Formation, evolution, and survival of massive star clusters
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Formation of the super star cluster RCW 38 triggered by cloud-cloud collision

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Abstract. RCW 38 is the youngest super star cluster in the Galaxy and is located at a distance of 1.7 kpc. Molecular observations revealed that the cluster is associated with two molecular clouds having velocity difference of 12 km s^{-1}. We interpret that the two clouds are colliding with each other and the collision triggered the cluster formation. The natal molecular gas still survives within ∼0.5 pc of the central O stars which have an age of 0.1 Myrs as inferred from the collision morphology. We suggest that the high column density of one of the clouds 10^{23} cm^{-2} enabled formation of ∼20 O stars in the cluster center and discuss the implications on massive cluster formation.

Keywords. ISM: clouds — ISM: molecules — ISM: kinematics and dynamics — stars: formation

1. Introduction

It is an important question how massive stellar clusters are formed in the Universe. The globular clusters in the Galactic halo having mass of 10^5 $M_\odot$ are the most extreme of such massive clusters, whereas we are not able to witness their formation which happened more than 10 Byrs ago. An alternative way to approach the question is to make a detailed study of rich young clusters in the Local Group, while they are not as massive as the globular clusters.

The young super star clusters having 10^4 $M_\odot$ may allow us to explore the mechanism of massive cluster formation. There are 13 super star clusters known to date in the Galaxy; they include RCW38 in addition to 12 clusters listed by Portegies Zwart *et al.* (2010). RCW 38 is a rich and young super star cluster having 2000 stars with 30 O stars and is located at 1.7 kpc in the Galaxy (e.g., Wolk *et al.* 2008). RCW 38 whose age is estimated to be ∼0.5 Myrs (Wolk *et al.* 2006) is younger than any of the other 12 clusters. RCW 38 therefore deserves a detailed study of the natal molecular gas which may still hold the initial condition of massive cluster formation.

Recent molecular observations show that the two young super star clusters Westerlund 2 and NGC 3603 are formed by triggering of cloud-cloud collision (Furukawa *et al.* 2009, Ohama *et al.* 2010, Fukui *et al.* 2014). A theoretical study of colliding molecular gas flows (Inoue and Fukui 2013) demonstrates that the collision creates a turbulent interface layer where dense massive cores are formed, leading to high-mass star formation. It is important to explore if the other super star clusters are also formed via cloud-cloud collision, and RCW38 is one of the primary targets in such a follow-up study. We present the main results of the study in this contribution, while a fuller account of this work will be published elsewhere (Fukui *et al.* 2015).

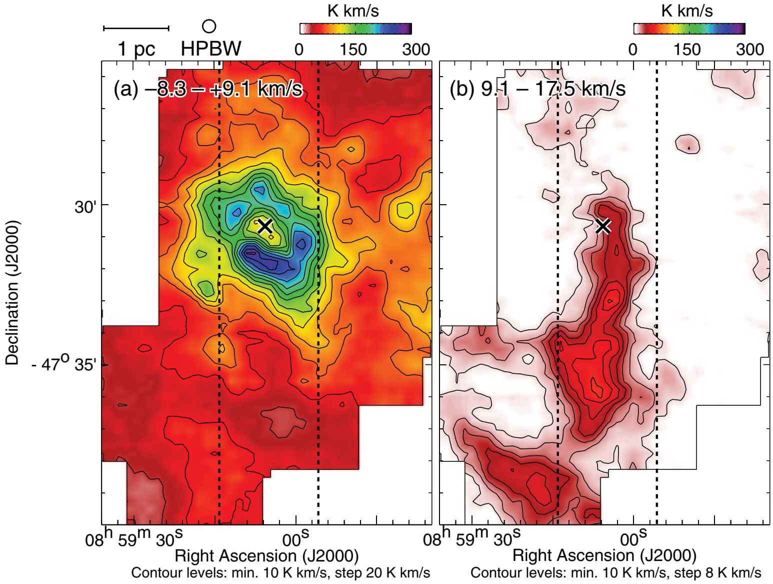

Figure 1. Mopra ^{12}CO J = 1–0 distributions of the two velocity clouds toward RCW 38 are presented. Cross indicates the position of IRS 2. Vertical dashed lines in each panel show the integration range of the declination-velocity diagram shown in Figure 2.

2. Results and interpretation

Observations of the molecular clouds were made in the rotational transition, ^{12}CO J = 1–0, J = 3–2, and ^{13}CO J = 1–0, with the three telescopes NANTEN2, ASTE and Mopra. The Mopra results, obtained through guiding by the NANTEN2 large scale data, are shown in Figure 1. The CO results show two clouds at velocities 2 km s^{-1} and 14 km s^{-1} toward RCW 38. The cloud at 2 km s^{-1} shows a ring-like shape (hereafter "ring cloud") where the cluster is located inside the ring and the other at 14 km s^{-1} is finger-like (hereafter "finger cloud"). We find a high ratio of the J = 3–2 transition to the J = 1–0 transition, $R_{3-2/1-0}$, greater than 0.8 toward the cluster in the two clouds. This high ratio indicates kinetic temperature higher than 30 K according to the LVG calculations and demonstrates that the two clouds are physically associated with the cluster and are radiatively heated up. The two clouds are linked by a bridging feature whose velocity is between the two clouds as shown in the declination-velocity diagram (Figure 2). The location of the central 20 O stars in the cluster shows good spatial correspondence with the top of the finger cloud and the bridging feature (Figure 3). We note similar bridging features are found in two regions in the southern outer skirt of the ring cloud where no star formation is seen (Figure 2). The physical association of the two clouds with the cluster is consistent with the similar distribution of the molecular clouds with the infrared dust features heated by the cluster; the ring cloud shows remarkable correlation with the extend dust features, and the finger cloud corresponds to the infrared ridge IRS 1 (Smith *et al.* 1999) toward the cluster.

Since the total mass of the clouds and the cluster is small, less than $10^5\ M_{\odot}$, the velocity separation 12 km s^{-1} is too large to be gravitationally bound. Based on these results, we frame a hypothesis that cloud-cloud collision took place recently and triggered formation of the O stars in RCW 38. It has been demonstrated that supersonic collision between molecular clouds forms a compressed interface layer where dense and massive cloud cores are formed (Inoue and Fukui 2013). This explains formation of the O stars and

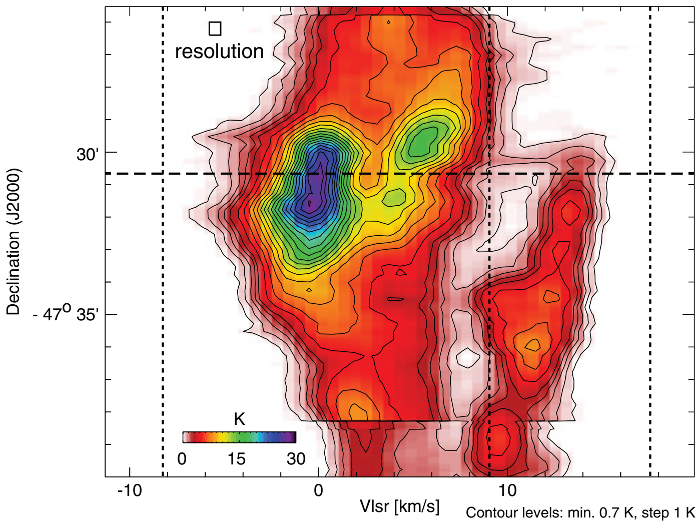

Figure 2. Declination-velocity diagram of the Mopra ^{12}CO $J = 1$–0 emission for the two clouds in RCW 38. Vertical dashed line indicates the direction of IRS 2.

the bridging feature, a typical signature of collision, as resulting from the gas acceleration in the collision (e.g., Haworth *et al.* 2015a, 2015b).

3. Discussion

The timescale of the collision is estimated to be very short $\sim 1 \times 10^5$ yrs as calculated by the ratio of the typical cloud size and the velocity, $\sim 1\,\mathrm{pc}/10\,\mathrm{km\ s^{-1}}$, where we adopt the width of the finger cloud as the cloud size. In the collision scenario, the formation time scale of the O stars is in the same order of magnitude with the collision time scale. The most massive star in RCW 38 is IRS 2 (DeRose *et al.* 2009), and the mass of this O5.5 star is around $40\,M_\odot$. The rest of the member O stars perhaps have $\sim 20\,M_\odot$ for each on average. The mass accretion rate for a $40\,M_\odot$ star is estimated to be $4 \times 10^{-4}\,M_\odot\,\mathrm{yr}^{-1}$ if the star was formed by a constant mass accretion rate in $\sim 1 \times 10^5$ yrs. The molecular mass in the collisional region is estimated to be $\sim 500\,M_\odot$ for typical molecular column density of 10^{23} cm^{-2} of the ring cloud. This suggests very high formation efficiency of the O stars whose total mass is $\sim 400\,M_\odot$ ($\simeq 20 \times 20\,M_\odot$).

RCW 38 is the youngest super star cluster known to date in the Galaxy. The age of the O stars estimated in the present collision interpretation is 0.1 Myrs, which does not contradict the estimate, $\sim$0.5 Myrs, obtained from the stellar photometric data (Wolk *et al.* 2006). RCW 38 is a rare case where the natal molecular gas still survives against the stellar feedback. The other two young super star clusters, Westerlund 2 and NGC 3603, where cloud-cloud collision played a role in triggering cluster formation, have an age of 2–3 Myrs (Furukawa *et al.* 2009, Ohama *et al.* 2010, Fukui *et al.* 2014). In these two clusters the molecular gas is almost fully ionized within a few pc of the cluster, and this does not allow one to see the details of the collisional interaction of the natal molecular gas (Figure 4).

The natal molecular gas in RCW 38 reveals significant details of the O star formation. Most importantly, the size of the O star distribution is similar to that of the collisional interaction, which shows the bridging feature. This suggests that the initial O star distribution is primarily determined by the collision. We also suggest that the O stars

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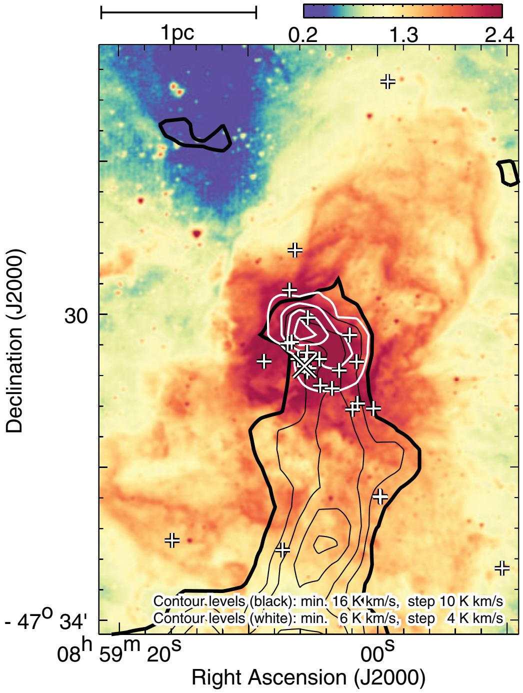

Figure 3. Contour maps of the finger cloud (black contours) and the bridge feature (white contours) are shown superimposed on the Spitzer/IRAC 3.6 μm image (Wolk *et al.* 2008). White crosses indicate IRS 2 (the O 5.5 star) and O star candidates identified by Wolk *et al.* (2006), where the large cross depicts IRS 2.

are formed toward the high molecular column density, 10^{23} cm^{-2}, in the ring cloud. A comparison of RCW 38 with regions of single O star formation in M 20 and RCW 120 indicates that column density is higher in RCW 38 than in M 20 and RCW 120 by an order of magnitude (Torii *et al.* 2011, 2015). This suggests that the high column density 10^{23} cm^{-2} is a necessary condition for multiple O star formation with O star density of 30 (pc)$^{-2}$ as found in RCW 38.

RCW 38 includes 2000 stars, most of which are low mass stars extended over the ring cloud beyond the region of the collisional interaction. These low mass stars are probably formed prior to the collision in the dense ring cloud over a time scale of a few Myrs. The low mass stars are not powerful enough to disperse the ring cloud and were coexistent with the ring cloud until the collision forms the O stars. At present the O stars are violently ionizing the ring cloud.

In the Galaxy, we have 13 super star clusters known to date. Five of them are associated with infrared nebulosity and are young with an age of 0.1 – 3 Myrs. We find that all the five clusters are associated with colliding two clouds including the two clusters, DSB[2003] 179 and Trumpler14 (Kuwahara *et al.* 2016 in preparation, Fukui *et al.* 2016 in preparation).

Magetohydrodynamical numerical simulations of colliding molecular gas demonstrate increase of the mass accretion rate by two orders of magnitude in the shock compressed interface after collision (Inoue and Fukui 2013), providing a theoretical ground for the rapid O star formation. It is possible that low-velocity collision between two molecular clouds causes smaller turbulence in the interface layer and may trigger formation of lower-mass stars by a lower mass accretion rate. Observations of low-mass star formation triggered by cloud-cloud collision are presented and discussed by several authors (Duarte-

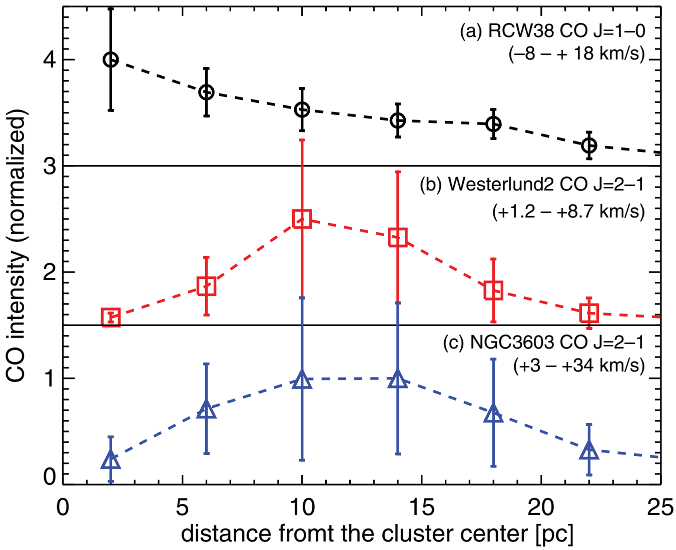

Figure 4. Radial distributions of the CO emission in the three massive star clusters RCW 38 (a), Westerlund 2 (b), and NGC 3603 (c). The CO data are taken from Fukui *et al.* (2015) for RCW 38, Furukawa *et al.* (2009) for Westerlund 2, and Fukui *et al.* (2014) for NGC 3603.

Cabralet al. 2010; Higuchi *et al.* 2010; Nakamura *et al.* 2013). The relative velocity as small as a few km s^{-1} in these works, however, leaves room for non-triggered star formation in a gravitationally bound system.

4. Implications on formation of massive clusters

The two scenarios for high-mass star formation in the literature, the monolithic collapse and competitive accretion, are not yet established by confrontation with observations (e.g., Zinnecker and York 2007, Tan *et al.* 2014). On the other hand, cloud-cloud collision provides another possible scenario for O star formation, and offers directly testable four observational signatures including (1) two clouds associated with young O stars with (2) relative velocity greater than 10 km s^{-1}, as long as the projection effect is not too large to significantly decrease observed velocity difference, (3) the bridging feature between the two velocities, and (4) the nested distribution between the two clouds as expected by numerical simulations of colliding clouds (Habe and Ohta 1992, Anathpindika 2010, and Takahira *et al.* 2014). The present observations of RCW 38 show signatures (1), (2) and (3). The lack of the nested distribution may be ascribed to the extreme youth of RCW38 which does not allow yet formation of a cavity in the extended cloud by the collision. The ionization by the O stars may also tend to destruct the nest distribution.

Although the samples of collision-induced super-star-cluster formation are limited to the five clusters at the moment, Westerlund 2, NGC 3603, RCW 38, DBS[2003] 179 and Tr 14, they are only clusters in the Galaxy where we are able to witness the natal molecular cloud. The rest of the clusters have no associated interstellar medium due to stellar feedback, prohibiting us from observing the possible colliding clouds. Along with the single O star formation in the other regions M 20 and RCW 120, it seems reasonable to consider cloud-cloud collision as one of the formation scenarios of massive cluster including globular clusters. It deserves further intensive efforts to study if cloud-cloud collision is a viable mechanism of massive cluster formation both observationally and theoretically.

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 mm/sub-mm telescopes. The main conclusions of the present study are summarized as follows; We observed two molecular clouds at velocities of 2 km s^{-1} and 14 km s^{-1} toward RCW 38. The two clouds, the ring cloud and the finger cloud, are physically associated with the cluster as verified by the high ratio of the J = 3–2 transition to the J = 1–0 transition, $R_{3-2/1-0}$, toward the cluster. In addition, the two clouds are linked with each other by bridging features in velocity in three places including the direction of the cluster, supporting the physical connection. We present an interpretation that the two clouds collided 0.1 Myrs ago at ∼10 km s^{-1} with each other to trigger formation of the O stars in the cluster. The ∼20 O star candidates were formed in this timescale with a high mass accretion rate. RCW 38 is the third super star cluster alongside of Westerlund 2 and NGC 3603 where cloud-cloud collisions triggered the O star formation in the cluster, lending further support for an important role of supersonic collision in formation of a super star cluster. 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 ionization. RCW 38 provides a rare sample to learn how super star clusters are forming in detail.

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