The formation of the young massive cluster B1 in the Antennae galaxies (NGC 4038/NGC 4039) triggered by cloud-cloud collision

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Abstract

The Antennae Galaxies is one of the starbursts in major mergers. Tsuge et al. (2020) showed that the five giant molecular complexes in the Antennae Galaxies have signatures of cloud-cloud collisions based on the ALMA archival data at 60 pc resolution. In the present work we analyzed the new CO data toward the super star cluster (SSC) B1 at 14 pc resolution obtained with ALMA, and confirmed that two clouds show complementary distribution with a displacement of $\sim$70 pc as well as the connecting bridge features between them. The complementary distribution shows a good correspondence with the theoretical collision model (Takahira et al. 2014), and indicates that SSC B1 having $\sim 10^6 M_\odot$ was formed by the trigger of a cloud-cloud collision with a time scale of $\sim 1$ Myr, which is consistent with the cluster age. It is likely that SSC B1 was formed from molecular gas of $\sim 10^7 M_\odot$ with a star formation efficiency of $\sim 10$ \% in 1 Myr. We identified a few places where additional clusters are forming. Detailed gas motion indicates stellar feedback in accelerating gas is not effective, while ionization plays a role in evacuating the gas around the clusters at a $\sim 30$-pc radius. The results have revealed the details of the parent gas where a cluster having mass similar to a globular is being formed.

Key words: galaxies: interactions, galaxies: starburst, globular clusters: general

1 Introduction

Super star clusters (SSCs) are attracting keen interest of the researchers, since SSCs are highly energetic and affect the galactic evolution substantially. SSCs are also supposed to be a present-day analog to the ancient globulars, whose formation is deeply connected to the environment of the early universe. The Antennae Galaxies is an outstanding major merger where tens of young SSCs are discovered.

Genzel et al. (1998) showed that the galaxy mergers have
Fig. 1 (a) An optical image of NGC 4038/4039 produced by the Hubble Space Telescope data. B-band image is shown in blue, V-band image in green, and a combination of the I-band and Hα images in red. (b) Total integrated intensity map of $^{12}$CO (3--2) toward superstar cluster B1. The black crosses show the positions of two point-like sources toward B1. The lowest contour level and intervals are 250 and 250 K km s$^{-1}$. The dashed lines show the integration range in R. A. in (c). (c) Declination–velocity diagram of $^{12}$CO(3--2). The black arrows indicate the position of bridge features. (d) Typical spectrum of $^{12}$CO($J=3$--2) toward integrated intensity peak at the position of yellow cross (R.A., Dec.)=( 12$^h$01$^m$54.8s, $-18^\circ53'10"$). The horizontal axis and vertical axis indicate $V_{\text{LSR}}$ [km s$^{-1}$] and intensity [K], respectively. Green and red shaded regions are $V_{\text{LSR}}=1450$ to 1525 km s$^{-1}$ (blue-shifted cloud) and 1550 to 1700 km s$^{-1}$ (redshifted cloud), respectively. Green and red dashed vertical lines show the average velocity of blue shifted and red shifted clouds, respectively. Grey shaded region shows velocity range of bridge features in the intermediate velocity range between the blue-shifted and red-shifted clouds. The velocity ranges of shaded area correspond to the integration ranges as shown in Figure 2.

excess infrared luminosity as compared with the isolated galaxies, lending support for the active star formation triggered by galaxy interactions in mergers. The Antennae Galaxies is the most outstanding major merger closest to the Milky Way at a distance of 22 Mpc (Schweizer et al. 2008). The galaxies consist of the two spirals NGC 4038 (R.A. = 12$^h$01$^m$53.00, Dec. = $-18^\circ52'10"$) and NGC 4039 (RA=12$^h$01$^m$53'60, Dec=$-18^\circ53'11"$). The interaction between NGC 4038 and NGC 4039 has been continuing probably since a few 100 Myr ago (Mihos et al. 1993; Karl et al. 2010; Renaud et al. 2015 and references therein). The Antennae is prominent because of the unusually active star formation including tens of young SSCs (e.g., Whitmore & Schweizer 1995), and clear signatures of the galactic interaction as the two long tails. Such numerous SSCs, often called starbursts, are rarely observed in the other non-interacting galaxies within 100 Mpc of the Milky Way. In a smaller distance, we have increasing evidence for similar cloud-cloud interactions are triggering the formation of SSCs, which include R136 in the Large Magellanic Cloud (Fukui et al. 2017) and NGC604 in M33 (Tachihara et al. 2018) as well as several SSCs in the Milky Way (Furukawa et al. 2009; Ohama et al. 2010; Fukui et al. 2014; 2016; Kuwahara et al. 2020; Fujita et al. 2020).

Molecular observations are crucial in studying cluster formation in mergers. In particular, ALMA offers an ideal opportunity to investigate the molecular gas distribution and kinematics at the highest resolution achieved so far, which are possibly related not only to the feedback by the SSCs but also directly to the SSC formation.

The previous works on the ALMA data investigated the distribution of molecular clouds and dense gas (Whitmore et al. 2014; Schirm et al. 2016), the effect and mechanism of stellar feedback (Herrera et al. 2017), and progenitors of SSCs (Herrera et al. 2011, 2012; Johnson et al. 2015), whereas the mechanism of cluster formation has not been well understood. Whitmore et al. (2014) briefly suggested a possible role of filamentary cloud collision induced by tidal interaction in SSC formation, but no further exploration of cluster formation was undertaken in these articles. Most recently, Tsuge et al. (2020) studied the ALMA CO data and presented evidence for cloud-cloud collisions in the five giant molecular cloud complexes (SGMCs), opening a new window in the pursuit of SSC formation. These authors used ALMA cycle0 data at 50 pc resolution, while the Firecracker, a SSC candidate, was studied at 10 pc resolution of cycle 4 (Finn et al. 2019) and complementary distribution between two colliding clouds was revealed.
Fig. 2 (a) The spatial distribution of blue shifted cloud. The integration velocity range of \( V_{\text{LSR}} = 1450–1525 \, \text{km s}^{-1} \). The contour levels are 300, 450, 600, 750, 900, 1060, 1070, and 1090 K km s\(^{-1}\). (b) The spatial distribution of red shifted cloud. The integration velocity range of \( V_{\text{LSR}} = 1570–1700 \, \text{km s}^{-1} \). (c) Intensity map of \(^{12}\text{CO}(J=3–2)\) consisting of three velocity components. The black image indicates bridge features (\( V_{\text{LSR}} = 1525–1570 \, \text{km s}^{-1} \)). The red and green contours indicate the red-shifted cloud and blue-shifted cloud, respectively. The contour levels of three velocity components are 40 \( \sigma \) (95 K km s\(^{-1}\) for bridge; 156 K km s\(^{-1}\) for red-shifted cloud; 120 K km s\(^{-1}\) for blue-shifted cloud). The symbols are the same as in Figure 1.

In the Antennae, 40 % of youngest SSCs are located in the overlap region as indicated in Figure 1a, where two galaxies are merging (Wilson et al. 2000). The SSCs are cataloged by using the near infrared data taken with Hubble Space Telescope (Gilbert & Graham 2007; Whitmore et al. 2010). Five out of 8 SSCs whose mass is larger than 10\(^6\) \( M_\odot \) and age is younger than 10 Myr are concentrated to the southern part of the overlap region as shown in Figure 1b. We first focus on SSC B1, the most luminous embedded cluster candidate in the Antennae, which was identified by Whitmore & Schweizer (1995) as WS 80 (IR source). This cluster received much attention as the strongest CO source (Wilson et al. 2000), the strongest ISO source (Vigroux et al. 1996; Mirabel et al. 1998), and the strongest radio source (Neff & Ulvestad 2000). Wilson et al. (2000) briefly suggested a possibility of collision between super giant molecular complexes SGMCs as the origin of strong mid-infrared emission, whereas more details of the SSC formation was not discussed.

In the present paper, we analyze the ALMA cycle3 data of CO 3–2 toward SSC B1 and present detailed gas distribution associated with the cluster, Section 2 described the datasets, and Section 3 the results of the analysis. We discuss the implications in SSC formation and feedback in Section 4 and give conclusions in Section 5.

2 The ALMA archive of the Antennae and data reduction

In the present work we made use of the archival \(^{12}\text{CO}(J=3–2)\) data of Band 7 (345 GHz) of the Antennae (NGC 4038/39) from Cycle 0 project 2011.0.00876 (P.I., B. Whitmore). The detailed descriptions of the observations are given by Whitmore et al. (2014). We re-did the imaging process from the visibility data by using the CASA (Common Astronomy Software Application) package (McMullin et al. 2007) version 5.0.0. We used the tclean task with multiscale CLEAN algorithm (Cornwell 2008) implemented in the CASA. The resultant synthesized beam size is 0\('\)70 \( \times \) 0\('\)46 and the 1\(\sigma\) RMS noise is \( \sim 4.8 \times 10^{-3} \) Jy/beam at a velocity resolution of 5.0 km s\(^{-1}\), which corresponds to a surface brightness sensitivity of \( \sim 0.15 \) K.

We also reduced the higher resolution \(^{12}\text{CO}(J=3–2)\) data of Cycle 3 project 2015.1.00038S (P.I., C. Herrera) toward SSC B1. ALMA Cycle 3 Band 7 observations have been carried out in September 2016 using 36 antennas of the 12-m main arrays. The observations used the single-pointing mode centered at (\(\alpha\)J2000, \(\delta\)J2000)\(\sim\) (12\(h\)01\('\)m54\('\)s, \(-18^\circ53’4’’\)). The baseline length ranges from 27.09 to 3143.76 m, corresponding to u-v distances from 31.25 to 3626.08 k\(\lambda\). Three quasars, J1256-0547, J1203-1612, and J1215-1731 were observed as the complex gain calibrator, the flux calibrator, and the phase calibrator, respectively. To reduce the datasets, we also used CASA package version 5.5.0 and multiscale CLEAN.
Fig. 3 (a)(b) 1st moment map of $^{12}$CO(3–2) toward superstar cluster B1. Velocity ranges using for calculating momentum are $V_{LSR} = 1450–1525$ km s$^{-1}$ (blue-shifted cloud) for (a); $V_{LSR} = 1570–1700$ km s$^{-1}$ (red-shifted cloud) for (b). (c)(d) 2nd moment map of $^{12}$CO(3–2) toward superstar cluster B1. Velocity ranges using for calculating momentum are the same as in (a) and (b). The symbols are the same as in Figure 1.

3 Results

3.1 CO Distribution

Figure 1a shows the optical image of the Antennae Galaxies and Figure 1b shows the distribution of the $^{12}$CO ($J=3–2$) emission obtained with ALMA cycle 0 in the overlap region combined with cycle 3 data. Spatial resolution is improved by $\sim 4$ times, and cluster scale distribution is resolved at $\sim 10$ pc with a peak toward SSC B1. Figure
Fig. 4 (a)(b) False color image toward SGMC 4/5 obtained with HST overlaid with integrated intensity distribution of $^{12}$CO($J=3–2$) for the blue-shifted cloud and red-shifted cloud. B-band image is shown in blue, V-band image in green, and a combination of the I-band and Hα images in red. The integrated velocity ranges are the same as in Figure 2. The contour levels are 300, 450, 600, 750, 900, 1060, 1070, and 1090 K km s$^{-1}$ for (a); 120, 220, 320, 420, 520, 620, 720, 820, 920, 1020 K km s$^{-1}$ for (b). (c)(d) Integrated intensity distribution of $^{13}$CO($J=3–2$) for the blue-shifted cloud and red-shifted cloud by contours superposed on Hα image obtained with HST. The integrated velocity ranges and contour levels of (c) and (d) are the same as in (a) and (b). The symbols are the same as in Figure 1.
The correspondence shows that the two clouds are physically associated with SSC B1 and are the parent clouds of SSC B1. If we adopt the stellar mass of SSCB1, (4.2–6.8)×10^6 M_⊙ (see Table 1 of Tsuge et al. 2020), the cloud mass (5.6–8.4)×10^7 M_⊙ is large enough to form the cluster with a star formation efficiency of 5–8 %.

### 3.2 Complementary distribution and bridge features

Figure 5 shows an overlay of the distributions of the two velocity components from the present analysis, the theoretical simulation result and a schematic of the two clouds. According to the previous works, in two colliding clouds which show complementary distribution, we often find displacement between them (e.g., Fukui et al. 2018; Takahira et al. 2014), which is a general signature for a collision whose velocity makes an angle not close to either 0 deg. or 90 deg. Takahira et al. (2014) made hydrodynamical numerical simulations of two spherical clouds with different radii in a head-on collision. In the collision the small cloud creates a cavity having a size of the small cloud in the large cloud. The cavity should have complementary distribution with the small cloud. Fukui et al. (2018) presented synthetic observations of such collision by using the results of Takahira et al. (2014), and showed that the complementary distribution usually has a displacement in the sky because of the projection effect of the collision path which makes a certain non-zero angle to the line of sight.

Following the algorithm by Fujita et al. (2020a), we moved the red-shifted cloud from the original position over ±90 pc with a 1.8 pc (size of pixel) step in the two orthogonal directions of RA and Dec., and calculated the correlation coefficient with the integrated intensity of the blue-shifted cloud for each pixel. We calculated Spearman’s correlation co-efficient between the integrated intensity of two velocity components, and looked for the position where the correlation coefficient is minimum. The method is appropriate when the feedback is not significant and the shapes of the two clouds are well kept after the collision. In Figure 4a we see the two clouds exhibit a complementary distribution with a possible displacement. Figure 4b shows the result after the displacement of 70 pc in length and a position angle of 126°. These parameters give the minimum correlation coefficient of −0.7, and their coincidence looks good. Figure 5c shows a schematic of two clouds be-
Fig. 5  (a) CO intensity map of the blue-shifted cloud by contours superposed on the red-shifted cloud. The contour levels and symbols are the same as in Figure 2b. (b) Same as (a), but the contour of blue shifted cloud is displaced. The contour level is 300 K km s\(^{-1}\). (c) The projected displacement is 70 pc with a position angle of 126 deg. Right panel shows rectangular solid model clouds before the collision (i), during the collision (ii), and after the collision (iii) for SGMC 4/5. (a) and (b) correspond to (iii) and (ii), respectively. (d) Result of synthetic observation based on the numerical simulation by Takahira et al. (2014). Contour and image indicate blue-shifted cloud and red-shifted cloud, respectively.
fore, during and after the collision modified from Figure 14 in Tsuge et al. (2020). In Figure 5dc the two colliding spherical clouds with different radii (Takahira et al. 2014) are overlaid for a case with the collision velocity same with the line of sight.

### 4 Discussion

#### 4.1 Collision picture toward SSC B1

Tsuge et al. (2020) suggested that the two clouds are colliding toward SSC B1 based on the complementary distribution and bridge features of the ALMA cycle 0 data. The present analysis of the cycle 3 data at four-time higher resolution showed significant details of the complementary distribution and bridge features of the two clouds, allowing us to elaborate the collision picture. In particular, a displacement of 70 pc with a position angle of 126° was derived by the fitting procedure between the small cloud and the cavity of the large cloud (Fujita et al. 2020; see also Fukui et al. 2018a).

The new collision picture above helps to estimate better collision parameters. The collision time scale is calculated by a ratio of the travelled distance ∼70 pc divided by the collision velocity ∼100 km s⁻¹ to be 0.7 Myr. The time scale is valid if the collision angle is 45 deg. If the collision direction makes an angle of 30 deg. or 60 deg. to the line of sight, the time scale can vary from 0.4 to 1.4 Myrs corrected for the projection. This value is consistent with the estimated cluster age, 1–3.5 Myrs (Gilbert & Graham 2007; Whitmore et al. 2010).

According to the picture the blue-shifted small cloud collided close to the center of the red-shifted large cloud, where the small cloud moved from the south to the north and fully passed through the large cloud. As a result, the collision created the cavity in the large cloud, and compressed the interface layer between the two clouds (a schematic diagram in Figure 5). Part of the remnant of the interface layer is seen as the bridge stellar objects (Figure 2c), while the rest of the gas has been ionized. The near infrared bright and compact features in the both clouds correspond to the intensity depressions toward the stellar objects and the extended feature associated. This suggests that part of the two clouds is converted to the stars of the cluster in the collision.

We estimate the typical size and column density of the depressions to be around 30 pc and 10²³ cm⁻², and molecular mass of ~10⁷ M☉ in each depression prior to star formation. We find additional CO peaks in the two clouds which are candidates for future stellar members, or some of them may be already forming stellar members. The mass accretion rate in each of the several stellar objects is estimated to be 10²³ M☉/Myr = 0.1 M☉/yr. The stellar objects are spaced by ~50 pc from each other, and the age of the stellar objects may range over 1 Myr. In SSC B1 the spatial distribution of star formation and its age spread cause naturally a SSC whose members have an age spread of more than ∼1 Myr. We calculated the luminosity of the brightest peak corresponds to 300 O stars (Martins et al. 2005), which is about an order of magnitude larger than that in R136. This confirms that the mass of SSC B1 is around 10⁶ M☉.

It is suggested that the high-pressure environment is a requirement for the SSC formation (Elmegreen & Efremov 1989; Elmegreen & Efremov 1997). Johnson et al. (2015) and Finn et al. (2019) found the high-pressure environment in the overlap region. Furthermore, Tsuge et al. (2020) revealed a positive correlation between the compressed gas pressure generated by collision and total stellar mass of cluster. The typical pressure of the colliding clouds is estimated to be (1.6–2.5)×10⁸ K cm⁻³ by using the relationship, \( P_e = \frac{3Mv^2}{4\pi R^2} = \rho_e v^2 \), which is consistent with the relationship derived by Tsuge et al. (2020). \( M \) is the cloud mass, \( v \) is the colliding velocity (difference of peak velocity of colliding clouds), \( R \) is the radius of cloud, and \( \rho_e \) is the density at the cloud edge. \( \Pi \) is defined by \( \rho_e = \Pi \rho \), where \( \rho \) is the mean density in the cloud. We adopt \( \Pi = 0.5 \) (Janson et al. 2015; Finn et al. 2019).

Feedback is believed to be important in high-mass star formation. The present results reveal some novel aspects of the feedback. Figure 3 shows the distribution of mom1 and mom2. The stellar objects in the cluster is plotted by crosses and show no variation of the average velocity or the velocity dispersion is seen, suggesting that the stellar feedback is not affecting appreciably the gas dynamics. We suggest that the velocity distribution of the clouds is more influenced by the collisional interaction than the feedback as indicated by the enhancement of mom2 having a spatial gradient from the east to west which has no correlation with the stellar objects. The area of the cluster formation is strongly dispersed by the feedback of the forming stars in the cluster in the both clouds as depicted in Figure 3. The present high resolution shows the cavity is fully enclosed by the large cloud (Figure 4d).

### 5 Conclusion

The Antennae galaxies is the most outstanding major merger closest to the Milky Way. We analyzed the ALMA cycle3 dataset of the \(^{12}\text{CO}(J=3–2)\) emission toward the SSC B1 and derived the molecular distribution at 10 pc resolution. The main conclusions of the present study is
summarized as follows;

1. The present results confirm that the molecular gas in SSC B1 has two velocity peaks at 1500 km s⁻¹ and 1600 km s⁻¹ (Paper I). The spatial distributions of the clouds resolved at a resolution of 10 pc shows complementary distribution with a displacement of 70 pc which was determined more accurately than in Paper I. The two clouds are connected with bridge features in the intermediate velocity range. The complementary distribution well matches the numerical simulation by Takahira et al. (2014).

2. The new CO distributions allowed to compare the CO with the HST images of near infrared emission and Hα emission. The bright compact sources are found toward the intensity depression of CO, which indicates the effects of ionization by the high-mass stars. We estimate the luminosity of the brightest Hα source corresponds to 300 O3 stars, which amounts to almost ten times the number of O3 stars, 39, in R136 (Massey & Hunter 1998). The number of O3 stars is consistent with the cluster mass of \( \sim 10^6 M_\odot \), if the mass is proportional to the number of O3 stars. The mass of the two clouds are (2.4–6.0) \( \times 10^7 M_\odot \) with a typical peak molecular column density of \( 10^{23} \text{ cm}^{-2} \). The molecular mass which was distributed in the ionized cavity, having a 30-pc radius, is estimated to be \( \sim 10^7 M_\odot \), corresponding star formation efficiency of \( \sim 10 \% \).

3. The velocity distribution in the two CO clouds are derived as mom1 and mom2, and are compared with compact near infrared sources and the Hα image. The result shows that the gas motion has no sign of perturbed velocity field by the stellar sources. We therefore argue that significant kinematic feedback by the newly formed stars is not important except for the ionization which probably evacuated the molecular gas. This suggests that the cloud kinematics is dominated by the galactic tidal interaction.

**Acknowledgments**

This paper makes use of the following ALMA data: ADS/JAO.ALMA #2011.0.00876, and #2015.1.00383.S . ALMA is a partnership of the ESO, NSF, NINS, NRC, MOST, and ASIAA. The Joint ALMA Observatory is operated by the ESO, AUI/NRAO, and NAOJ. This paper is also based on observations made with the NASA/ESA Hubble Space Telescope, obtained from the data archive at the Space Telescope Science Institute. STScI is operated by the Association of Universities for Research in Astronomy, Inc. under NASA contract NAS 5-26555. K. Tsuge was supported by the Japanese Research Grant of NAOJ ALMA Project, NAOJ-ALMA-232. This study was financially supported by JSPS KAKENHI (Grant Numbers 15H05694 and 18K13582).

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Appendix 1  CO channel maps of position diagrams

We show the 21 declination-velocity diagrams of the $^{12}\text{CO}(J=3\rightarrow2)$. The integration range is $0\farcs5$ ($\sim$54 pc), and the integration range is shifted from east to west in $0\farcs5$ step.

Appendix 2  Velocity channel maps

We show the velocity channel maps of the $^{12}\text{CO}(J=3\rightarrow2)$ of SGMC 4/5 in Figure 8. The velocity range is between 1400 km s$^{-1}$ and 1700 km s$^{-1}$. 
Fig. 6 Channel maps of declination-velocity diagrams. (a) Total integrated intensity map of SGMC 4/5. The integration velocity range is the same as in Figure 1b. Dashed vertical lines indicate the integration ranges of declination-velocity diagrams in R.A.. (b)–(l) Declination-velocity diagrams of $^{12}$CO ($J=3–2$). The upper right number denotes the integration range in (a).
Fig. 7 Channel maps of declination-velocity diagrams. (a) Total integrated intensity map of SGMC 4/5. The integration velocity range is the same as in Figure 1b. Dashed vertical lines indicate the integration ranges of declination-velocity diagrams in R.A.. (b)–(l) Declination-velocity diagrams of $^{12}$CO ($J=3\rightarrow 2$). The upper right number denotes the integration range in (a).
Fig. 8 Velocity channel maps of $^{12}$CO(3–2) toward the SGMC 4/5 with velocity step of 25 km s$^{-1}$. The symbols are the same as in Figure 1.