THE TWO MOLECULAR CLOUDS IN RCW 38: EVIDENCE FOR THE FORMATION OF THE YOUNGEST SUPER STAR CLUSTER IN THE MILKY WAY TRIGGERED BY CLOUD–CLOUD COLLISION

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Abstract

We present distributions of two molecular clouds having velocities of 2 and 14 km s$^{-1}$ toward RCW 38, the youngest super star cluster in the Milky Way, in the $^{12}$CO J = 1–0 and 3–2 and $^{13}$CO J = 1–0 transitions. The two clouds are likely physically associated with the cluster as verified by the high intensity ratio of the J = 3–2 emission to the J = 1–0 emission, the bridging feature connecting the two clouds in velocity, and their morphological correspondence with the infrared dust emission. The velocity difference is too large for the clouds to be gravitationally bound. We frame a hypothesis that the two clouds are colliding with each other by chance to trigger formation of the $\sim$20 O stars that are localized within $\sim$0.5 pc of the cluster center in the 2 km s$^{-1}$ cloud. We suggest that the collision is currently continuing toward part of the 2 km s$^{-1}$ cloud where the bridging feature is localized. This is the third super star cluster alongside Westerlund 2 and NGC 3603 where cloud–cloud collision has triggered the cluster formation. RCW 38 is the youngest super star cluster in the Milky Way, holding a possible sign of on-going O star formation, and is a promising site where we may be able to witness the moment of O star formation.

Keywords: ISM: clouds – ISM: kinematics and dynamics – ISM: molecules – stars: formation

1. INTRODUCTION

1.1. Important Role of High-mass Stars

High-mass stars are very energetic and have a great influence on the dynamics of the interstellar medium via stellar winds, ultraviolet radiation, and supernova explosions. Injection of heavy elements at the end of their lives is another important effect of high-mass stars in galactic evolution. It is therefore one of the most important issues in astrophysics to understand the formation of high-mass stars and considerable efforts have been made by a number of works published so far (for recent reviews see Zinnecker & Yorke 2007; Tan et al. 2014, p. 149).

1.2. Theoretical Attempts to Understand High-mass Star Formation

It is now generally accepted, after some years of debate, that most high-mass stars are formed by mass accretion instead of collisional stellar merger. In the current paradigm, monolithic collapse (Yorke & Sonnhalter 2002) and competitive accretion (Bonnell et al. 2004) are the two scenarios of the mass accretion processes. In monolithic collapse a massive dense molecular cloud is the initial condition for star formation, and is followed by disk accretion, whereas in competitive accretion a massive cluster of stars/pre-stellar cores is assumed to grow in mass by accretion of the ambient gas. The two scenarios still lack detailed confrontation with the initial conditions provided by observations. This is in part due to the lack of well-resolved observational views of high-mass star formation at small distances; even the Orion Nebular Cluster, the most outstanding high-mass star-forming region at the smallest distance, 400 pc, is three times more distant than typical low-mass star-forming regions like Taurus, and the second nearest such regions are at a distance of around 2 kpc. Therefore, our understanding of high-mass star formation is yet to be significantly corroborated.

It is interesting to note that insightful discussion is made on the mechanisms of high-mass star formation in the review article by Zinnecker & Yorke (2007), where we find the following sentence: “Rapid external shock compression (i.e., supersonic gas motions) generating high column densities in less than a local free-fall time rather than slow quasi-static build-up of massive cores may be the recipe to set up the initial conditions for local and global bursts of massive star formation.” This idea of supersonic gas motions to collect gas has not been explored further in the literature in the context of high-mass star formation except for the several papers on cloud–cloud collision discussed in Section 1.3.

1.3. Increasing Evidence for Cloud–Cloud Collision as a Trigger of High-mass Star Formation

Molecular observations with NANTEN2 have shown that O-type star formation in the Milky Way disk is triggered by supersonic collisions between two clouds at a velocity of 10–30 km s$^{-1}$ in several places. The first discovery was made in the super star cluster Westerlund 2, which is ionizing an H region RCW 49 (Furukawa et al. 2009; Ohama et al. 2010), and the authors suggested that two giant molecular clouds collided to trigger formation of the cluster some 2 Myr ago. These observations were followed by the discovery of cloud–cloud collisions that triggered formation of the super star cluster/
mini-starburst in NGC 3603 (Fukui et al. 2014) and formation of the single O star in H\textsuperscript{ii} regions M20 (Torii et al. 2011) and RCW 120 (Torii et al. 2015). Most recently, ALMA observations of the Large Magellanic Cloud led to the discovery of formation of a 40$M_\odot$ star N159W-S triggered by collision between two filamentary clouds at a relative velocity of \textasciitilde10 km s\textsuperscript{-1} (Fukui et al. 2015). These results raise the novel possibility that formation of O stars may be due to, or at least facilitated by, the supersonic compression in cloud–cloud collision, which was not considered in the theories of high-mass star formation, either in the monolithic collapse scenario or in the competitive accretion model. On the global scale of galaxies, numerical simulations show that collisions between clouds are fairly frequent at every \textasciitilde10 Myr (Tasker & Tan 2009; Dobbs et al. 2015), which is similar to the evolutionary timescale of giant molecular clouds (Fukui et al. 1999; Kawamura et al. 2009; Fukui & Kawamura 2010). It is thus becoming possible to consider cloud–cloud collision as one of the modes of high-mass star formation.

Cloud–cloud collision was studied using hydrodynamics simulations by Habe & Ohtia (1992), Ananthpadmika (2010), and Takahira et al. (2014). These authors found that cloud–cloud collision induces the formation of cloud cores by enhanced self-gravity as a consequence of shock compression, while the connection of cloud–cloud collision to high-mass star formation was not discussed in depth. Recent magnetohydrodynamic (MHD) numerical simulations on cloud–cloud collision show that colliding molecular gas can indeed create dense and massive cloud cores, precursors of high-mass stars, in the shock-compressed interface, giving a theoretical basis for the triggering of O star formation (Inoue & Fukui 2013). In the simulations after the collision the density increases from 300–1000 cm\textsuperscript{-3} to \textasciitilde10\textsuperscript{5} cm\textsuperscript{-3} and the turbulent velocity and magnetic field increase by about a factor of five, leading to a hundredfold higher mass accretion rate for the formation of stars. This indicates that the conditions for the high mass accretion rate postulated in high-mass star formation theories (McKee & Tan 2003) are created by cloud–cloud collision.

Following these findings, as a next step we need to have a better understanding of the physical details of the collision, which include direct observations of the shock interaction as well as the statistical properties of cloud–cloud collisions. We are carrying out a systematic study of high-mass star formation toward H\textsuperscript{ii} regions in order to elucidate the role of cloud–cloud collision with NANTEN2, Mopra, and ASTE telescopes. These H\textsuperscript{ii} regions include Spitzer bubbles, compact H\textsuperscript{ii} regions, and mini-starbursts including NGC 6334, NGC 6357, W43, etc.

1.4. RCW 38 as the Youngest Super Star Cluster in the Milky Way

Hoping to better understand the origin of massive clusters, we focus in this paper on the super star cluster RCW 38 (Rodgers et al. 1960), which is the youngest super star cluster in the Milky Way, with an age of \textasciitilde1 Myr (Wolk et al. 2006, 2008; see also Table 2 in Portegies Zwart et al. 2010).

Wolk et al. (2006) estimated the age of RCW 38 as 0.5 Myr with an upper limit of 1 Myr so that it does not conflict with the number of O stars for the size of the cluster, and Getman et al. (2014) measured the ages of several members of the cluster, which range from 0.1 to 3.5 Myr. The cluster age may be even less than 0.5 Myr as discussed in the present paper (Section 4).

The extreme youth will benefit study of the molecular gas close to the central O stars, which is particularly important for addressing the ionization/dispersal of the molecular gas. RCW 38 has a large total mass, similar to that of the Orion Nebula Cluster, and is an active high-mass star-forming region, the second nearest to the Sun, at a distance of 1.7 kpc. An overview of previous studies of RCW 38 is summarized in an article by Wolk et al. (2008).

RCW 38 is known as one of the closest high-mass star-forming regions containing \textasciitilde10,000 stars (Wolk et al. 2006; Broos et al. 2013; Kuhn et al. 2015; see also Lada & Lada 2003) (Figure 1). In the central part of RCW 38, two remarkable infrared peaks have been identified (Frogel & Persson 1974). The brightest, at 2 μm, is labeled IRS 2, and corresponds to an O5.5 binary located at the center of the RCW 38 cluster (DeRose et al. 2009). Furniss et al. (1975) derived the total infrared luminosity toward IRS 2 to be 7 \times 10\textsuperscript{5} L\odot. The brightest feature at 10 μm is found 0.1 pc west of IRS 2, and is labelled IRS 1. This is a dust ridge extending by 0.1–0.2 pc in the north–south direction (Figure 1(b)), and has a color temperature of about 175 K and includes several dust condensations (Smith et al. 1999). Infrared and millimeter-wave observations have indicated a “ring-like” or “horseshoe” structure around IRS 2 about 1′–2′ across (Huchtmeier 1974; Vigil 2004; Wolk et al. 2006, 2008). Inside the ring-like shape two regions are cleared of dust and form cavities; one is the region centered on IRS 2 with a diameter of \textasciitilde0.1 pc, and the other is just west of IRS 1 with a similar size (Smith et al. 1999; Wolk et al. 2008), suggesting that they were formed by feedback from high-mass stars. A large-area infrared image shows that RCW 38 includes numerous filaments and bubbles (see Figure 1(a)). Kaneda et al. (2013) made comparisons of the maps of dust and polycyclic aromatic hydrocarbons (PAHs) with the map of C[III] 158 μm, and discussed that the PAHs and dust grains are well mixed along the line of sight and that PAHs play an important role in photoelectric heating of gas in photodissociation regions.

Many observational studies to investigate the cluster members of RCW 38 have been carried out. Near-infrared observations by using the Very Large Telescope (VLT) identified more than 300 young stars in the \textasciitilde0.5 pc\textsuperscript{2} area centered on IRS 2 (DeRose et al. 2009). Chandra observations reported by Wolk et al. (2006) were used to identify 345 X-ray sources likely associated with RCW 38, and completeness arguments suggest a total estimated cluster size of between 1500 and 2400 stars. Winston et al. (2011) identified 624 young stellar objects (YSOs) from the Spitzer/IRAC observations toward a 30′ × 30′ region of RCW 38. In a part of the Massive Young star-forming Complex Study in Infrared and X-rays (MYStIX), 886 pre-main sequence stars have been identified in RCW 38, which are concentrated within 0.5 pc of the cluster center (Broos et al. 2013; Feigelson et al. 2013; Kuhn et al. 2013). Around the high-mass stars, nearly 60 O star candidates have been identified by Wolk et al. (2006) and Winston et al. (2011) in a large area of RCW 38. Of them, about 20 O star candidates are found in the central \textasciitilde0.5 pc (Wolk et al. 2006), Kuhn et al. (2015) also pointed out that the RCW 38 cluster shows a particularly high central stellar density compared with other nearby clusters with O stars (e.g., the Orion Nebula Cluster, W40, RCW 36, M17, etc.). It seems natural that such an O star cluster has tens of O stars as cluster members, while only IRS 2 is confirmed to be a double O5.5
The volume of the Ophiuchus molecular cloud (DeRose et al. 2009). We note cautiously
that the number of O stars is still to be corroborated observationally by considering the uncertainty of the stellar
mass determination based on pre-main-sequence models for the
K-band stellar magnitude (Wolk et al. 2006).

Molecular line observations toward RCW 38 are very
limited. Yamaguchi et al. (1999) observed a large area of
RCW 38 in the $^{12}$CO and $^{13}$CO $J = 1$–0 transitions during a period from 2012 May to December. The
4 K cooled SIS mixer receiver that is part of NANTEN2
provided a typical system temperature $T_{\text{sys}}$ of ~250 K in the
double sideband. The backend was a digital spectrometer that
provided 4096 channels across 137.5 MHz in each of the
superharmonics.

2. OBSERVATIONS

2.1. NANTEN2 CO $J = 1$–0 Observations

The NANTEN2 4 m millimeter/submillimeter telescope
situated in Chile was used to observe a large area, $1^\circ.8 \times 1^\circ.8$, of RCW 38 in the $^{12}$CO and $^{13}$CO $J = 1$–0
transitions during a period from 2012 May to December. The
4 K cooled SIS mixer receiver that is part of NANTEN2
provided a typical system temperature $T_{\text{sys}}$ of ~250 K in the
double sideband. The backend was a digital spectrometer that
provided 16384 channels at 1 GHz bandwidth and 61 kHz
resolution, corresponding to 2600 km s$^{-1}$ and 0.17 km s$^{-1}$, respectively, at 110 GHz. The obtained data were smoothed to
a velocity resolution of 0.8 km s$^{-1}$ and angular resolution of
240$''$. The pointing accuracy was checked to be better than 15$''$
with daily observations toward the Sun and IRC 10216 (R.A., decl.) = (9$^h$47$'$57$''$.406, 13$^\circ$16$'$43$''$.56). The equinox of the
celestial coordinates used in this paper is J2000.0. The absolute
intensity calibration was done with daily observations of the $\rho$
Oph molecular cloud (R.A., decl.) = (16$^h$32$'$23$''$.3, $-24^\circ$28$'$39$''$.2) and Perseus molecular cloud (R.A., decl.) = (3$^h$29$'$19$''$.0, 31$^\circ$24$'$49$''$.0).

2.2. Mopra CO $J = 1$–0 Observations

Detailed CO $J = 1$–0 distributions around RCW 38 were
obtained by using the 22 m ATNF (Australia Telescope
National Facility) Mopra millimeter telescope in Australia at an
angular resolution of 33$''$ in 2012 July. We simultaneously
observed the $^{12}$CO $J = 1$–0, $^{13}$CO $J = 1$–0, and C$^{18}$O $J = 1$–0
transitions toward an 11$'$ × 15$'$ area of RCW 38 in the OTF
mode with a unit field of 4$'$$' \times 4'$. $T_{\text{sys}}$ was 400–600 K in the
single sideband (SSB). The Mopra backend system “MOPS,”
which provided 4096 channels across 137.5 MHz in each of the

Figure 1. (a) The 3.6 mm image of RCW 38 obtained with the Spitzer/IRAC observations (Wolk et al. 2008). YSOs and O star candidates obtained by Wolk et al. (2006) and Winston et al. (2011) are plotted in (b). Red circles and white circles indicate the class 0/I and flat-spectrum YSOs, respectively, while black dots indicate the class II and III YSOs. White crosses indicate the candidate O stars. (b) A close-up of the central region of RCW 38 from the VLT observations (Wolk et al. 2006). The Z band is shown in blue, the H band is green, and the K band is red. The bright infrared emission regions IRS 1 and IRS 2 are shown by arrows.
two orthogonal polarizations, was used in the observations. The velocity resolution was 0.088 km s\(^{-1}\) and the velocity coverage was 360 km s\(^{-1}\) at 115 GHz. The obtained data were smoothed to a HPBW of 40\(^\prime\) with a 2D Gaussian function and to 0.6 km s\(^{-1}\) velocity resolution. The pointing accuracy was checked every 1 hr to keep within 7\(^\prime\) with observations of 86 GHz SiO masers. We made daily observations of Orion-KL (R.A., decl.) = (−5\(^\circ\)35\(^\prime\)14\(^\prime\).5, −5\(^\circ\)22\(^\prime\)29\(^\prime\).6) to estimate “extended beam efficiency” by making comparisons with the peak temperature of 100 K in Orion-KL shown in Figure 6 of Ladd et al. (2005). We finally obtained an extended beam efficiency of 0.48.

2.3. ASTE \(^{12}\)CO \(J = 3–2\) observations

Observations of RCW 38 in the \(^{12}\)CO \(J = 3–2\) transition were performed in 2013 by using the ASTE 10 m telescope located in Chile (Ezawa et al. 2004, 2008). We used the waveguide-type sideband-separating SIS mixer receiver for the SSB “CAT345” having a system temperature of 250 K (Inoue et al. 2008) and the digital spectrometer “MAC” with the narrow-band mode providing 128 MHz bandwidth and 0.125 MHz resolution (Sorai et al. 2000), which correspond to 111 km s\(^{-1}\) velocity coverage and 0.11 km s\(^{-1}\) velocity resolution at 345 GHz. The observations were made with the OTF mode at a grid spacing of 7\(^\circ\).5, and the HPBW was 22\(^\prime\) at the \(^{12}\)CO \(J = 3–2\) frequency. The pointing accuracy was checked every ∼1.5 hr and kept within 5\(^\prime\) with observations of RAFGL 5254 (R.A., decl.) = (09\(^\circ\)13\(^\prime\)53\(^\prime\).94, −24\(^\circ\)51\(^\prime\)25\(^\prime\).1). The absolute intensity calibration was done with observations of Orion-KL (R.A., decl.) = (−5\(^\circ\)35\(^\prime\)14\(^\prime\).5, −5\(^\circ\)22\(^\prime\)29\(^\prime\).6), and the day-to-day fluctuations of the peak intensity were within 10%.

3. RESULTS

3.1. Large-scale Molecular Distributions with NANTEN2

We first present large-scale molecular distributions of RCW 38 using the NANTEN2 \(^{12}\)CO \(J = 1–0\) data set. Compared with the NANTEN observations given by Yamaguchi et al. (1999), although the beam size of 180\(^\prime\) is the same, the grid spacing of 60\(^\prime\) in the present NANTEN2 observations is a third of the size, which enables us to reveal the gas distributions in more detail.

As shown in the CO distributions in Figure 2, toward the direction of RCW 38, two CO clouds are distributed at radial velocities \(v\)\(_{\text{LSR}}\) of −4 to +8 km s\(^{-1}\) and +9 to +14 km s\(^{-1}\). In Figure 2(a), the blueshifted cloud has a strong peak just coinciding with the central part of RCW 38. The compact peak with a size of 0\(^\prime\)21 (∼3 pc at RCW 38) has a feature elongated toward the southwest of RCW 38, showing a “head–tail” structure, which was also detected in Yamaguchi et al. (1999). The head–tail structure is surrounded by the diffuse CO emission distributed at around \(v\)\(_{\text{LSR}}\) of 0 to +8 km s\(^{-1}\), covering the present observed region.

In contrast to the blueshifted cloud shown in Figure 2(a), the redshifted cloud has a weak and dispersed CO distribution. A CO peak at (l, b) ∼ (268\(^\circ\).0, −1\(^\circ\)1.5) with relatively strong emission is located just to the southeast of RCW 38, pointing toward its center. This CO peak is well covered with the Mopra and ASTE observations as indicated by a box with solid lines in Figure 2(b). There are several other CO components around the CO peak, and they all seem to be continuously distributed along the east–west direction roughly at a range of (l, b) ∼ (267\(^\circ\).5–268\(^\circ\).4, −1\(^\circ\)0.0). In the declination–velocity diagram in Figure 2(c), the redshifted cloud can be identified separately from, although it looks to be connected with, the blueshifted cloud and the diffuse emission, suggesting a possible physical relationship of the redshifted cloud with RCW 38.

3.2. Detailed Molecular Distributions with Mopra and ASTE

We present the detailed molecular distributions around RCW 38 using the Mopra and ASTE data sets. In Figure 3, the integrated intensity distributions (left and central panels) and the declination–velocity diagram (right panels) are shown for the \(^{12}\)CO \(J = 1–0\) emission (upper panels) and the \(^{13}\)CO \(J = 1–0\) emission (lower panels). The R.A.–velocity diagram in the \(^{12}\)CO \(J = 1–0\) emission is also shown in Figure 4. In Figures 3(a) and (d), the outstanding compact peak seen in Figure 2(a) is resolved. It shows a ring-like structure having a
diameter of 1–2 pc, with a cavity centered on IRS 2, and several filamentary and bubble-like structures extend radially outside the ring-like structure by 1–2 pc. In the \( ^{12}\text{CO} \) position–velocity diagrams in Figures 3(c) and 4, a decrease in intensity is seen at around \( v_{\text{LSR}} \) of 2–4 km s\(^{-1}\). The \( ^{13}\text{CO} \) emission in Figure 3(f) shows a single peak at \( \approx 2 \) km s\(^{-1}\), indicating that the dip at the same velocity in the \( ^{12}\text{CO} \) is due to self-absorption.\(^9\) The blueshifted cloud has a peak at 2 km s\(^{-1}\). The ring-like structure in \( ^{13}\text{CO} \) consists of four clumps (clumps I–IV), and the ring-like structure itself has an elongated shape along the northeast–southwest direction (Figure 5). The size of the clumps ranges from 0.3 to 0.5 pc, and the linewidth \( \Delta v \) from 4 to 5 km s\(^{-1}\) (Table 1).

In contrast to the complicated distributions of the 2 km s\(^{-1}\) cloud, the 14 km s\(^{-1}\) cloud has a simple ridge elongated from north to south (Figures 3(b) and (e)). We shall hereafter call the 2 km s\(^{-1}\) cloud and the 14 km s\(^{-1}\) cloud the ring cloud and the finger cloud, respectively, because of their shapes. The finger cloud is not likely affected by self-absorption in \( ^{12}\text{CO} \), since \( ^{12}\text{CO} \) and \( ^{13}\text{CO} \) show similar distributions in the declination–velocity maps in Figures 3(c) and (f). We find three “bridging”

\( ^9 \) The two velocity features reported by Gyalbudaghiian & May (2008) in \( ^{12}\text{CO} \) \( J = 1-0 \) correspond to the two peaks caused by self-absorption.
features in velocity between the ring cloud and the finger cloud at decl. $\approx -47^\circ 30'0''$ (toward the cluster), $-47^\circ 34'5'''$, and $-47^\circ 39'5'''$, respectively, as indicated by arrows in Figure 3(c), and they are not seen beyond the velocity of the finger cloud. Their positions are denoted as BR1, BR2, and BR3 in Figure 6. The bridging feature distributed toward the cluster is also seen in the R.A.–velocity diagram in Figure 4. At its bottom, the ridge intersects another elongated structure running from east to west, and these two orthogonal elongated structures comprise the finger cloud in the present observed area (Figures 3(b) and (e)). As shown in Figures 3(c) and (f), the finger cloud shows a uniform velocity gradient of $\sim 1$ km s$^{-1}$ pc$^{-1}$ along the ridge.

3.3. Intensity Ratios of the $^{12}$CO $J = 3$–2 Emission to the $^{12}$CO $J = 1$–0 Emission

In order to investigate the physical properties of the ring cloud and the finger cloud, we present distributions of the intensity ratio of the $^{12}$CO $J = 3$–2 emission to the $^{12}$CO $J = 1$–0 emission (hereafter $R_{3/2-1/0}$). Taking intensity ratios between different J-levels of CO is a useful diagnostic of the molecular gas properties (e.g., Ohama et al. 2010; Torii et al. 2011; Fukui et al. 2014).

As seen in the declination–velocity diagram of $R_{3/2-1/0}$ in Figure 7, both the ring cloud and the finger cloud have typical ratios of 0.6–0.8, up to over 1.0. Since the ring cloud is strongly affected by the self-absorption in $^{12}$CO spectra around its central velocity range, $\sim 0$–4 km s$^{-1}$, the ratio in this velocity range is not reliable. On the other hand, low intensity ratios are seen in the northern part (decl. $> -47^\circ 27'0''$) and the southern part (decl. $< -47^\circ 34'0''$) of the ring cloud, where the diffuse CO emission is widely distributed, while the finger cloud retains its relatively high intensity ratios of $\sim 0.6$–0.8 throughout the cloud.

3.4. Temperature and Density of the Molecular Gas

We utilize the large velocity gradient (LVG) analysis (e.g., Goldreich & Kwan 1974) to estimate kinetic temperature $T_k$ and molecular number density $n$(H$_2$) of the two clouds in order to interpret their intensity ratio distributions. We first present curves of $R_{3/2-1/0}$ as a function of $T_k$ in Figure 8 for various densities from 10 to $10^4$ cm$^{-3}$, where $X$(CO)/(dv/dr), $10^{-5}$ (km s$^{-1}$ pc$^{-1}$)$^{-1}$ is assumed. We adopt an abundance ratio $X$(CO) = $^{12}$CO/[H$_2$] = $10^{-4}$ (e.g., Frerking et al. 1982; Leung et al. 1984), and a typical dv/dr is estimated for clumps I–IV as 4 km s$^{-1}$/0.4 pc = 10 km s$^{-1}$ pc$^{-1}$.

Figure 8 provides a guide for the $R_{3/2-1/0}$ distributions in Figures 7. If $R_{3/2-1/0}$ is larger than 0.7, which is depicted by a dashed line in Figure 8, $T_k$ is always higher than 10 K for every value of n(H$_2$). 10 K is a canonical value of the galactic molecular gas without significant star formation, suggesting that the gas with $T_k$ higher than 10 K is caused by some additional heating. On the other hand, if $R_{3/2-1/0}$ is as small as 0.4, $T_k$ cannot be determined, since it has a large variation from $<10$ K to $>100$ K depending on n(H$_2$). Both the ring cloud and the finger cloud show $R_{3/2-1/0}$ higher than 0.7 up to over 1.0 at many points, suggesting that these two clouds have $T_k$ higher than 10 K. It is reasonable that the heating is mainly due to the O stars in RCW 38. On the other hand, the diffuse CO emission surrounding the ring cloud with $R_{3/2-1/0}$ of 0.4 is of low excitation.

In order to provide more quantitative constraints for $T_k$ and n(H$_2$), we add the ratio of $^{13}$CO $J = 1$–0 to $^{12}$CO $J = 1$–0 (hereafter $R_{13/12}$) in the LVG analysis, with the assumption of the abundance ratio $^{12}$CO/$^{13}$CO = 77 (Wilson & Rood 1994). Ten target regions A–J are selected for estimates of $T_k$ and n(H$_2$) in the two clouds. The CO spectra and the LVG results are presented in Figures 9 and 10 for the individual target regions. In the CO spectra, the velocity ranges used for the LVG analysis are shown shaded. For the ring cloud, the five target regions are chosen to have apparent self-absorption in their $^{12}$CO spectra. For the ring cloud, regions A–C are taken in the high $R_{3/2-1/0}$ regions around the rim of the dense part, while regions D and E are in the low $R_{3/2-1/0}$ regions widely distributed in the north and the south. Regions F–J in Figure 10 are taken to cover a large area of the finger cloud. In the diagrams of the LVG results, $R_{3/2-1/0}$ and $R_{13/12}$ distributions are shown by the blue lines and red lines, respectively, and their errors are shown by the colored area. The errors are estimated with 1σ noise fluctuations of the spectra and the 10% relative calibration error for each CO transition. Since the $^{13}$CO $J = 1$–0 emission and the $^{13}$CO $J = 1$–0 emission were taken simultaneously with the same receiver and the same backend at Mopra, we assume that the 10% relative calibration error is canceled for $R_{13/12}$ and adopt the error only for $R_{3/2-1/0}$. In addition, dv/dr is estimated for the individual regions, and X(CO) is assumed to be $10^{-4}$, the same as in Figure 8. Finally, $T_k$ and n(H$_2$) are given in the region where the curves of $R_{3/2-1/0}$ and $R_{13/12}$ overlap.

The results are summarized as follows: regions A–C in the ring cloud and all the regions in the finger cloud (regions F–J) show $T_k$ higher than 10 K, typically 30–40 K, up to more than 50 K. Typical n(H$_2$) values for these regions are about $10^3$–$10^4$ cm$^{-3}$, where only lower limits are given for regions A, B, and F2 and no solutions are given for regions F1 and I. Regions D and E located in the south of the ring cloud show...
significantly low \( T_k \) of less than 10 K and \( n(H_2) \) of \( \sim 3 \times 10^3 \) cm\(^{-3}\).

As a summary, both the ring cloud and the finger cloud show remarkably high temperatures of \( T_k > 20–30 \) K. Some heating source/mechanism is necessary to understand the results, and radiative heating by the O stars in RCW 38 is a reasonable mechanism. The present results suggest that, despite a large velocity separation of \( \sim 12 \) km s\(^{-1}\), both the ring cloud and the finger cloud are associated with RCW 38.

### 3.5. Molecular Masses of the Ring Cloud and the Finger Cloud

By adopting the distance of RCW 38, 1.7 kpc, for both the ring cloud and the finger cloud, their molecular masses are estimated. For a large scale, the NANTEN2 \(^{12}\)CO \( J = 1–0 \) data presented in Figures 2(a) and (b) are used to estimate the total molecular masses of the two clouds. We use an \( X(\text{CO}) \) factor of \( 2 \times 10^{20} \) cm\(^{-2}\) (K km s\(^{-1}\))\(^{-1}\) (Strong et al. 1988), which is an

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**Table 1**

Parameters of the \(^{13}\)CO Clumps I–IV

| Name     | R.A. (h m s) | Decl. (° m s) | \( \nu_{\text{LSR}} \) (km s\(^{-1}\)) | \( \Delta \nu \) (km s\(^{-1}\)) | Size (pc) | \( M_{\text{LTE}} \) (\( M_\odot \)) |
|----------|-------------|---------------|---------------------------------|-------------------------------|-----------|------------------|
| Clump I  | 8:59:9.2    | −47:29:1.5    | 5.0                             | 4.2                           | 0.5       | \( 1.0 \times 10^3 \) |
| Clump II | 8:59:12.5   | −47:30:16.9   | 1.7                             | 4.1                           | 0.4       | \( 8.8 \times 10^2 \) |
| Clump III| 8:59:8.4    | −47:31:29.7   | 2.3                             | 5.3                           | 0.3       | \( 5.7 \times 10^2 \) |
| Clump IV | 8:59:1.2    | −47:30:27.3   | 2.3                             | 4.8                           | 0.4       | \( 5.6 \times 10^2 \) |

**Note.** Columns: (1) Name, (2, 3) Position in J2000, (4, 5) Peak \( \nu_{\text{LSR}} \) and velocity width \( \Delta \nu \) (FWHM) of the \(^{13}\)CO \( J = 1–0 \) profile, where fitting with a Gaussian function is used to derive the parameters, (6) Size of the \(^{13}\)CO clump, measured as geometric average of major and minor diameters at the \(^{13}\)CO integrated intensity 45 K km s\(^{-1}\), (7) Molecular mass within the clump size with the assumption of LTE.

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**Table 2**

CO Velocity Range Corresponding to the Infrared Filaments in Figure 12

| Name       | \( \nu_{\text{LSR}} \) range (km s\(^{-1}\)) |
|------------|---------------------------------|
| a          | −1.7 to +0.7                     |
| b          | −1.7 to +0.7                     |
| c          | +0.7 to +3.1                     |
| d (two filaments) | −1.7 to +0.7          |
| e          | +0.7 to +3.1                     |
| f          | +0.7 to +3.1                     |
| g          | −1.7 to +0.7                     |
| h          | −4.1 to −1.7                     |

**Note.** Columns: (1) Name of the filament, (2) The typical velocity range in which \(^{13}\)CO \( J = 3–2 \) emission corresponds to the filament.
empirical conversion factor from $^{12}$CO $J = 1–0$ integrated intensity into H$_2$ column density. The masses estimated with the X(CO) factor (hereafter $M_{X(CO)}$) of the head–tail structure of the ring cloud and the finger cloud are calculated as $3.0 \times 10^4 M_\odot$ and $1.9 \times 10^3 M_\odot$ toward the regions enclosed with dashed lines in Figures 2(a) and (b), respectively. $M_{X(CO)}$ of the finger cloud is more than one order of magnitude smaller than that of the ring cloud.

The molecular masses of the central region of RCW 38 shown in Figure 3(b) are estimated with the Mopra CO data set. $M_{X(CO)}$ of the finger cloud is estimated to be $1.2 \times 10^3 M_\odot$ at a $^{12}$CO $J = 1–0$ integrated intensity $W(^{12}$CO $J = 1–0) \geq 10$ K km s$^{-1}$ ($= 3\sigma$). On the other hand, because the $^{12}$CO $J = 1–0$ intensity is reduced by the strong self-absorption, particularly in the central 1–2 pc of the ring cloud (see Figure 3(c)), we estimate the mass of the ring cloud using the Mopra $^{13}$CO $J = 1–0$ data assuming local thermodynamic equilibrium (LTE). In estimating the molecular mass with the assumption of LTE (hereafter $M_{LTE}$), excitation temperature $T_{ex}$ must be provided, and the peak intensity of the $^{12}$CO $J = 1–0$ emission $T(^{12}$CO) is usually used to estimate $T_{ex}$ with the following equation:

$$T_{ex}(K) = \frac{5.53}{\ln\{1 + 5.53/(T(^{12}$CO) + 0.819)\}}$$

Despite the strong self-absorption in the $^{12}$CO profiles, the observed brightness temperature in the $^{13}$CO clumps is typically very high, up to 45 K in clump III, which corresponds to $T_{ex}$ of 49 K in Equation (1). This figure is roughly consistent with the LBG analysis, resulting in $T_k > 30–50$ K (Figure 9) in regions A–C, which are located in the outskirts of the ring cloud. We therefore adopt a uniform $T_{ex}$ of 49 K and estimate $M_{LTE}$ of the dense ring structure of the ring cloud in Figure 3(d) to be $5.2 \times 10^5 M_\odot$ at a $^{13}$CO $J = 1–0$ integrated intensity $W(^{13}$CO $J = 1–0) \geq 22.5$ K km s$^{-1}$. $M_{LTE}$ of the four $^{13}$CO clumps in Figure 5(a) is estimated to be $1.0 \times 10^3 M_\odot$ for clump I, $8.8 \times 10^2 M_\odot$ for clump II, $5.7 \times 10^2 M_\odot$ for clump III, and $5.6 \times 10^2 M_\odot$ for clump IV at $W(^{13}$CO $J = 1–0) \geq 32.5$ K km s$^{-1}$ (see also Table 1). The H$_2$ column density $N$(H$_2$) of the $^{13}$CO clumps is typically as high as $1 \times 10^{23}$ cm$^{-2}$.

3.6. Comparisons with Infrared Images

Figure 11 shows a comparison between the $^{12}$CO $J = 1–0$ distribution and the Spitzer 3.6 μm image, which consists of several filamentary features around the central peak. Only panel (c) is for $^{13}$CO. Figure 11(a), a large-scale view, shows that the
Figure 9. LVG results on the $n$(H$_2$)--$T_k$ plane for the regions A–E in the ring cloud (see text). $^{12}$CO ($J = 3–2$)/($J = 1–0$) is plotted in black, and $^{13}$CO/$^{12}$CO $J = 1–0$ is in red. The regions A–E are plotted with black crosses in the CO integrated intensity map in the upper-left panel, where $^{13}$CO $J = 3–2$ is shown in color while $^{13}$CO $J = 1–0$ is shown with contours. Spectra of $^{12}$CO $J = 1–0$ (black), $^{12}$CO $J = 3–2$ (red), and $^{13}$CO $J = 1–0$ (blue) are also shown. Intensities of the $^{13}$CO $J = 1–0$ spectra are multiplied by three. The white cross indicates the position of IRS 2.
Figure 10. LVG results for the regions F–J in the finger cloud in the same manner as Figure 9.
ring cloud and the intense 3.6 μm emission correspond well with each other. The finger cloud in Figure 11(b) shows possible correspondence with the southern part of the 3.6 μm distribution at (R.A., decl.) = (08h 59m 5s, -47° 35'). Figure 11(c) compares the YSOs and O star candidates in the ring cloud. The YSO distribution corresponds to the overall distribution of the ring cloud, and the O stars to the northwestern part of the cavity of the ring cloud.

Figure 11(d) indicates that nearly 20 of the O stars are located toward the tip of the finger cloud overlapping with the bridging feature, while the distribution of the O stars shows an offset slightly toward the south of the peak of the finger cloud. The other YSOs do not show strong correlation with the finger cloud in the south (Figure 11(c)).

Figure 12 shows velocity channel distributions of CO overlaid on the infrared image. We label the nine infrared
filamentary features by a–h in the first panel of Figure 12. The CO features generally show good correspondence with the infrared features as listed in Table 2. Correspondence of the infrared image with the finger cloud is not so obvious in Figure 12. Figure 13, an overlay of the ring cloud and the finger cloud with the VLT image at a smaller scale, however, shows a good agreement between the finger cloud and IRS 1, which is elongated north to south, while the angular resolution of the CO distribution is too coarse for spatially resolving the bridging feature to a resolution comparable to the infrared image. We interpret that the dark lane toward IRS 1 along with another dust feature comprising the western cavity correspond to the finger cloud, which probably lies on the near side of the cluster. IRS 1 is clearly irradiated by the cluster and the physical association of the bridging feature with the cluster is supported.
Comparison of Five Regions of Cloud–Cloud Collision

| Name      | Cloud Masses ($M_\odot$) | Column Densities ($10^2$ cm$^{-2}$) | Velocity Separation (km s$^{-1}$) | # of O Stars | References |
|-----------|--------------------------|-------------------------------------|----------------------------------|--------------|------------|
| RCW 38    | $(2 \times 10^8, 3 \times 10^8)$ | $(1 \times 10^{22}, 1 \times 10^{22})$ | 12                              | ~20          | This study |
| NGC 3603  | $(7 \times 10^4, 1 \times 10^4)$ | $(1 \times 10^{22}, 1 \times 10^{22})$ | 20                              | ~30          | (1)        |
| Westerlund 2 | $(8 \times 10^4, 9 \times 10^4)$ | $(2 \times 10^{22}, 2 \times 10^{22})$ | 13                              | 14           | (2, 3)     |
| M20       | $(1 \times 10^3, 1 \times 10^3)$ | $(1 \times 10^{22}, 1 \times 10^{22})$ | 7                               | 1            | (4)        |
| RCW 120   | $(4 \times 10^3, 5 \times 10^3)$ | $(8 \times 10^{21}, 3 \times 10^{21})$ | 20                              | 1            | (5)        |

Note. Columns: (1) Name, (2, 3) Molecular masses and column densities of the two colliding clouds (blueshifted cloud, redshifted cloud), (4) Relative radial velocity between the two clouds, (5) Number of O stars created via cloud–cloud collision. (6) References: (1) Fukui et al. (2014), (2) Furukawa et al. (2009), (3) Ohama et al. (2010), (4) Torii et al. (2011), (5) Torii et al. (2015).

Figure 13. $^{12}$CO $J = 3-2$ distributions of the ring cloud (blue contours) and the finger cloud (red contours) superimposed on the VLT image in Figure 1. The contours are plotted at every 15 K km s$^{-1}$ from 130 K km s$^{-1}$ for the ring cloud and at every 5 K km s$^{-1}$ from 20 K km s$^{-1}$ for the finger cloud.

4. DISCUSSION

4.1. RCW 38 as the Youngest Super Star Cluster in the Milky Way

The number of known super star clusters in the Milky Way is 13, including RCW 38 and the 12 clusters listed in Table 2 of Portegies Zwart et al. (2010). The cluster members of RCW 38 were previously estimated to be a few thousand (Wolk et al. 2008) and RCW 38 was not included in the table by Portegies Zwart et al. (2010), which limited the cluster mass to be more than $10^4 M_\odot$. A recent estimate shows that RCW 38 harbors 10,000 stars (Kuhn et al. 2015) and it is appropriate to include RCW 38 as one of the super star clusters. Among the 13, RCW 38 is the youngest, with an estimated age of less than 1 Myr (Wolk et al. 2006; Sections 4.2 and 4.3 of the present work) and the ages of the others are $\gtrsim 2$ Myr. The Orion Nebula Cluster is listed as an OB association with an age of 1 Myr in Portegies Zwart et al. (2010). The ambient interstellar medium will reflect the youth of a cluster, and cloud dispersal by feedback will be less intensive in younger clusters than in more evolved clusters. According to visual inspection of the infrared images, only five clusters among the 13—RCW 38, NGC 3603, Westerlund 2, DBS[2003]179, and Trumpler 14—are associated with dust nebulosity, and their ages are from 2 to 3.5 Myr except for RCW 38. The remaining eight clusters, most of which have ages between 3.5 and 18 Myr, have no associated nebulosity, with the exception of the Arches cluster having an age of 2 Myr. It is likely that the interstellar medium around the eight clusters is completely dispersed by stellar feedback including ionization and stellar winds.

Figure 14 shows the averaged CO intensity in three clusters with nebulosity—RCW 38, NGC 3603, and Westerlund 2—and indicates that RCW 38 still has significant molecular mass within $\sim 3$ pc of the cluster. In Westerlund 2 and NGC 3603, whose ages are 2 Myr, the central part of the molecular clouds within 10 pc of the cluster is already strongly ionized/dispersed. The rich remaining gas toward the cluster is a
unique feature of RCW 38 and is consistent with its age being significantly less than 2 Myr. RCW 38 may therefore provide the best opportunity to study the initial conditions for the formation of a super star cluster.

4.2. The Two Clouds: Physical Association and Evidence for Collision

The present observations have revealed the distribution of the two molecular clouds with 12 km s\(^{-1}\) velocity separation toward RCW 38 at a spatial resolution of \(\sim 0.1\) pc. The following pieces of evidence offer robust verification of the association between the two clouds and the cluster.

1. The ring cloud shows a central cavity created by the feedback of the cluster. The ring cloud is also associated with the infrared filamentary/bubble-like features heated by the cluster. The finger cloud shows good correspondence with IRS 1 and the western cavity. The morphological correspondence supports the physical association of the clouds with the cluster.

2. The line intensity ratio of the \(^{12}\text{CO}\) \(J = 3−2\) emission to \(^{12}\text{CO}\) \(J = 1−0\) emission shows significantly high values, indicating high gas temperatures toward the cluster. LYG calculations show that the temperature there is higher than 20–30 K, consistent with local heating by the O stars in the cluster.

3. Another sign of the connection between the two clouds is the bridging features in velocity between them in at least three planes including the direction of the cluster center. An alternative possibility that the bridging features are due to stellar winds is unlikely, as discussed later in this section.

In RCW 38 the observed cloud velocity separation is large, 12 km s\(^{-1}\), as seen in the previous two cases Westerlund 2 and NGC 3603 (Furukawa et al. 2009; Fukui et al. 2014). The velocity is too large for the clouds to be gravitationally bound by the total mass of the clouds and cluster, which is less than \(10^4 M_\odot\). This indicates that the association of the two clouds is by chance. We frame a hypothesis that the two clouds collided with each other recently and that the collision triggered the formation of stars, primarily O stars, as has been suggested for Westerlund 2 and NGC 3603. We note that the fourth and fifth super star clusters with nebulosity, DBS[2003]179 and Trumpler 14, are also associated with two molecular clouds that appear to be colliding to form the cluster (S. Kuwahara et al. 2016, in preparation; Y. Fukui et al. 2016, in preparation). Therefore, it is possible that the formation of all five super star clusters with nebulosity is triggered by cloud–cloud collision, suggesting the important role of collision in the formation of a super star cluster and multiple O stars. In the remaining eight super star clusters without associated nebulosity it is not likely that we are able to detect the parent molecular clouds.

Stellar wind acceleration may be an alternative interpretation to cloud–cloud collision (e.g., see discussion in Furukawa et al. 2009). We see a velocity gradient in the finger cloud of RCW 38 (Section 3), which may suggest some acceleration by the O stars via the stellar winds. This is not likely, however, because the gradient extends outside the cluster and is rather uniform over the finger cloud; the velocity shift should be most prominent toward the cluster if the winds originating from the O stars play a role. We also note that the finger cloud is located on the nearside of the cluster as suggested by its coincidence with IRS 1 (Figure 13), implying that the wind acceleration will cause a blueshift instead of the observed redshift. The collision between the two clouds is therefore a plausible interpretation, and we exclude wind acceleration as the cause of the two velocities of the clouds.

The possible role of the winds in acceleration raises an alternative to the origin of the bridging feature toward the cluster center. Since the bridging feature, having a tight link with the finger cloud, shows a good correspondence with the O stars (Figure 11(d)), it may be part of the finger cloud accelerated by the stellar winds and not created by the collision. The mass of the bridging feature in Figure 11(d) is estimated to be \(17 M_\odot\) from the \(^{12}\text{CO}\) intensity with the \(X(\text{CO})\) factor. The kinetic energy in the bridging feature is estimated to be \(10^{46}\) erg, small enough to be accelerated by the winds of \(\sim 20\) O stars, whose kinetic energy can be more than \(10^{51}\) erg (e.g., in Furukawa et al. 2009). In this scenario, the wind-accelerated gas will be blueshifted since the finger cloud lies in front of the O stars. This contradicts the redshift of the bridging feature. The velocity range of the bridging feature, which lies only between the two velocities of the colliding clouds and not beyond the velocity of the finger cloud, is also consistent with the collision (Takahira et al. 2014; Haworth et al. 2015a, 2015b; Torii et al. 2015). The other two bridging features in the south (Figure 6) are not associated with O stars and it is unlikely that the winds are a source of acceleration. To summarize, the three bridging features are likely formed by the collisional interaction between the ring cloud and the finger cloud, lending additional support to the cloud–cloud collision.

Recent theoretical studies of global numerical simulations of galactic disks indicate that collisions between giant molecular clouds are frequent with a mean free interval of \(\sim 10\) Myr (Tasker & Tan 2009; Dobbs et al. 2015). This is comparable to the typical lifetime of a giant molecular cloud of 20 Myr (Fukui et al. 1999; Yamaguchi et al. 1999, 2001; Kawamura et al. 2009; Fukui & Kawamura 2010), suggesting that a giant molecular cloud experiences cloud–cloud collision more than once in its lifetime. It is also possible that the relatively rich molecular gas in the Vela molecular ridge where RCW 38 is located (Yamaguchi et al. 1999) favors more frequent encounters between clouds than the average over the Wilky Way.

4.3. Details of the Collisional Interaction

Currently, we see the two clouds, the bridging feature, and the O star cluster, all of which are within 1 pc of the cluster center. The ring cloud has a cavity of 0.3 pc radius that is likely ionized by IRS 2 and the other O stars. The finger cloud is probably being ionized and observed as IRS 1, whose surface is irradiated by the O stars. Theoretical studies of the collision scenario show that a shock-compressed interface layer is formed between the two clouds (Habe & Ohta 1992; Anathpindika 2010). It is likely that the major part of the interface layer has already been converted to O stars and that the bridging feature is a remnant of the interface layer.

By assuming tentatively that the relative cloud motion is inclined to the line of sight by 45°, we estimate the relative velocity of the two clouds to be 17 km s\(^{-1}\). The actual velocity of the shocked interface layer may be reduced by momentum conservation in the collision between the two clouds (e.g., Haworth et al. 2015a), and we adopt 10 km s\(^{-1}\) as the relative velocity of the interface layer. The distribution of the O stars formed by triggering...
is extended by about 1 pc (Figure 11). We estimate the typical collision timescale to be \( \sim 1 \text{ pc}/10 \text{ km s}^{-1} \approx 0.1 \text{ Myr} \), which gives roughly the age of the O stars in the cluster.

If we assume the O stars are formed by a constant mass accretion rate on the collision timescale of \( 10^3 \) years, the mass accretion rate is estimated to be \( 4 \times 10^{-4} M_\odot \text{ yr}^{-1} \) for a 40 \( M_\odot \) star (an O5.5 star). Magnetohydrodynamic numerical simulations of a cloud–cloud collision have shown that the turbulence is enhanced and the magnetic field is amplified in the interface layer (Inoue & Fukui 2013). This leads to an increase by two orders of magnitude in the mass accretion rate from the pre-collision state; e.g., a core of 126 \( M_\odot \) is formed in 0.3 Myr in the shocked interface layer as shown by model 4 of Inoue & Fukui (2013), and such a massive core is a promising precursor of an O star. The total mass of the O stars in RCW 38 is estimated to be \( \sim 20 \times 20 M_\odot = 400 M_\odot \), if we assume the typical mass of an O star to be 20 \( M_\odot \). This corresponds to \( \sim 10\% \) of the total \( ^{13}\text{CO} \) clump mass of the ring cloud, 3000 \( M_\odot \) (see Table 1).

The cavity of the ring cloud is created by ionization of the O stars. The propagating velocity of the ionization front is roughly estimated to be 3 km s\(^{-1}\) from a ratio of 0.3 pc/10\(^5\) yr. This is consistent with the velocity of the ionization front in a molecular cloud driven by H\(\text{II} \) regions (Spitzer & Tomasko 1968). In Figure 14 RCW 38 shows a molecular peak within 3 pc of the center, whereas the other two clusters, NGC 3603 and Westerlund 2, show a decrease of molecular gas within 10 pc of the cluster. This trend is explained as due to ionization. The latter two clusters have an age of 2 Myr, an order of magnitude greater than RCW 38. By taking a ratio of 10 pc/2 Myr, we roughly estimate the average velocity of the ionization front to be 5 km s\(^{-1}\), which is comparable to 3 km s\(^{-1}\) in RCW 38. If we assume the velocity of the ionization front to be 3–5 km s\(^{-1}\) and a common molecular cloud density, the ring cloud of 1 pc radius will be ionized within 0.2–0.3 Myr and triggered star formation will be completely terminated. This poses an upper limit of a few times 0.1 Myr for the age spread of the stars formed by triggering.

We note that the age spreads of the youngest members of the two super star clusters, NGC 3603 and Westerlund 1, are determined to be 0.1–0.3 Myr, an order of magnitude less than their cluster age of 2–5 Myr, by a careful photometric study with VLT for proper-motion-selected young cluster members with the Hubble Space Telescope (Kudryavtseva et al. 2012). We note that model calculations of NGC 3603 by Banerjee & Kroupa (2013, 2014) also suggest the rapid cluster formation through a single starburst event followed by significant residual gas explosion. The small age spread is possibly explained by the collision scenario so that formation of \( \sim 20 \) O stars by triggering is terminated quickly due to the ionization in the order of 0.1 Myr. Most of the low-mass stars were probably formed in the ring cloud prior to the cloud–cloud collision, since they are extended over the ring cloud with a radius of a few pc (Figure 1). We suggest that this naturally causes duality in the stellar age in RCW 38, i.e., young O stars of 0.1 Myr age and older low-mass stars of 1 Myr age, which is to be observationally confirmed for the cluster members in the infrared and X-rays. Such duality in age is also found in the other super star clusters (e.g., for NGC 3603, see Harayama et al. 2008).

### 4.4. Conditions for Multiple O Star Formation

It is shown that cloud–cloud collision triggered the formation of the O stars in center of the super star cluster RCW 38. The present two clouds show a sign of collisional interaction, the bridging features, in the three regions denoted as BR1, BR2, and BR3 in Figure 6. Only BR1 shows the formation of multiple O stars with a projected density of \( \sim 30 \text{ pc}^{-2} \) ([15/(1.0 pc \times 0.5 pc)], and BR2 and BR3 show no O star formation. The ring cloud has the highest molecular column density, \( 1 \times 10^{23} \text{ cm}^{-2} \), around BR1 and has a lower column density of \( (1–2) \times 10^{22} \text{ cm}^{-2} \) in BR2 and BR3. On the other hand, the finger cloud has a nearly uniform column density of \( 1 \times 10^{22} \text{ cm}^{-2} \), and the relative velocities between the two clouds are almost the same in the three regions. We suggest that the high column density is a necessary condition for O star formation in a cloud–cloud collision. The total molecular masses toward the three regions are estimated to be \( \sim 260 M_\odot, \sim 90 M_\odot, \) and \( \sim 100 M_\odot \), respectively, suggesting that BR2 and BR3 are probably not massive enough to form multiple O stars like in BR1, while it is possible that the collision is in its early phase prior to O star formation in BR2 and BR3.

Table 3 compares the observational properties of the molecular clouds in RCW 38 with the other two super star clusters, Westerlund 2 (Furukawa et al. 2009; Ohama et al. 2010) and NGC 3603 (Fukui et al. 2014), and with the single O stars in M20 (Tori et al. 2011) and RCW 120 (Tori et al. 2015), where cloud–cloud collision is suggested to be a trigger of O star formation. The comparison shows the trend that multiple O star formation as in RCW 38 is found only for a high column density of \( 10^{23} \text{ cm}^{-2} \) in either of the two clouds, whereas the cloud mass and relative velocity do not show a particular trend in multiple O star formation, i.e., the mass range is from \( 10^3 M_\odot \) to \( 10^5 M_\odot \) and the observed relative velocity is \( 10–30 \text{ km s}^{-1} \) in either multiple or single O star formation. The high column density in one of the two colliding clouds is therefore possibly a necessary condition for multiple O star formation.

The two scenarios for high-mass star formation—monolithic collapse and competitive accretion—are not yet verified by confrontation with observations (Tan et al. 2014, p. 149). Cloud–cloud collision, another possible scenario for high-mass star formation, provides three directly testable observational signatures: (1) two clouds associated with young O star(s) with (2) relative velocity greater than \( 10 \text{ km s}^{-1} \), and (3) the bridging feature between the two clouds. RCW 38 shows all three signatures.

According to Inoue & Fukui (2013), the effective sound speed in the shocked interface layer is isotropic and given roughly as the velocity separation of the two colliding gases. It is then possible that a low-velocity collision of molecular gas may lead to a lower mass accretion rate and formation of a lower mass star. Observations of low-mass star formation without O stars triggered by cloud–cloud collision have been presented by several authors (Duarte-Cabral et al. 2010; Higuchi et al. 2010; Nakamura et al. 2012). The relative velocity of these collisions is as small as a few km s\(^{-1}\), and leaves room for non-triggered star formation in a gravitationally bound system. The role of cloud–cloud collisions in low-mass star formation remains to be explored.
5. CONCLUSIONS

We have carried out CO J = 1−0 and J = 3−2 observations toward the super star cluster RCW 38 with Mopra, ASTE, and NANTEN2 millimeter/submillimeter telescopes. The main conclusions of the present study are summarized as follows.

1. We have revealed distributions of two molecular clouds at velocities of 2 and 14 km s$^{-1}$ toward RCW 38. The ring cloud (the 2 km s$^{-1}$ cloud) shows a ring-like shape with a cavity ionized by the cluster and has a high molecular column density of $\sim$10$^{23}$ cm$^{-2}$. The other, the finger cloud (the 14 km s$^{-1}$ cloud), has a tip toward the cluster and has a lower molecular column density of $\sim$10$^{22}$ cm$^{-2}$. The total masses of the ring cloud and the finger cloud are $3.0 \times 10^3 M_\odot$ and $1.9 \times 10^3 M_\odot$, respectively.

2. It is likely that the two clouds are physically associated with the cluster as verified by the high intensity ratio of the J = 3−2 transition to the J = 1−0 transition, $R_{J} \sim 2/1$−0, toward the cluster. The observed ratio indicates a kinetic temperature of $\geq$20−30 K according to the LVG calculations, which is significantly higher than the canonical molecular cloud temperature of 10 K with no extra heat source. The heating is mainly due to the O stars. The association is further supported by the distribution of the molecular clouds corresponding to the cluster and the infrared dust features; the ring cloud shows the cavity toward the cluster center and good coincidence with the extended dust features, and the finger cloud corresponds to the infrared ridge IRS 1. In addition, the two clouds are linked with each other by bridging features in velocity in at least three places including the direction of the cluster, supporting further the physical connection between the two clouds.

3. The total mass of the clouds and the cluster is less than $10^5 M_\odot$. The velocity separation of 12 km s$^{-1}$ is too large for the clouds to be gravitationally bound, and we suggest that the clouds encountered each other by chance. We present an interpretation in which the two clouds collided with each other 0.1 Myr ago at 17 km s$^{-1}$ to trigger formation of the O stars in the cluster. We argue that the double O5.5 star (IRS 2) was formed within this timescale at an average mass accretion rate $\sim$4 × 10$^{-4} M_\odot$ yr$^{-1}$.

4. The tip of the finger cloud and the bridging feature connecting the two clouds coincide well with the O stars within 0.5 pc of the cluster center, indicating that the triggering happened only toward the inner 0.5 pc and the other member low-mass stars outside 0.5 pc are pre-existing, being extended over the ring cloud where collisional interaction is not taking place. RCW 38 is the third super star cluster alongside Westerlund 2 and NGC 3603 where cloud–cloud collision triggered O star formation in a super star cluster, lending further support to the important role of supersonic collision in O star formation. Among the three super star clusters, RCW 38 is unique because it is the youngest cluster where the initial conditions prior to the O star formation still hold without significant cloud dispersal by stellar feedback beyond 1 pc.

5. The present findings suggest a possible recipe for O star formation in a super star cluster. Multiple O star formation is triggered where two clouds collide at a velocity of 10−30 km s$^{-1}$. One of the clouds has a high column density of $\sim$10$^{23}$ cm$^{-2}$ and the other has a lower column density. Since O star formation takes place only at the points of collision, the distribution of O stars retains the distribution of the collisional interaction as long as gravitational rearrangement of O stars after the collision does not play a role. This picture provides a natural setup for a highly turbulent interstellar medium as the initial condition for O star formation along the lines suggested by Zinnecker & Yorke (2007).

In order to better establish the role of cloud–cloud collision in O star formation, we need an extensive systematic study of molecular clouds toward a number of young H II regions and young stars whose mass exceeds 20 $M_\odot$. Such a study is ongoing and will allow us to test how cloud–cloud collision triggers and regulates O star formation. It is imperative to attain very high angular resolution in imaging the molecular gas to resolve dense cores in the shocked region, and ALMA is the most important instrument toward this goal. It is also a challenge to test whether mini-starbursts in galaxies are triggered by supersonic collisions between molecular clouds.

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REFERENCES

Anathpindika, S. V. 2010, MNRAS, 405, 1431
Banerjee, S., & Kroupa, P. 2013, ApJ, 764, 29
Banerjee, S., & Kroupa, P. 2014, ApJ, 787, 158
Bonnell, I. A., Vine, S. G., & Bate, M. R. 2004, MNRAS, 349, 735
Broos, P. S., Getman, K. V., Povich, M. S., et al. 2013, ApJS, 209, 32
DeRose, K. L., Bourke, T. L., Gutermuth, R. A., et al. 2009, AJ, 138, 33
Dobbs, C. L., Pringle, J. E., & Duarte-Cabral, A. 2015, MNRAS, 446, 3608
Duarte-Cabral, A., Fuller, G. A., Peretto, N., et al. 2010, A&A, 519, A27
Ezawa, H., Kawabe, R., Kohno, K., & Yamamoto, S. 2004, Proc. SPIE, 5489, 763
Ezawa, H., Kohno, K., Kawabe, R., et al. 2008, Proc. SPIE, 7012, 701208
Feigelson, E. D., Townsley, L. K., Broos, P. S., et al. 2013, ApJS, 209, 26
Freking, M. A., Langer, W. D., & Wilson, R. W. 1982, ApJ, 262, 590
Frogel, J. A., & Persson, S. E. 1974, ApJ, 192, 351
Fukui, Y., Harada, R., Tokuda, K., et al. 2015, ApJL, 807, L4
Fukui, Y., & Kawamura, A. 2010, ARA&A, 48, 547
Fukui, Y., Mizuno, N., Yamaguchi, R., et al. 2019, PASJ, 71, 745
Fukui, Y., Ohama, A., Hanaoka, N., et al. 2014, ApJ, 780, 36
Furniss, I., Jennings, R. E., & Moorwood, A. F. M. 1975, ApJ, 202, 400
Furukawa, N., Dawson, J. R., Ohama, A., et al. 2009, ApJL, 696, L115
Getman, K. V., Feigelson, E. D., Kahn, M. A., et al. 2014, ApJ, 787, 108
Goldreich, P., & Kwan, J. 1974, ApJ, 189, 441
Gyulbudaghian, A. L., & May, J. 2008, Ap, 51, 18
Habe, A., & Ohta, K. 1992, PASJ, 44, 203
Harayama, Y., Eisenhauer, F., & Martins, F. 2008, ApJ, 675, 1319
Haworth, T. J., Shima, K., Tasker, E. J., et al. 2015a, MNRAS, 454, 1634
Haworth, T. J., Tasker, E. J., Fukui, Y., et al. 2015b, MNRAS, 450, 10
Higuchi, A. E., Kurono, Y., Saito, M., & Kawabe, R. 2010, ApJ, 719, 1813
Huchtmeier, W. 1974, A&A, 32, 335

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