Molecular Clouds Toward the Super Star Cluster NGC 3603; Possible Evidence for a Cloud–Cloud Collision in Triggering the Cluster Formation

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ABSTRACT

We present new large field observations of molecular clouds with NANTEN2 toward the super star cluster NGC 3603 in the transitions 12CO(J = 2–1, J = 1–0) and 13CO(J = 2–1, J = 1–0). We suggest that two molecular clouds at 13 km s$^{-1}$ and 28 km s$^{-1}$ are associated with NGC 3603 as evidenced by higher temperatures toward the H$\textsc{ii}$ region, as well as morphological correspondence. The mass of the clouds is too small to gravitationally bind them, given their relative motion of $\sim$20 km s$^{-1}$. We suggest that the two clouds collided with each other 1 Myr ago to trigger the formation of the super star cluster. This scenario is able to explain the origin of the highest mass stellar population in the cluster, which is as young as 1 Myr and is segregated within the central sub-pc of the cluster. This is the second super star cluster along with Westerlund 2 where formation may have been triggered by a cloud–cloud collision.

Key words: ISM: clouds – open clusters and associations: individual (NGC 3603) – radio lines: ISM

Online-only material: color figures

1. INTRODUCTION

High-mass stars dynamically agitate and ionize the interstellar medium (ISM) in galaxies through strong radiation, stellar winds, and, eventually, supernova (SN) explosions. For example, the ultraviolet (UV) photons emitted from high-mass stars heat up cold molecular clouds and may inhibit star formation (e.g., Whitworth 1979; Franco et al. 1994). On the other hand, compressive effects such as the expansion of H$\textsc{ii}$ regions and SN explosions can collect diffuse gas to enhance star formation (e.g., Elmegreen & Lada 1977; Hosokawa & Inutsuka 2006). These feedback effects play an important role in regulating star formation in galaxies.

High-mass stars must be formed rapidly in dense molecular clumps in order to overcome the feedback effects from forming stars such as radiation pressure, which inhibits mass accretion (Tan & McKee 2004). The alternative scenario of stellar merging requires unreasonably large stellar densities of $\sim$10$^8$ M$\odot$ pc$^{-3}$ (Bonnell et al. 1998) and is not feasible in high-mass star formation in most galaxies. Elmegreen (1998) outlines three mechanisms by which the formation and collapse of dense clumps in giant molecular clouds (GMCs) may be dynamically triggered by external events. The first is globule squeezing, in which pre-existing dense clumps are compressed, either by high ambient pressures in H$\textsc{ii}$ regions or by shock waves propagating from SNe or other disturbances. The second is “collect and collapse,” in which gas accumulated into a shell or ridge by expanding H$\textsc{ii}$ regions, stellar winds or SNe collapses to form new dense clumps and stars. The third is cloud–cloud collisions, where two molecular clouds collide, leading to star formation via gravitational instabilities.

Most high-mass stars are formed in stellar clusters. Super star clusters (SSCs) are the most massive clusters in the Galaxy, with stellar densities exceeding 10$^4$ stars pc$^{-3}$ in their cores (Johnson 2005). There are several known SSCs in external galaxies, for example, R136 in the Large Magellanic Cloud (Hunter et al. 1995b; Massey & Hunter 1998) and NGC 604 in M33 (Hunter et al. 1995a; Maíz-Apellániz et al. 2004). In addition, the two colliding Antennae galaxies NGC 4038 and NGC 4039 have young massive star clusters of 10$^5$–10$^6$ M$\odot$, distributed across several kpc (Wilson et al. 2000). Collisions between galaxies will accumulate the ISM in a compact region, leading to the formation of gravitationally unstable dense clumps, and it is likely that such a collision can trigger massive cluster formation. It is, however, difficult to resolve the distribution of the parent molecular clouds in the Antennae galaxies because of their large distance, 20 Mpc. The detailed mechanism of SSC formation is therefore still a mystery because detailed observations of the parent clouds are not available at a sufficiently high spatial resolution. Within the Milky Way, there are eight known young SSCs with an age of a few Myr (Portegies Zwart et al. 2010). They are the Arches, Quintuplet, RCW38, Westerlund 2, Tr14, NGC 3603, Westerlund 1, and [DBS2003]179; in four of them (the Arches, Quintuplet, Tr14, and Westerlund 1), their parent molecular clouds appear to have been dissipated already due to stellar winds and/or UV photons (see Table 1). In the remaining four SSCs (RCW38, Westerlund 2, NGC 3603, and [DBS2003]179), we see signs of associated nebulousity at infrared wavelengths, and they are good candidates for identifying parent clouds.

Furukawa et al. (2009) and Ohama et al. (2010) presented observational evidence that a cloud–cloud collision may have
triggered the formation of the SSC Westerlund 2. These authors report two GMCs centered at 4 km s\(^{-1}\) and 16 km s\(^{-1}\). They argue that acceleration by stellar winds from Westerlund 2 is insufficient to explain the entire observed velocity dispersion of the molecular gas and suggest a scenario in which a collision between the two clouds may have triggered the formation of the SSC. Theoretical studies have modeled the triggering of star formation via cloud–cloud collisions (Habe & Ohta 1992; Anathpindika 2010), and such collisions are believed to be frequent in gas-rich galaxies (Tasker & Tan 2009).

Following the molecular line studies on Westerlund 2, this paper focuses on NGC 3603, which is similar in stellar age and mass. NGC 3603 is located at \((l, b) = (291.6, -0:5)\), close to the tangent of the Carina spiral arm. Discovered by Sir John Herschel in 1834, it is known at present as one of the most massive clusters in the Milky Way (Goss & Radhakrishnan 1969; Walborn 1973; Moffat 1983). The estimated age of the cluster is 1–2 Myr (e.g., Sung & Bessell 2004; Harayama et al. 2008), and the total stellar mass has been estimated to be \((1.0-1.6) \times 10^5 M_\odot\) (Harayama et al. 2008) and \((1.76 \pm 0.38) \times 10^4 M_\odot\) (Rochau et al. 2010). This rich stellar population includes more than 30 O-type stars (Moffat et al. 1989), and as high as 8 or even 10 kpc (Goss & Radhakrishnan 1969; Moffat 1974; Crowther & Dessart 1998). In the present work, we shall adopt a distance of 7 kpc, the mean of the published values.

Only a few molecular line observations of the NGC 3603 region have been reported to date. Grabelsky et al. (1988) carried out a large-scale \(^{12}\)CO(\(J = 1-0\)) observations of the Carina region at an 8.8 resolution and identify a molecular cloud at 15 km s\(^{-1}\) toward NGC 3603 listed as cloud No. 17. The total molecular mass of the cloud is \(4 \times 10^4 M_\odot\). These authors also identified another cloud near NGC 3603 at 29 km s\(^{-1}\) (No. 18), with an estimated molecular mass of \(1 \times 10^5 M_\odot\).

| Name       | \(l\) (deg) | \(b\) (deg) | \(D\) (kpc) | Age (Myr) | \(\log(M_{\text{mol}}/M_\odot)\) | Radius (pc) | IR Nebulosities | Referencea | Referenceb |
|------------|-------------|-------------|-------------|-----------|-------------------------------|-------------|----------------|-------------|-------------|
| Arches     | 0.12        | 0.02        | 8.0         | 2.0       | 4.3                           | 0.4         | No             | 1           |             |
| Quintuplet | 0.16        | -0.06       | 8.2         | 4.0       | 4.0                           | 2.0         | No             | 1           |             |
| RCW38      | 268.03      | -0.98       | 1.7         | \(<1.0\)  | \ldots                        | 0.8         | Yes            | 2           |             |
| Westerlund 2 | 284.25     | -0.40       | 5.4         | 2.0       | 4.0                           | 0.8         | Yes            | 3           | 7, 8        |
| Trumpler 14 | 287.41      | -0.58       | 2.6         | 2.0       | 4.0                           | 0.5         | No             | 4           |             |
| NGC 3603   | 291.62      | -0.52       | 7.0         | 2.0       | 4.1                           | 0.7         | Yes            | 5           |             |
| Westerlund 1 | 339.55      | -0.40       | 5.2         | 3.5       | 4.5                           | 1.0         | No             | 6           |             |
| [DBS2003]179 | 347.58     | 0.19        | 7.9         | 3.5       | 3.8                           | 1.2         | Yes            | 3           |             |

Notes. Column 1: name of cluster; Columns 2 and 3: position of cluster; Column 4: distance; Column 5: age of cluster; Column 6: mass of cluster; Column 7: radius of cluster; Column 8: association of IR nebulosities.

References.

\(^a\) Papers of clusters: (1) Figer et al. 1999; (2) Mizutani et al. 1987; (3) Pfalzner 2009; (4) Ascenso et al. 2007; (5) Harayama et al. 2008; (6) Clark et al. 2010, 2015.

\(^b\) Papers of molecular clouds: (7) Furukawa et al. 2009; (8) Ohama et al. 2010.

2. OBSERVATIONS

Observations of the \(J = 2–1\) transition of CO were made with the NANTEN2 4 m submillimeter telescope of Nagoya University at Atacama (4865 m above sea level) in 2008 October–November for \(^{12}\)CO(\(J = 2–1\)) and in 2009 October for \(^{13}\)CO(\(J = 2–1\)). The half-power beam width (HPBW) of the telescope was 90\(^\prime\) at 230 GHz. The 4 K cooled superconductor–insulator–superconductor (SIS) mixer receiver provided a typical system temperature of \(\sim 200\) K in a single sideband at 220–230 GHz, including the atmosphere toward the zenith. The spectrometer was an acousto-optical spectrometer with 2048 channels, providing velocity coverage of 392 km s\(^{-1}\) at 230 GHz. The pointing was checked regularly by observing the radio continuum emission from Jupiter and was accurate to within 10\(^\prime\). The target region was observed between elevation angles of 30\(^\circ\) and 60\(^\circ\). We observed a large area surrounding...
NGC 3603 in $^{12}$CO($J = 2–1$), while $^{13}$CO($J = 2–1$) observations are limited to a smaller region (see Figure 1). The OTF (on-the-fly) mapping mode was used in the observations, and the output grid of the region is 30”. We smoothed the velocity and spatial resolutions to 0.19 km s$^{-1}$ and 100”, respectively, to achieve a better noise level. Finally, we obtained rms noise fluctuations of $\sim 0.2$ K and $\sim 0.1$ K per channel in $^{12}$CO($J = 2–1$) and $^{13}$CO($J = 2–1$), respectively. The standard sources Ori KL (α, δ)$_{2000}$ = (5$^h$32$^m$14$^s$.5, −5$^\circ$22′27″.6) for $^{12}$CO($J = 2–1$) and $^{12}$CO($J = 2–1$), and $^{13}$CO($J = 2–1$) were observed for intensity calibration for $^{13}$CO($J = 2–1$) every 2 hr. We assumed true main-beam temperatures, $T_{mb}$, of 75–83 K in $^{12}$CO($J = 2–1$) as observed by the KOSMA telescope (Schneider et al. 1998) and 17 K in $^{13}$CO($J = 2–1$) as observed by the 60 cm Survey telescope (Nakajima et al. 2007).

Observations of the $^{12}$CO($J = 1–0$) and $^{13}$CO($J = 1–0$) transitions were made with the NANTEN2 telescope during 2011 September–November. The observations were carried out with a 4 K cryogenically cooled Nb SIS mixer receiver. The typical system temperature was $\sim 270$ K in the double sideband. Two digital spectrometers provided a bandwidth and resolution of 1 GHz and 61 kHz, which corresponds to 2600 km s$^{-1}$ with velocity resolution of 0.17 km s$^{-1}$, respectively, at 110 GHz. The pointing was checked regularly on the Sun by radio continuum emission. The HPBW of the telescope was 2′.6. Observations of $^{12}$CO($J = 1–0$) and $^{13}$CO($J = 1–0$) were simultaneously made in the OTF mode with a 1′ grid spacing. We smoothed the velocity and spatial resolutions to 0.66 km s$^{-1}$ and 163″, respectively. Finally, we obtained rms noise fluctuations of $\sim 0.3$ K and $\sim 0.2$ K per channel in $^{12}$CO($J = 1–0$) and $^{13}$CO($J = 1–0$), respectively. We used the standard sources Ori KL (α, δ)$_{2000}$ = (5$^h$32$^m$14$^s$.5, −5$^\circ$22′27″.6) for $^{12}$CO($J = 1–0$) and $^{13}$CO($J = 1–0$).

3. RESULTS

3.1. Morphological and Kinematic Analysis

Figure 1 shows the large-scale $^{12}$CO($J = 1–0$) distribution toward NGC 3603, including only the positive velocity clouds on the far side of the Carina arm (Mizuno & Fukui 2004). NGC 3603 is located between the two brightest peaks of $^{12}$CO($J = 1–0$) in the center of Figure 1. Figures 2–5 show the velocity channel distributions of the $^{12}$CO($J = 2–1$), $^{13}$CO($J = 2–1$), $^{12}$CO($J = 1–0$), and $^{13}$CO($J = 1–0$) emission, respectively. The velocity range of these figures (from 3.2 km s$^{-1}$ to 34.7 km s$^{-1}$) was chosen to include all features in the vicinity of NGC 3603. The bright CO cloud peaked at around 13 km s$^{-1}$ (cloud No. 17; Grabelsky et al. 1988) has two peaks on the north and south of NGC 3603 and is obviously associated with NGC 3603, and the other weak CO features at around 28 km s$^{-1}$ are additional candidates for associated clouds (cloud No. 18; Grabelsky et al. 1988). We name the former the blueshifted cloud and the latter the redshifted cloud. The blueshifted cloud is compact and intense, while the redshifted cloud is extended and weak. We give the parameters toward the two peaks of the two clouds in Table 2. The molecular column density is generally 10 times higher in the blueshifted cloud than in the redshifted cloud.

Figures 6(a) and (b) show $^{12}$CO($J = 1–0$) position–velocity diagrams of NGC 3603. We see the two velocity components at 13 km s$^{-1}$ and 28 km s$^{-1}$ and a bridging feature in the velocity range 18–25 km s$^{-1}$ between the two clouds at $b = −0.6$ in Figure 6(a) and at $l = 291.5–291.7$ in Figure 6(b).

Figures 7 and 8 show the distributions of the two clouds in $^{12}$CO($J = 2–1$) overlaid on the infrared images in $JHK$ bands, 8.3 μm, and 25 μm. For the blueshifted cloud, we see that the molecular distribution is correlated with the cluster and the H II region. First, the cloud shows a depression toward the cluster at all CO lines, which suggests that the molecular gas toward the cluster has been dispersed by ionization/stellar winds. Second, the $JHK$ distribution (Figure 7(b)) shows that the northern peak of the blueshifted cloud coincides with $K$-band obscuration whose southeastern edge is delineated clearly at ($l, b$) = 291.5–291.65, $−0.5$ to $−0.55$; Figures 7(c) and (d)). For the redshifted cloud, we also see a hint of association between the cloud and the cluster/H II region, because the cloud shows a similar depression toward the cluster, suggesting cloud dispersal due to the cluster. Obscuration by the redshifted cloud is too small to affect the near-infrared image ($A_j, A_H, A_K = 0.1–0.7$ mag; see Table 2), and it is unclear if the cloud lies in front of or behind the cluster.

3.2. Temperature and Density of the Molecular Clouds

In order to investigate the temperature of the molecular gas, which is a good indicator of physical association of the clouds with the cluster, we first examine the ratio of the CO($J = 2–1$) and CO($J = 1–0$) line intensities.

Figures 9(a) and (b) show the distributions of the ratio of $J = 2–1$ to $J = 1–0$ line integrated intensities in $^{12}$CO and $^{13}$CO, for the blueshifted cloud. The $^{12}$CO distribution shows that the ratio is enhanced significantly near the cluster. We also see another enhancement of the ratio at the northern edge of the cloud. The high ratio of $^{12}$CO (above 1.0) suggests high temperatures due to extra heating by high-mass stars, since the typical ratio is around 0.6 in clouds with no extra heat source (e.g., Sakamoto et al. 1997; Torii et al. 2011). We infer that the
Figure 2. Velocity channel maps of $^{12}$CO($J=2\rightarrow1$) intensity integrated over 3.5 km s$^{-1}$ bins. Contours are drawn every 6.0 K km s$^{-1}$ from 2.4 K km s$^{-1}$. The cross corresponds to the position of the cluster NGC 3603. (A color version of this figure is available in the online journal.)

Table 2

Observed Properties of the Blueshifted Cloud and the Redshifted Cloud

| Name                  | $l$  | $b$  | $W[^{12}$CO($J=1\rightarrow0$)] (K km s$^{-1}$) | $N_{H_{2}}$ ($10^{21}$ cm$^{-2}$) | $A_{V}$ (mag) | $A_{J}$ (mag) | $A_{H}$ (mag) | $A_{K}$ (mag) |
|-----------------------|------|------|------------------------------------------------|-------------------------------|---------------|---------------|---------------|---------------|
| Blueshifted Cloud North | 291.58 | -0.42 | 150                                           | 30                            | 31.8          | 9.0           | 6.0           | 3.6           |
| Blueshifted Cloud South | 291.64 | -0.55 | 80                                            | 16                            | 17.0          | 4.8           | 3.2           | 1.9           |
| Redshifted Cloud North | 291.56 | -0.50 | 6                                             | 1.2                           | 1.3           | 0.4           | 0.2           | 0.1           |
| Redshifted Cloud South | 291.64 | -0.58 | 12                                            | 2.4                           | 2.5           | 0.7           | 0.5           | 0.3           |

Notes. Column 1: name of the cloud. Columns 2 and 3: peak position of the cloud. Column 4: integrated intensity of the $^{12}$CO($J=1\rightarrow0$) emission. Column 5: molecular column density. Column 6: visual extinction given by $A_{V}/N_{H_{2}} = 5.3 \times 10^{-22}$ mag cm$^{-2}$ H$^{-1}$ (Bohlin et al. 1978) and $N_{H_{2}} = 2 N_{H}$. Here we assumed $R_V = A_V/E(B-V) = 3.1$. Column 7-9: extinction at $J$ (1.2 $\mu$m), $H$ (1.7 $\mu$m), and $K$ (2.2 $\mu$m) bands, respectively. Here we adopted an extinction law of Cardelli et al. (1989); $A_J/A_V = 0.28$, $A_H/A_V = 0.19$, and $A_K/A_V = 0.11$.

The blueshifted cloud as a whole is heated up by the cluster. The heating is especially significant in the region within $\sim$5 pc of the cluster, where the ratio is higher than 1.5. The $^{13}$CO ratio is also enhanced to 1.0–2.7 within 10 pc of the cluster. We suggest that the irradiated surface layer of the cloud is better traced in the optically thick $^{12}$CO than in the optically thin $^{13}$CO. The redshifted cloud is not significantly detected in $^{13}$CO, and we show only the distribution of the $^{12}$CO ratio in Figure 9(c). The redshifted cloud also shows enhanced ratios above 1.0 within a few pc of the cluster, suggesting that the cloud is also heated up by the cluster.

We chose here four positions for a detailed analysis of temperature and density. They are shown by letters A–D in Figure 9, and their coordinates are given in Table 3. The CO line profiles are shown in Figure 10. All four lines of $^{13}$CO and $^{12}$CO are detected in the four positions in the blueshifted cloud, while only the two $^{12}$CO lines are detected in the two positions in the redshifted cloud.
In order to estimate the kinetic temperature and number density of the molecular clouds, we carried out a large velocity gradient (LVG) analysis (Goldreich & Kwan 1974). The employed model assumes a spherically symmetric cloud where kinetic temperature $T_{\text{kin}}$, number density $n(H_2)$, and the radial velocity gradient $dV/dr$ are taken to be uniform. We varied $T_{\text{kin}}$ and $n(H_2)$ within $T_{\text{kin}} = 6$–500 K and $n(H_2) = 10^2$–$10^6$ cm$^{-3}$, where we fix $X(\text{CO})/(dV/dr) = 6.3 \times 10^{-5}$ (km s$^{-1}$ pc$^{-1}$)$^{-1}$. We assume $X(\text{CO}) = [^{12}\text{CO}]/[\text{H}_2] = 10^{-4}$ (e.g., Frerking et al. 1982; Leung et al. 1984) and a velocity gradient of 1.4 km s$^{-1}$ pc$^{-1}$. This value of $dV/dr$ was derived by taking the average ratio between the cloud size and velocity width for the four clouds shown in Figure 10 (A–D). For the isotope ratio of $^{12}$C/$^{13}$C, we adopt 75 at the Galactocentric distance of $\sim$9 kpc (Milam et al. 2005). We derived $T_{\text{kin}}$ and $n(H_2)$ in the four positions of the blueshifted cloud. We used the line intensity ratios of the $^{12}$CO($J = 2–1$), $^{13}$CO($J = 2–1$), and $^{13}$CO($J = 1–0$) transitions. The $^{12}$CO($J = 1–0$) line was not used here because it may be optically thick and samples mainly the surface layer of the cloud. Figure 11 shows the results, and the derived values are listed in Table 3. The temperature is significantly enhanced with respect to quiescent molecular cloud temperatures, falling in the range $30$–$50$ K in the blueshifted cloud for a density of $(3–5) \times 10^3$ cm$^{-3}$, confirming significant heating by the cluster.

We then estimate the temperature range of the redshifted cloud from the line intensity ratio of $^{12}$CO($J = 2–1$) to $^{12}$CO($J = 1–0$). Figure 12 shows the ratio as a function of density and temperature, where the line intensity is calculated by the LVG approximation. The molecular column density at positions A and C is estimated from the $^{12}$CO($J = 1–0$) integrated intensity by using an empirical X-factor of $2.0 \times 10^{20}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$. By assuming the width of the cloud to be $\sim$1 pc from the $^{12}$CO($J = 2–1$) distribution, we estimate that the density is lower than $\sim 10^3$ cm$^{-3}$ and that the secure lower limit for temperature is estimated to be higher than 20 K for the 3$\sigma$ error limit in Figure 12. This indicates that the redshifted cloud is also heated up by the cluster NGC 3603, the only known strong heat source toward the direction.

Based on the analysis above, we conclude that the two clouds are located within $\sim$10 pc of the cluster and adopt 7 kpc as the distance, the same value as that of the cluster, instead of their kinematic distances of 8–9 kpc. For this distance the cloud masses are estimated to be $7.2 \times 10^3 M_\odot$ and $1.2 \times 10^4 M_\odot$ for the blueshifted cloud and the redshifted cloud, respectively (Table 4).

### 4. DISCUSSION

Previous work has shown that the 13 km s$^{-1}$ molecular cloud is physically linked to the SSC NGC 3603 as shown by the PDR irradiated by the cluster (Röllig et al. 2011). The present observations confirm this and also show that there is another extended molecular cloud at 28 km s$^{-1}$ toward NGC 3603. We suggest that the 13 km s$^{-1}$ molecular cloud (blueshifted cloud) and the 28 km s$^{-1}$ molecular cloud (redshifted cloud) are both physically associated with NGC 3603. The association is

| Name          | Position | $l$ (deg) | $b$ (deg) | $V_{lsr}$ (km s$^{-1}$) | $R_1$ | $R_2$ | $T_{\text{kin}}$ (K) | $n(H_2)$ (cm$^{-3}$) |
|---------------|----------|-----------|-----------|-------------------------|-------|-------|----------------------|----------------------|
| Blueshifted   | A        | 291.55    | −0.50     | 12.4–17.7               | 1.20  | 0.84  | $23^{+7}_{-5}$        | $1.5 \pm 0.3 \times 10^3$ |
|               | B        | 291.58    | −0.43     | 12.4–17.7               | 1.57  | 1.40  | $43^{+10}_{-8}$       | $2.6 \pm 0.6 \times 10^3$ |
|               | C        | 291.60    | −0.50     | 12.4–17.7               | 1.62  | 1.39  | $45^{+10}_{-9}$       | $2.5 \pm 0.6 \times 10^3$ |
|               | D        | 291.66    | −0.58     | 12.4–17.7               | 1.37  | 1.47  | $44^{+10}_{-9}$       | $3.0 \pm 0.5 \times 10^3$ |
| Redshifted    | A        | 291.55    | −0.50     | 26.0–30.0               | 0.92  | ...   | $\gtrsim 20$          | $\lesssim 10^{3}$ $^a$ |
|               | C        | 291.60    | −0.50     | 26.0–30.0               | 0.92  | ...   | $\gtrsim 20$          | $\lesssim 10^{3}$ $^b$ |

**Notes.** Column 1: name of the cloud; Column 2: observed points of the cloud; Column 3: galactic longitude of the position; Column 4: galactic latitude of the position; Column 5: range of velocity integrated; Column 6: ratio of $^{12}$CO($J = 2–1$)/$^{12}$CO($J = 1–0$); Column 7: ratio of $^{13}$CO($J = 2–1$)/$^{13}$CO($J = 1–0$); Column 8: kinetic temperature; Column 9: number density of H$_2$.

$^a$ Lower limit.

$^b$ Upper limit.
Figure 4. Velocity channel maps of $^{12}$CO($J=1$–0) intensity integrated over 3.5 km s$^{-1}$ bins. Contours are drawn every 6.0 K km s$^{-1}$ from 2.4 K km s$^{-1}$. The cross corresponds to the position of the cluster NGC 3603.

(A color version of this figure is available in the online journal.)

Table 4

| Name           | Mass  | $R$  |
|----------------|-------|------|
|                | ($10^4$ $M_\odot$) | (pc) |
| Blueshifted cloud | 7.2   | 12.3 |
| North          | 5.5   | 12.3 |
| South          | 1.7   | 8.4  |
| Redshifted cloud | 1.2   | 5.1  |
| North          | 0.4   | 5.1  |
| South          | 0.8   | 6.9  |

Notes. Column 1: name of the cloud; Column 2: position of the cloud; Column 3: cloud mass derived using an X-factor of $2.0 \times 10^{20}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$; Column 4: radius of the cloud.

verified by the high temperature of the molecular clouds toward the cluster as derived from an analysis of multiple CO transitions and is consistent with the morphological correlation between CO and NGC 3603. This is a similar situation to the two molecular clouds associated with the SSC Westerlund 2/RCW49. For Westerlund 2, it is suggested that a collision between the two clouds triggered formation of the cluster, where the relative velocity is ascribed to the original bulk motion of the clouds (Ohama et al. 2010), and it is possible that a similar collisional process is also working in NGC 3603.

By considering possible projection effects, the observed line-of-sight velocity separation gives a lower limit for the actual relative velocity. If we assume random cloud motions primarily restricted to the Galactic plane, we obtain $\sqrt{2} \times 15$ km s$^{-1}$ as the relative velocity. The total mass required to gravitationally bind the two clouds is $10^6$ $M_\odot$ within 10 pc of the cluster, which is an order of magnitude larger than the total mass inside the system of $\sim 10^5$ $M_\odot$. We examine an idea that the cloud velocity separation is due to feedback from the cluster or nearby objects. Supernova remnants (SNRs) may be a possible source of the kinetic energy. There are two SNRs near the region: SNR G292.5–0.1 (Whiteoak & Green 1996) and SNR G292.5–0.5 (Crawford et al. 2001) with a pulsar PSR J1119–6127 (Gonzalez et al. 2007; Safi-Harb & Kumar 2008). These are, however, separated from NGC 3603 by 0.5° and are not likely to be affecting the molecular clouds. It is also possible that nearby SNRs older than $10^5$ yr may have affected the cloud motion via SN shock waves in the last Myr. If they were influential, one may expect a curved velocity field in the two.
Figure 5. Velocity channel maps of $^{13}$CO($J = 1–0$) intensity integrated over 3.5 km s$^{-1}$ bins. Contours are drawn every 2.0 K km s$^{-1}$ from 1.4 K km s$^{-1}$. The cross corresponds to the position of the cluster NGC 3603.

(A color version of this figure is available in the online journal.)

Figure 6. (a) Velocity vs. galactic latitude diagram for $^{12}$CO($J = 1–0$) emission integrated over a longitude range of 291$^\circ$51–291$^\circ$71. Contours are plotted every 0.06 K degree from 0.02 K degree. The solid lines depict the extent of the H II region observed by the Spitzer Space Telescope. The dashed line depicts the latitude position of NGC 3603. (b) Velocity vs. galactic longitude diagram for $^{12}$CO($J = 1–0$) emission integrated over a latitude range of $-0.70$ to $-0.20$. Contours are plotted every 0.15 K degree from 0.15 K degree.

(A color version of this figure is available in the online journal.)
GMCs that may last over 1 Myr. The peak velocity distributions of the present two GMCs are, however, fairly uniform (Figure 6), suggesting that such stellar acceleration was not influential.

The velocity difference is not likely due to the stellar-wind acceleration, either. It is noted that the stellar winds in NGC 3603 are affecting an area only within 1 pc of the cluster (Balick et al. 1980; Clayton 1986, 1990), while the H II region ionized by the cluster is extended within a 10 pc radius (Clayton 1986, 1990). The redshifted cloud is extended far beyond 10 pc with no large velocity shift in the order of 10 km s$^{-1}$, indicating that the cloud is not strongly affected by the stellar winds, while a small velocity redshift of $\sim 2$ km s$^{-1}$ toward the cluster within 10 pc in the redshifted cloud (Figure 6) may possibly be ascribed to the stellar-wind acceleration. The kinetic energy of this shift is estimated to be $\sim 3 \times 10^{57}$ erg and can be supplied by the stellar winds having kinetic energy $\sim 5 \times 10^{51}$ erg for a 1 Myr timescale of the highest mass O stars (Drissen et al. 1995). If the velocity separation between the two clouds is mainly due to the stellar winds, the velocity separation of the compact blueshifted cloud 20 km s$^{-1}$ might be ascribed to such acceleration. The kinetic energy of the blueshifted cloud relative to the redshifted cloud is $\sim 1.6 \times 10^{50}$ erg for the cloud mass $8.4 \times 10^{4} M_{\odot}$ and the relative velocity 20 km s$^{-1}$. This energy corresponds to several percent of the stellar wind energy, and the acceleration may be possible if the energy requirement alone is considered. A serious difficulty here, however, is that the blueshifted cloud shows no such a trend that the velocity separation from the redshifted cloud becomes large toward the cluster at a pc scale. The cluster is apparently located on the axis of the cloud elongation in the north to south, and the cloud geometry suggests that most of the cloud cannot be exposed to the winds from the cluster. This is a quite unfavorable configuration for the cloud to be accelerated. Remembering that the stellar winds are affecting only 1 pc radius (Balick et al. 1980; Clayton 1986, 1990), we conclude that it is highly unlikely that the blueshifted cloud as a whole was accelerated by the stellar winds of NGC 3603.

We consider that the association of the two clouds is by chance, and that they were moving independently before their encounter. The relative velocity 20 km s$^{-1}$ is likely due to random motion of the clouds. We here present a scenario that a cloud–cloud collision between the two clouds triggered the formation of NGC 3603. The bridging feature discussed in Section 3.1 suggests that the two clouds are physically interacting; numerical simulations of cloud–cloud collisions
find the intermediate velocity features between the two colliding clouds (Habe & Ohta 1992; Anathpindika 2010; Anathpindika & Bhatt 2012). In these models two colliding clouds form a compressed layer that is highly turbulent and dense, leading to the formation of dense clumps where high-mass stars are formed. NGC 3603 is the second case of such a collision-induced formation of an SSC along with Westerlund 2, if the scenario is correct. In NGC 3603, we infer that the collision took place \( \sim 1 \) Myr ago as estimated by the ratio of the cloud size 20 pc and the velocity separation 20 km s\(^{-1}\). This timescale is consistent with the age estimates for the starburst cluster in NGC 3603 in the range of 1–2 Myr (e.g., Kudryavtseva et al. 2012). The above obviously gives an order-of-magnitude estimate at best, and the value may be different by a factor of \( \sim 2 \) due to projection effects in space and velocity and to the unknown configuration of the clouds prior to the collision. It is nonetheless quite unnatural that the timescale can be different by a factor of 10. We suggest that the molecular mass compressed by the collision is around \( 10^4 M_\odot \), which corresponds to the mass of a cloud with a molecular column density of \( 10^{23} \) cm\(^{-2}\) for a radius of 1.5 pc. The highest molecular column density observed is \( 6 \times 10^{22} \) cm\(^{-2}\) toward the northern peak of the blueshifted cloud, supporting the assumption of such a high column density as the initial condition prior to the collision.

In NGC 3603 recent observations indicate that the age spread of the member stars is very short, less than 0.1 Myr (Kudryavtseva et al. 2012). This spread is significantly shorter than the sound-travel time of 1 Myr for an effective sound speed of 1 km s\(^{-1}\) over 1 pc. The small age spread supports the idea of external triggering with a supersonic shock wave transversing the molecular clouds (e.g., Habe & Ohta 1992; Anathpindika 2009; Inoue & Fukui 2013), and the cloud–cloud collision at a high speed of 20 km s\(^{-1}\) provides a reasonable explanation for the age spread. Brandner et al. (1997) derived a systemic
velocity of $V_{\text{LSR}} = 19$ km s$^{-1}$ for the ring nebula associated with a B-type supergiant Sher 25 in NGC 3603; the velocity is between those of the two GMCs and is closer to that of the more massive (the blueshifted) cloud. In addition, the velocities of the recombination lines and OH absorption lines measured for the nebula surrounding NGC 3603 are 8–14 km s$^{-1}$ in $V_{\text{LSR}}$ (Moffat & Niemela 1984, and references therein), similar to that of the blueshifted cloud, which has a larger molecular column density than the redshifted cloud. This is consistent with the fact that the formed cluster tends to inherit the velocity of the more massive cloud.

The higher mass stars above 20 $M_\odot$ have a different slope from that of the lower mass stars in the mass function in NGC 3603 (Harayama et al. 2008). It is possible that stars of less than 20 $M_\odot$ may have large ages of more than several Myr and may have been already formed prior to the collision. Recent studies show some low-mass cluster members obviously older than 3 Myr (e.g., Kudryavtseva et al. 2012; Pang et al. 2013), suggesting a low level of star formation activity prior to the cloud–cloud collision. The formation of high-mass stars can take place on the order of 10$^5$ yr at a very high mass accretion rate of $10^{-3} M_\odot$ yr$^{-1}$ as theoretically suggested (Tan & McKee 2002). This high mass accretion rate is sustainable because of the increased turbulence in the shocked layer, which is created by the supersonic collision (Anathpindika 2010; Inoue & Fukui 2013). Another issue is the mass segregation of higher mass stars toward the cluster (e.g., Sung & Bessell 2004); it has been a puzzle how the mass segregation of the higher mass stars takes place in rich clusters, including NGC 3603, because gravitational segregation is a long-term process that takes over 10 Myr (Zinnecker & Yorke 2007; Harayama et al. 2008). Cloud–cloud collisions have the potential to cause such mass segregation at the spot of the collisional interaction where molecular density distribution has peaked prior to the collision.
Figure 10. CO spectra at the positions of the clouds shown in Figure 9. CO intensity is plotted at half of its true value for point B. $^{12}$CO($J=1-0$), $^{12}$CO($J=2-1$), $^{13}$CO($J=1-0$), and $^{13}$CO($J=2-1$) are plotted in black, red, green, and blue, respectively. All spectra were smoothed to be a beam size of 2.6.

Figure 11. LVG results for $X_{\text{CO}}/(dv/dr) = 6.3 \times 10^{-5} \text{ (km s}^{-1} \text{ pc}^{-1})^{-1}$, assuming a distance of 7.0 kpc, are shown in the density–temperature plane. Solid line and dashed lines show $^{12}$CO($J=2-1)/^{12}$CO($J=1-0$) intensity ratios, respectively. All spectra were smoothed to be a beam size of 2.6.

Figure 12. LVG results for $X_{\text{CO}}/(dv/dr) = 6.3 \times 10^{-5} \text{ (km s}^{-1} \text{ pc}^{-1})^{-1}$, assuming a distance of 7.0 kpc, are shown in the density–temperature plane. Solid line and dashed lines show $^{12}$CO($J=2-1)/^{12}$CO($J=1-0$) intensity ratios, respectively. All spectra were smoothed to be a beam size of 2.6.

The present study has shown that the SSC NGC 3603 may be the second SSC whose formation was triggered by a cloud–cloud collision, along with the SSC Westerlund 2. This suggests that the rare rich star clusters are formed preferentially in the dense interface layer created between two colliding clouds. As mentioned in Section 1, there are only four SSCs in the Galaxy that show nebulosity, a hint of the parent cloud(s) of the clusters, but the remainder has no such nebulosity, indicating that their parent clouds are fully dissipated via ionization, etc. It is important to make molecular observations of the other two with associated nebulosity to test if they are also formed by cloud–cloud collisions.

The frequent occurrence of cloud–cloud collisions has been suggested by global numerical simulations of a galactic disk (Tasker & Tan 2009), and recent observations suggest the importance of cloud–cloud collisions in triggering star formation. Some authors have reported the collision between smaller molecular clouds with 100–1000 $M_\odot$. For instance, Torii et al. (2011) presented CO($J=2-1$) and CO($J=1-0$) observations of M20 with NANTEN2 and argued that a first-generation O-type star (Walborn 1973; Chaisson & Willson 1975) was formed by a cloud–cloud collision on the order of 0.5 Myr or less. Also, a triggered formation is suggested in NGC 1333 (Loren 1976), Sgr B2 (Hasegawa et al. 1994; Sato et al. 2000), W49N (Buckley & Ward-Thompson 1996; Miyawaki et al. 2009), IRAS 0400+5025 (Xue & Wu 2008), W51 (Kang et al. 2010), S87, S88B, AFGL5142, AFGL5180 (Higuchi et al. 2010), Serpens north (Duarte-Cabral et al. 2010), the stellar cluster L1641-N (Nakamura et al. 2012), and in a further 201 candidates identified from cold IRAS sources (Li & Wang 2012). We note that some of these observational results only present circumstantial evidence. The cloud–cloud collision is not a unique interpretation of these observations, because the relatively small velocity separations observed allow the clouds/clumps to be gravitationally bound. The colliding clouds in the two SSCs, NGC 3603 and Westerlund 2, Sgr B2, and M20 have large velocity separations.
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