result, we found no significant difference within the error margin, and hence the missing flux density is considered to be negligible.

3 Results

Figure 1a shows an optical composite image of M33 obtained with the VLT Survey Telescope (VST). The ALMA FoV includes several Hα regions located in a spiral arm near the galactic center. Figure 1b shows a large-scale map of ALMA 12CO(J = 2–1) superposed on Hα contours. A giant molecular cloud (GMC)—M33GMC 37—is mainly located on the western-half of the ALMA FoV with filamentary structures. Some of CO filaments are likely associated with M33SNR 35, which will be described in a forthcoming paper (H. Sano et al. in preparation). We also note that a bright Hα source with two local peaks at the positions of (α2000, δ2000) ~ (01h33m35s24, 30°36′28″0) and (01h33m35s20, 30°36′26″3) are superposed on the GMC.

To derive the mass of GMC, we used the following equations:

$$M = m_\text{H} D^2 \Omega \sum_i [N_i(H_2)],$$  

$$N(H_2) = X_{\text{CO}} \cdot W(\text{CO}_{10}),$$

where $m_\text{H}$ is the mass of hydrogen, $\mu$ is the mean molecular weight of ~2.74, $D$ is the distance to M33 in units of cm, $\Omega$ is the solid angle of each data pixel, $N_i(H_2)$ is the column density of molecular hydrogen for each data pixel $i$ in units of cm$^{-2}$, $X$ is the CO-to-H$_2$ conversion factor in units of (K km s$^{-1}$)$^{-1}$ cm$^{-2}$, and $W(\text{CO}_{10})$ is integrated intensity of 12CO($J = 1–0$) line emission. In the present study, we adopt $D = 2.5 \times 10^{24}$ cm, corresponding to the distance of 817 kpc (Freedman et al. 2001). Following the previous study by Gratier et al. (2012), we used $X = 4.0 \times 10^{20}$ (K km s$^{-1}$)$^{-1}$ cm$^{-2}$. We also derived a typical intensity ratio of 12CO($J = 2–1$) / 12CO($J = 1–0$) ~ 0.7 toward M33GMC 37 through the comparison with an archival 12CO($J = 1–0$) cube data obtained with the Nobeyama Radio Observatory 45-m telescope (Tosaki et al. 2011). Finally, the derived size and mass of the GMCs are ~60 pc and ~5 × 10$^5 M_\odot$, respectively. These values are roughly consistent with the previous study by Miura et al. (2012) using the Atacama Submillimeter Telescope Experiment.
size of $63 \times 54$ pc and virial mass of $(6.7 \pm 4.8) \times 10^5 M_\odot$.

Figure 2a shows an enlarged view of M33GMC 37. The $^{12}$CO($J = 2$–$1$) clouds (red color) are detected as diffuse emission with a ring-like structure in southwest, while the $^{13}$CO($J = 2$–$1$) clouds (green color) are concentrated in the central region of GMC where the $^{12}$CO($J = 2$–$1$) clouds are also bright. There are three bright sources in 1.3 mm continuum—GMC37-MMSs 1–3 (hereafter refer to as MMSs 1–3)—, which are detected at a 5σ level or higher. The basic physical properties of three continuum sources are listed in Table 1. The peak brightness temperatures of the three sources are comparable, but the spatial extent of MMS 2 is twice as large than that of MMSs 1 and 3.

It is possible that these radio continuum sources are physically related to the Hα emission. In particular, two of them (MMSs 2 and 3) are located in the vicinity of the two Hα peaks associated with the brightest CO cloud, indicating that the exciting stars of MMSs 2–3 and Hα peaks are the same. These regions are also bright in the Spitzer 24 μm image (Verley et al. 2007).

The typical CO spectra of positions A and B vicinity of MMSs 2–3 are also shown in Figures 2b and 2c. We find double-peak profiles in both the $^{12}$CO($J = 2$–$1$) and $^{13}$CO($J = 2$–$1$) line emission in the position A, suggesting that there are two individual clouds toward the line-of-sight. We hereafter refer to the component at $V_{\text{LSR}} = -143.0$–$134.0$ km s$^{-1}$ as the “blue cloud” and that at $V_{\text{LSR}} = -133.0$–$-127.0$ km s$^{-1}$ as the “red cloud.” We also find that the brightest CO cloud—position B—is significantly detected not only in $^{12}$CO($J = 2$–$1$), but also in C$^{18}$O($J = 2$–$1$). Their central velocities of $V_{\text{LSR}} \sim -133.5$ km s$^{-1}$ are roughly corresponding to the mean velocity of red and blue clouds.

Figures 3a and 3b show spatial distributions of blue and

| Table 1. Physical properties of 1.3 mm continuum sources |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| Name            | $\alpha_{\text{J2000}}$ | $\delta_{\text{J2000}}$ | $T_{\text{peak}}$ | Size |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| GMC37-MMS 1     | 01 33 35.219    | 30 36 29.0      | 0.12            | 1.7             |
| GMC37-MMS 2     | 01 33 35.219    | 30 36 27.8      | 0.13            | 3.0             |
| GMC37-MMS 3     | 01 33 35.220    | 30 36 26.4      | 0.11            | 1.6             |

Note. — Col. (1): Name of radio continuum source. Cols. (2–3) Positions of the maximum intensity. Col. (4): Maximum brightness temperature. Col. (5): Size of continuum source defined as $(S/\pi)^{0.5} \times 2$, where $S$ is the total surface area of continuum source surrounded by a contour of the 5σ level.
red clouds. The blue cloud is elongated in the northwestern direction, while the red cloud is stretched in the southwestern direction. Both clouds have filamentary CO structures. The typical width and length of filaments are $\sim 3$ pc and $\sim 10$ pc, respectively. The total mass is estimated to be $\sim 2.4 \times 10^5 \, M_\odot$ for the blue cloud and $\sim 1.9 \times 10^5 \, M_\odot$ for the red cloud using equations (1) and (2). Note that the continuum peaks are likely associated not only with the brightest peak of blue cloud, but also with that of red cloud. The peak column density of molecular hydrogen is $\sim 4.5 \times 10^{22} \, \text{cm}^{-2}$ for the blue-cloud, and $\sim 4.1 \times 10^{22} \, \text{cm}^{-2}$ for the red-cloud. We also find a small hole-like structure in the blue cloud centered at $(\alpha_{J2000}, \delta_{J2000}) \sim (01^h35^m35^s, 30^\circ36'27''.1)$. Note that the peak positions of Hα and radio continuum are placed on the edge of the hole-like structure, not on the center of it.

Figure 4 shows the position–velocity diagram of $^{12}$CO$(J = 2\rightarrow1)$. The integration range in Right Ascension is from 01$^h$33$m$35$^s$.243 to 01$^h$33$m$35$^s$.341, corresponding to the spatial extent of the small hole-like structure appeared in the blue cloud (see also Figure 3a). The blue cloud is clearly seen whose radial velocity is centered at $V_{\text{LSR}} \sim -137 \, \text{km s}^{-1}$. We find a V-shaped structure in the position–velocity diagram (see dashed black lines in Figure 4). The center velocity of red cloud ($V_{\text{LSR}} \sim -132 \, \text{km s}^{-1}$) is corresponding to the vertex of the V-shaped structure. The cavity-like structure and intensity peak of $^{12}$CO$(J = 2\rightarrow1)$ are seen at $(\delta_{J2000}, V_{\text{LSR}}) \sim (30^\circ36'27''.1, -135.0 \, \text{km s}^{-1})$ and $\sim (30^\circ36'26''.0, -134.0 \, \text{km s}^{-1})$, respectively.

Fig. 3. Integrated intensity maps of $^{12}$CO$(J = 2\rightarrow1)$. The velocity range is $-143$ to $-134 \, \text{km s}^{-1}$ for (a) and $-133$ to $-127 \, \text{km s}^{-1}$ for (b). The vertical dashed lines indicate the integration velocity range for Figure 4. The crosses represent peaks positions of 1.3 mm continuum. The white contours indicate Hα emission as shown in Figure 1b. The scale bar and beam size are also shown in the bottom and top right corners for each panel.

Fig. 4. Declination–velocity diagram of $^{12}$CO$(J = 2\rightarrow1)$. The integration range is from 01$^h$33$m$35$^s$.243 to 01$^h$33$m$35$^s$.341. The vertical lines indicate integration velocity ranges for Figure 3. The three allows indicate the Declination positions of MMS 1–3. The beam size is shown in the top right corner.
4.1 Presence of high-mass stars and their spectral types

Although there is no previous study of the stars embedded within the H\(\alpha\) region in M33, detection of bright H\(\alpha\) emission, 1.3 mm continuum sources MMSs 1–3, and 24 \(\mu\)m emission indicates several high-mass stars are associated with the two molecular clouds. To confirm the presence of high-mass stars, we compared them with archival optical datasets obtained with the Hubble Space Telescope (HST). Figure 5 shows the high-spatial resolution optical images obtained with the HST WFPC2 and WFC3 detectors. We can clearly see \(\sim 10\) high-mass stars bright in the U-band, H\(\alpha\), and IR-band within the Kitt Peak National Observatory (KPNO) H\(\alpha\) contours. Hereafter, we assume that ten high-mass stars are associated with the H\(\alpha\), 1.3 mm continuum sources, and 24 \(\mu\)m emission.

According to Verley et al. (2007), the luminosity of the 24 \(\mu\)m emission is \(\sim 1.7 \times 10^{38}\) erg s\(^{-1}\) and that of the H\(\alpha\) emission is \(\sim 4.6 \times 10^{37}\) erg s\(^{-1}\) using the Spitzer MIPS and KPNO H\(\alpha\) datasets. To estimate the spectral types of high-mass stars, we used two different methods. One estimates the total infrared luminosity \(L(TIR)\) using the measured 24 \(\mu\)m luminosity \(L(24 \mu m)\) and the following equation (Verley et al. 2007):

\[
\log L(TIR) = \log L(24 \mu m) + 0.908
\]

The total infrared luminosity of the high-mass stars is estimated to be \(\sim 1.4 \times 10^{39}\) erg s\(^{-1}\), which corresponds to ten O7.5V stars (Martins et al. 2005), assuming that the ten high-mass stars have the same spectral types.

The other method is utilized Lyman continuum luminosities \(N_{\text{Lyman}}\) (in units of photons) that are derived from extinction corrected H\(\alpha\) luminosities \(L_{\text{H\alpha}}\) (in units of erg s\(^{-1}\)) using the following equation (Mayya & Prabhu 1996):

\[
N_{\text{Lyman}} = 7.3 \times 10^{14} L_{\text{H\alpha}}
\]

We then obtain \(N_{\text{Lyman}} = 1.1 \times 10^{49}\) photons, corresponding to ten B0V stars (Martins et al. 2005). To summaries, the spectral types of high-mass stars embedded within M33 GMC 37 are estimated to be B0V–O7.5V assuming that there are ten high-mass stars with the same spectral types. Further detailed photometric and spectroscopic observations are needed to clarify the number of high-mass stars and their spectral types.

4.2 High-mass Star Formation Triggered by Cloud-Cloud Collisions in M33 GMC 37

In the present study, we spatially resolved filamentary CO structures of M33 GMC 37 using ALMA with spatial resolution of \(\sim 2\) pc (\(\Delta\theta \sim 0.5''\)). There are two individual molecular clouds—red and blue clouds—with a velocity separation of \(\sim 6\) km s\(^{-1}\) and the mass of \(\sim 2 \times 10^5\) \(M_\odot\) for each. The densest part of the GMC is significantly detected in C\(^{18}\)O(\(J = 2\rightarrow 1\)), containing up to \(\sim 10\) high-mass stars with the spectral types of B0V–O7.5V.

To form high-mass stars via cloud-cloud collisions, a supersonic velocity separation of two colliding clouds is essential. According to magnetohydrodynamical numerical simulations, the effective Jeans mass in the shock-compressed layer is proportional to the third power of the effective sound speed (Inoue & Fukui 2013). Here, the effective sound speed is defined as \(< c_s^2 + c_A^2 + \Delta v^2 >^{0.5}\), where \(c_s\) is the sound speed, \(c_A\) is the Alfvén speed, and \(\Delta v\) is the velocity dispersion. A supersonic velocity separation of at least a few km s\(^{-1}\) therefore produces a large
mass accretion rate on the order of $\sim 10^{-4} - 10^{-3} M_\odot $ yr$^{-1}$, which allows mass growth of stars against the stellar feedback (Inoue & Fukui 2013). For the case of M33GMC 37, the observed velocity separation of red and blue clouds is $\sim 6$ km s$^{-1}$ (see CO spectra in Figure 2b). Although the velocity separation will be changed due to the projection effect, this is roughly consistent with the typical velocity separation in the Galactic high-mass star forming regions triggered by cloud-cloud collisions: e.g., M20 ($\sim 7.5$ km s$^{-1}$, Torii et al. 2011), RCW 36 ($\sim 5$ km s$^{-1}$, Sano et al. 2018), M42 ($\sim 7$ km s$^{-1}$, Fukui et al. 2018a), and RCW 166 ($\sim 5$ km s$^{-1}$, Ohama et al. 2018).

Another important signature of a collision is complementary spatial distribution of colliding clouds. In general, colliding clouds are not the same size, such as simulated by Habe & Ohta (1992) and Anathpindika (2010). In fact, observational results indicate that colliding clouds have different sizes, morphologies, and density distributions (e.g., Hasegawa et al. 1994; Furukawa et al. 2009; Fukui et al. 2014, 2018a, 2018c; Enokiya et al. 2018, Tokuda et al. 2018b, Dewangan et al. 2019a, 2019b). In such cases, one of the colliding clouds can create a hole-like structure in the other cloud, if the colliding cloud has a denser part and/or smaller size than the other cloud. This produces the complementary spatial distribution of two clouds with different systematic velocity. Furthermore, the angle of two colliding clouds $\theta$ is generally not 0 degrees or 90 degrees relative to the line-of-sight. It means that we can also observe a spatial displacement between the complementary distributions of two clouds.

In M33GMC 37, we find complementary spatial distributions of red and blue clouds with a spatial displacement. Figure 6 shows the map of blue cloud superposed on the red cloud contours with the spatial displacement of $\sim 3.5$ pc toward the direction of southeast, following the method of Fukui et al. (2018a). The brightest peak of the red cloud is fits within the hole-like structure of the blue cloud. The second and third minor peaks of the red cloud also show good complementary distributions with the blue cloud. Note that the 1.3 mm continuum sources MMSs 1–3 are also located as the edges of both the blue and red clouds, suggesting that the high-mass stars were possibly formed by strong gas compression / accretion via the cloud-cloud collision. We also estimate the collision time scale to be $\sim 0.5$ Myr assuming the collision angle $\theta = 45$ degree. It is consistent with the presence of dense molecular clouds surrounding the high-mass stars and small Hα regions with a few pc extent in Hα emission because of young age of high-mass stars (see Figures 1b and 3).

We next focus on the velocity structures of colliding two clouds. Previous numerical simulations and observational results demonstrated that colliding clouds create an intermediate velocity component—bridging feature—connecting two clouds due to the deceleration by collisions, if the projected velocity separation is significantly larger than the linewidth of colliding clouds (see Fukui et al. 2018a and references therein). When the two colliding clouds have roughly the same column density of gas, the two clouds will be merged and appears as a single peak CO profile centered at the mean velocity of the two colliding clouds (e.g., Fukui et al. 2017). In the case of M33GMC 37, the $V_{\text{LSR}} \sim -135$ km s$^{-1}$ feature in the $^{13}$CO spectrum at the position A is possibly a bridging feature (see Figure 2b), but is not significantly detected because of the small velocity separation of the two colliding clouds. However, CO spectra in the position B—the densest part of the colliding clouds—show the single peak CO profiles centered at $V_{\text{LSR}} \sim -133.5$ km s$^{-1}$, roughly corresponding to the mean velocity of the red and blue clouds (see also Figure 2c). It is consistent that the two clouds have roughly the same column density of $\sim 4-5 \times 10^{22}$ cm$^{-2}$, assuming the cloud-cloud collision has occurred.

The V-shaped structure in the position–velocity diagram as shown in Figure 4 provides us with suggestive ev-
idence for the cloud-cloud collision. As discussed above, an intensity depression or a hole-like structure might indicate the spot of collision between two clouds. If we make a position–velocity diagram that includes the collision region, we can find not only the bridging feature but also the V-shaped structure in the position–velocity diagram (e.g., Fukui et al. 2018a, 2018d, 2018e; Hayashi et al. 2018; Torii et al. 2018a, 2018b; Fujita et al. 2019b). For M33GMC 37, we can clearly see the V-shaped structure connecting the red and blue clouds as the intermediate velocity component that is called the bridging feature. Moreover, the presence of an intensity peak and depression in the V-shaped structure is predicted by the synthetic observations of a theoretical result of cloud-cloud collisions (e.g., Fukui et al. 2018d).

We also note that the number of high-mass stars ($<10$) in M33GMC 37 is consistent with previous observational studies of cloud-cloud collisions. According to Fukui et al. (2018a), the formation of super star clusters containing more than ten O-type stars requires collisions of two dense clouds, one of which has a high column density of at least $\sim 10^{23}$ cm$^{-2}$ (e.g., RCW 38, Fukui et al. 2016; NGC 3603, Fukui et al. 2014; Westerlund 2, Furukawa et al. 2009). On the other hand, the formation of single or a few O-type stars happens in a collision between molecular clouds with low column density of several $10^{22}$ cm$^{-2}$ or less (e.g., RCW 120, Torii et al. 2015; NGC 2359, Sano et al. 2017; S44, Kohno et al. 2018b; N4, Fujita et al. 2019a, more detailed results are summarized in R. Enokiya et al. submitted). For M33GMC 37, the two colliding clouds have a low column density of $\sim 4.5 \times 10^{22}$ cm$^{-2}$. Therefore, cloud-cloud collisions in M33GMC 37 can create $\sim 10$ high-mass stars at most. This is consistent with $\sim 10$ stars that are detected by HST optical images within the KPNO Hα boundary (see Figure 5).

To summarize, the red and blue clouds in M33GMC 37 fulfill four requirements of high-mass star formation triggered by cloud-cloud collisions as follows: (1) a super sonic velocity separation of two clouds, (2) complementary spatial distribution with a displacement of colliding clouds, (3) a presence of a bridging feature connecting the two clouds in velocity space, and (4) V-shaped structure in the position–velocity diagram. We therefore suggest that the high-mass stars corresponding to ten B0V–O7.5V types in M33GMC 37 were formed by cloud-cloud collisions. Further ALMA observations of M33 GMCs will allow us to study high-mass star formation via the cloud-cloud collisions in the spiral galaxy, the results of which can be directly compared with that of the Milky Way and Magellanic Clouds.

5 Conclusion

In the present study, we carried out new CO($J = 2$–1) and continuum observations of M33GMC 37 using ALMA with the angular resolution of $\sim 0''75$, corresponding to the spatial resolution of $\sim 2$ pc at the distance of M33. We revealed two individual molecular clouds with a velocity separation of $\sim 6$ km s$^{-1}$ that are associated with up to $\sim 10$ high-mass stars having the spectral types of B0V–O7.5V. The two molecular clouds show complementary spatial distribution with the spatial displacement of $\sim 3.5$ pc. The intermediate velocity component of the two clouds as the V-shaped structure in the position–velocity diagram is also detected. We propose a possible scenario that the high-mass stars in M33GMC 37 were formed by cloud-cloud collisions approximately 0.5 Myr ago.

Acknowledgments

This paper makes use of the following ALMA data: ADS/JAO. ALMA#2018.1.00378.S. ALMA is a partnership of ESO (representing its member states), NSF (USA) and NINS (Japan), together with NRC (Canada) and MOST and ASIAA (Taiwan) and KASI (Republic of Korea), in cooperation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AU/NRAO, and NAOJ. Based on observations made with the NASA/ESA Hubble Space Telescope, and obtained from the Hubble Legacy Archive, which is a collaboration between the Space Telescope Science Institute (STScI/NASA), the Space Telescope European Coordinating Facility (ST-ECF/ESA) and the Canadian Astronomy Data Centre (CADC/NRC/CSA). This study was financially supported by Grants-in-Aid for Scientific Research (KAKENHI) of the Japanese Society for the Promotion of Science (JSPS, grant Nos. 16K17664, 18J01417, and 19K14758). K. Tokuda was supported by NAOJ ALMA Scientific Research Grant Number of 2016-03B. M.S. acknowledges support by the Deutsche Forschungsgemeinschaft through the Heisenberg professor grants SA 2131/5-1 and 12-1.

References

Anathpindika, S. V. 2010, MNRAS, 405, 1431
Cornwell, T. J. 2008, IEEE Journal of Selected Topics in Signal Processing, 2, 793
Dewangan, L. K., Ojha, D. K., Baug, T., et al. 2019a, ApJ, 875, 138
Dewangan, L. K., Sano, H., Enokiya, R., et al. 2019b, ApJ, 878, 26
Drude, C., Braine, J., Schuster, K. F., et al. 2014, A&A, 567, A118
Enokiya, R., Sano, H., Hayashi, K., et al. 2018, PASJ, 70, S49
Freedman, W. L., Madore, B. F., Gibson, B. K., et al. 2001, ApJ, 553, 47
Fukui, Y., Ohama, A., Hanaoka, N., et al. 2014, ApJ, 780, 36
Fukui, Y., Harada, R., Tokuda, K., et al. 2015, ApJL, 807, L4
Fukui, Y., Torii, K., Ohama, A., et al. 2016, ApJ, 820, 26
Fukui, Y., Tsuge, K., Sano, H., et al. 2017, PASJ, 69, L5
Fukui, Y., Torii, K., Hattori, Y., et al. 2018a, ApJ, 859, 166
Fukui, Y., Tokuda, K., Saigo, K., et al. 2018b, arXiv e-prints, arXiv:1811.00812
Fukui, Y., Kohno, M., Yokoyama, K., et al. 2018c, PASJ, 70, S41
Fukui, Y., Kohno, M., Yokoyama, K., et al. 2018d, PASJ, 70, S44
Fukui, Y., Ohama, A., Kohno, M., et al. 2018e, PASJ, 70, S46
Fujita, S., Torii, K., Tachihara, K., et al. 2019a, ApJ, 872, 49
Fujita, S., Torii, K., Kuno, N., et al. 2019b, PASJ, 70, S46
Furukawa, N., Dawson, J. R., Ohama, A., et al. 2009, ApJL, 696, L115
Gratier, P., Braine, J., Rodriguez-Fernandez, N. J., et al. 2010, A&A, 522, A3
Gratier, P., Braine, J., Rodriguez-Fernandez, N. J., et al. 2012, A&A, 542, A108
Habe, A., & Ohta, K. 1992, PASJ, 44, 203
Hasegawa, T., Sato, F., Whiteoak, J. B., et al. 1994, ApJL, 429, L77
Hayashi, K., Sano, H., Enokiya, R., et al. 2018, PASJ, 70, S48
Inoue, T., & Fukui, Y. 2013, ApJL, 774, L31
Inoue, T., Hennebelle, P., Fukui, Y., et al. 2018, PASJ, 70, S53
Kohno, M., Torii, K., Tachihara, K., et al. 2018a, PASJ, 70, S50
Kohno, M., Tachihara, K., Fujita, S., et al. 2018b, PASJ, 126
Massey, P., Olsen, K. A. G., Hodge, P. W., et al. 2006, AJ, 131, 2478
Martins, F., Schaerer, D., & Hillier, D. J. 2005, A&A, 436, 1049
Mayya, Y. D., & Prabhu, T. P. 1996, AJ, 111, 1252
McMullin, J. P., Waters, B., Schiebel, D., Young, W., & Golap, K. 2007, Astronomical Data Analysis Software and Systems XVI, 376, 127
Miura, R. E., Kohno, K., Tosaki, T., et al. 2012, ApJ, 761, 37
Ohama, A., Kohno, M., Fujita, S., et al. 2018, PASJ, 70, S47
Saigo, K., Onishi, T., Nayak, O., et al. 2017, ApJ, 835, 108
Sano, H., Torii, K., Saeki, S., et al. 2017, arXiv e-prints, arXiv:1708.08149
Sano, H., Enokiya, R., Hayashi, K., et al. 2018, PASJ, 70, S43
Shima, K., Tasker, E. J., Federrath, C., et al. 2018, PASJ, 70, S54
Tachihara, K., Gratier, P., Sano, H., et al. 2018, PASJ, 70, S52
Takahira, K., Tasker, E. J., & Habe, A. 2014, ApJ, 792, 63
Tsutsumi, D., Ohama, A., Okawa, K., et al. 2017, arXiv e-prints, arXiv:1706.05664
Tokuda, K., Fukui, Y., Harada, R., et al. 2018a, arXiv e-prints, arXiv:1807.03500
Tokuda, K., Onishi, T., Saigo, K., et al. 2018b, ApJ, 862, 8
Torii, K., Enokiya, R., Sano, H., et al. 2011, ApJ, 738, 46
Torii, K., Hasegawa, K., Hattori, Y., et al. 2015, ApJ, 806, 7
Torii, K., Hattori, Y., Matsuo, M., et al. 2018a, PASJ, 121
Torii, K., Fujita, S., Matsuo, M., et al. 2018b, PASJ, 70, S51
Tosaki, T., Kuno, N., Onodera, S. M., et al. 2011, PASJ, 63, 1171
Tsuge, K., Sano, H., Tachihara, K., et al. 2019, ApJ, 871, 44
Verley, S., Hunt, L. K., Corbelli, E., et al. 2007, A&A, 476, 1161
Zinnecker, H., & Yorke, H. W. 2007, ARA&A, 45, 481