CO observations toward the isolated mid-infrared bubble S44: External triggering of O-star formation by a cloud-cloud collision

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Abstract

We have performed a multi-wavelength study of the mid-infrared bubble S44 to investigate the origin of isolated high-mass star(s) and the star-formation process around the bubble formed by the H II region. In this paper, we report the results of new CO observations (12CO, 13CO \( J = 1-0 \), and 12CO \( J = 3-2 \)) toward the isolated bubble S44 using the NANTEN2, Mopra, and ASTE radio telescopes. We found two velocity components in the direction of the bubble, at \(-84\) km s\(^{-1}\) and \(-79\) km s\(^{-1}\). These two clouds are likely to be physically associated with the bubble, both because of the enhanced 12CO \( J = 3-2/1-0 \) intensity ratio from a ring-like structure affected by ultraviolet radiation from embedded high-mass star(s) and from the morphological correspondence between the 8 \( \mu \)m emission and the CO distribution. Assuming a single object, we estimate the spectral type of the embedded star inside the bubble to be O8.5-9 (\( \sim 20 M_\odot \)) from the radio-continuum free-free emission. We hypothesize that the two clouds collided with each other 3 Myr ago, triggering the formation of the isolated high-mass star in S44, as also occurred with RCW 120 and RCW 79. We argue that this scenario can explain the origin of the isolated O-star inside the bubble.

Key words: ISM: clouds — Stars: formation ISM: individual objects: S44
1 Introduction

1.1 H II regions and Spitzer mid-infrared bubbles in the Milky Way

H II regions are formed around high-mass stars, which are mainly distributed in the spiral arms of the Milky Way. They ionize and destroy the parent molecular clouds and create cavity-like structures around the exciting stars via stellar winds and ultraviolet radiation (e.g., Whitworth 1979). These cavity-like structures in the interstellar medium (ISM) are often called interstellar bubbles” (e.g., Castor et al. 1975b, Weaver et al. 1977).

The Spitzer mid-infrared bubbles were identified by Churchwell et al. (2006, 2007) from the Galactic Legacy Infrared Mid-Plane Survey Extraordinaire (GLIMPSE) data. They cataloged about 600 bubbles in the northern and southern hemispheres in the Galactic plane (|l| ≤ 65°, |b| ≤ 1°). The authors suggested that most bubbles are H II regions that contain embedded OB-type stars or star clusters.

Several formation scenarios have been discussed for the mid-infrared bubbles, including radiation-driven implosions (RDI: Sandford et al. 1982, Lefloch & Lazareff 1994) and the collect-and-collapse process (C&C: Elmegreen & Lada 1977, Whitworth et al. 1994a). The first involves the compression of pre-existing clouds by the pressure of the ionized gas, while the second consists of sweeping-up of the diffuse ISM inside the wall of the expanding shell that is undergoing gravitational collapse. These scenarios can explain star formation at the edges of bubbles, which is triggered by the expanding H II regions (e.g., Deharveng et al. 2005, 2008, 2009, 2010, Zavagno et al. 2006, 2007). On the other hand, from their numerical simulations, Dale et al. (2015) have pointed out that it is difficult to distinguish between triggered and spontaneous star formation around H II regions solely from their observational morphologies.

Recently, Torii et al. (2015) carried out CO observations toward the mid-infrared bubble RCW 120. They showed that a cloud-cloud collision scenario can explain the morphologies of the bubbles and the formation of ionizing O stars, based on numerical simulations of a head-on collision between different-sized clouds (Habe & Ohta 1992, Anathpindika 2010). In this scenario, high-mass stars are formed in the compressed layer created by the collision of two clouds. These stars then ionize the parent clouds, leading to the formation of bubble-like H II regions (see Figure 12 of Torii et al. 2015). This scenario has also been suggested as the formation mechanism for many mid-infrared bubbles (e.g., N37, Baug et al. 2016; Sh2-48, Torii et al. 2018b; RCW 166, Ohama et al. 2018a; RCW 79, Ohama et al. 2018b; S116-117-118, Fukui et al. 2018b; N35, Torii et al. 2018a; N49, Dewangan et al. 2017; and N4, Fujita et al. 2018, in preparation).

Thus are many different star-formation scenarios may be related to the bubbles, but the dominant process is not clear.

1.2 S44 as an isolated mid-infrared bubble

S44 is an isolated mid-infrared bubble located at (l, b) = (334°523, 0°823). It was cataloged by Churchwell et al. (2006; see their Figure 2c), and corresponds to the closed bubble identified from the AKARI 9μm emission (Hanaoka et al. 2018 submitted). Simpson et al. (2012) also identified S44 as MWP1G334525+008255 by visual inspection as a part of the “Milky Way project” (see also Kendrew et al. 2012). Caswell and Haynes (1985) carried out a radio-recombination-line survey toward southern H II regions, deriving the radio recombination line velocity of ~77 km s^-1. From Table 4 of Churchwell et al. (2006), the distance of S44 is estimated to be either ~4.6±0.5 kpc (the nearer estimate) or ~10.8±0.5 kpc (the more-distant estimate), based on this velocity and the kinematic-distance model of Brand & Blitz (1993). Churchwell et al. (2006) suggested that the nearer kinematic distance is the more correct choice toward bubbles, because it is more likely to be detected in continuum emission than at the grater distance in the Galactic plane. Following previous studies, in this paper we adopt 4.6 kpc as the distance to S44, which suggests that it is located in the Norma spiral arm in the Milky Way (Brown et al. 2014). Hattori et al. (2016) estimated the total infrared luminosity of S44 to be 1.86 x 10^9 (10^9 - 10^10) L☉ by fitting the spectral energy distribution (SED) with polycyclic aromatic hydrocarbons (PAHs), warm-dust, and cold-dust components.

Figure 1 shows a three-color composite image of the Spitzer space telescope observations (GLIMPSE: Benjamin et al. 2003, Churchwell et al. 2009; MIPSGAL: Carey et al. 2009), where blue, green, and red correspond to the 3.6 μm, 8 μm, and 24 μm emission, respectively. The 3.6 μm emission mainly traces thermal emission from the stars, while the 8 μm emission traces the PAH features in the photo-dissociation region (e.g., Draine 2003, Draine & Li 2007, Churchwell et al. 2004). The 8 μm emission has a ring-like structure, with bright emission at the southern edge of S44, and the diameter of the bubble is about 5 pc in the extended 8 μm emission. The 24 μm emission traces hot dust grains heated by high-mass stars in the H II region (e.g. Carey et al. 2009), and it has an arc-like distribution. A bright infrared source exists at (l, b) = (334°46, 0°88) on the western side of S44, which corresponds to the OH/IR star (OH 334.458+0.877) identified from the OH maser survey at 1612.231MHz using the Australia Telescope Compact Array (ATCA; Sevenster et al. 1997b). The relationship to this infrared source to S44 is not clear. We also find
pillar-like structures in the 8 μm emissions at the edge of the bubble that are elongated in the direction of the center, with lengths of \( \sim 1 \text{pc} \) (The white dotted arrows in Figure 1b).

S44 is an isolated mid-infrared bubble, for which the 3-dimensional spatial distribution, velocity structures, and physical properties of the associated molecular gas have not yet been determined. In this paper, we carried out new CO observations in the direction of S44 using the NANTEN2, Mopra, and ASTE radio telescopes. This paper is organized as follows: Section 2 describes the observational information and Section 3 presents the observed cloud properties and comparisons with observations at other wavelengths. Section 4 discusses the formation mechanism of S44 based on a star-formation scenario, and Section 5 concludes this paper.

2 Observations

2.1 NANTEN2 \(^{12}\)CO \(J = 1–0\) observations

We carried out \(^{12}\)CO \(J = 1–0\) (115.271 GHz) observations with the NANTEN2 4 m millimeter/sub-millimeter radio telescope located in Chile and operated by Nagoya University. The observations were made using the on-the-fly (OTF) mode from May 2012 to December 2012 as a part of a Galactic plane survey. The half-power beam width (HPBW) is 2.7 at 115 GHz. This corresponds to 3.6 pc at the distance of 4.6 kpc. The pointing accuracy was checked to be within 2 GHz in the single-side band (SSB) mode. The back end was the XF-type digital spectro-correlator, MAC, with 1024 channels each of at 345 GHz. This corresponds to 0.5 pc at the distance of 4.6 kpc. The front end was the two-side band (2SB) SIS mixer called "CA TS," and the data sets is Sub-millimeter Telescope Experiment (ASTE, Ezawa et al. 2004, 2008, Kohno et al. 2004) located in Chile. The HPBW was into main-beam temperatures \( T_{\text{mb}} \) using daily observations of IRAS 16293-2422 \([\alpha^{12}_{J2000} = 16^h32^m23^s3, \delta^{12}_{J2000} = -24^d28^m39^s2]\], and we converted the intensity scale into main-beam temperatures \( T_{\text{mb}} \) by assuming its peak to be \( T_{\text{mb}} = 18 \text{K} \) (Ridge et al. 2006). The typical intensity uncertainty of the data sets is \( \sim 20\% \) from the NANTEN2 errors and reference data. We smoothed the data cube with a Gaussian kernel of 90", and the final beam resolution was 180" (FWHM). The typical root-mean-square (rms) noise level was \( \sim 1.2 \text{K} \) after smoothing and velocity-channel binning down to 0.43 km s\(^{-1}\).

2.2 Mopra \(^{12}\)CO and \(^{13}\)CO \(J = 1–0\) observations

In July 2014, we observed a 12′ × 12′ area toward S44 using the \(^{12}\)CO and \(^{13}\)CO \(J = 1–0\) transitions (115.271 and 110.201 GHz) using the Mopra 22 m telescope in the OTF mapping mode at Australia Telescope National Facility (ATNF) located in the Warrumbungle Mountains. The HPBW was \( \sim 33 \pm 2\'' \) at 115 GHz, as measured from planetary observations (Ladd et al. 2005). This corresponds to 0.7 pc at the distance of 4.6 kpc. The pointing accuracy was better than 15" from daily observations toward IRC +10216 and the Sun. We used the chopper-wheel method to calibrate the antenna temperature \( T^*_a \) (Penzias & Burrus 1973, Ulich & Haas 1976, Kutner & Ulich 1981). We calibrated the absolute intensity fluctuation using daily observations of IRAS 16293-2422 \([\alpha^{12}_{J2000} = 16^h32^m23^s3, \delta^{12}_{J2000} = -24^d28^m39^s2]\], and we converted the intensity scale into main-beam temperatures \( T_{\text{mb}} \) by assuming its peak to be \( T_{\text{mb}} = 18 \text{K} \) (Ridge et al. 2006). The typical intensity uncertainty of the data sets is \( \sim 20\% \) from the NANTEN2 errors and reference data. We smoothed the data cube with a Gaussian kernel of 30", and the final beam resolution was 180" (FWHM). The typical root-mean-square (rms) noise level was \( \sim 0.76 \text{K} \) for \(^{12}\)CO \(J = 1–0\) and \( \sim 0.53 \text{K} \) for \(^{13}\)CO \(J = 1–0\), with a velocity resolution of 0.43 km s\(^{-1}\).

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

In June 2014, we performed \(^{12}\)CO \(J = 3–2\) (345.796 GHz) observations toward an area of 10′ × 10′ around S44 using the Atacama Sub-millimeter Telescope Experiment (ASTE, Ezawa et al. 2004, 2008, Kohno et al. 2004) located in Chile. The HPBW was \( \sim 22\'' \) at 345 GHz. This corresponds to 0.5 pc at the distance of 4.6 kpc. The pointing accuracy was checked to be within 2" by observing RAFGL 4202 \([\alpha^{12}_{J2000} = 14^h52^m23^s82, \delta^{12}_{J2000} = -62^d04^m19^s2]\).
We checked the intensity calibration by observing W44 \([\alpha_{2000} = 18^h50^m46^s1, \delta_{2000} = 01^\circ11'11''0]\). Typical data fluctuations in the peak intensity were about \(\sim 10\%\). We convolved the intensity scale into \(T_{\text{mb}}\) by assuming the W44 peak to be \(T_{\text{mb}} = 35.5\) K (Wang et al. 1994). The rms noise level was \(\sim 0.3\) K for \(^{12}\)CO \(J = 3–2\), with a velocity resolution of 0.43 km s\(^{-1}\).

### 2.4 Archived data sets

We used the following archived datasets to compare with the CO data, i.e., to the near- and mid-infrared data from the Spitzer space telescope (GLIMPSE at 3.6 \(\mu\)m, and 8.0 \(\mu\)m, Benjamin et al. 2003, Churchwell et al. 2009; MIPSGAL at 24 \(\mu\)m, Carey et al. 2009). We obtained the 870 \(\mu\)m radio-continuum-emission data with the Atacama Pathfinder Experiment (APEX) Telescope Large Area Survey of the GALaxy (ATLASGAL, Schuller et al. 2009), and the 843 MHz (36 cm) radio continuum emission data from the Sydney University Molonglo Sky Survey (SUMSS: Bock et al. 1999) observed with the Molonglo Observatory Synthesis Telescope (MOST). We summarize the observational properties and archival information in Table 1.

### 3 Results

#### 3.1 CO distributions and velocity structures toward S44

Figure 2a shows a large scale \(^{12}\)CO \(J = 1–0\) integrated intensity map obtained by NANTEN2. The CO cloud is distributed over about 50 pc from the northern to southern side of the bubble with a peak at \((l, b) = (334^\circ52', 0^\circ77')\). Figure 2b presents a detailed CO distribution obtained with Mopra. The cloud distribution delineates the 8 \(\mu\)m emission at the southern side of the bubble, and the intensity is depressed inside the bubble. In order to investigate the detailed morphologies of the parent clouds, we focused on the molecular gas around the bubble using the high-spatial-resolution data sets obtained by Mopra. Figures 3 and 4 show velocity-channel maps of \(^{12}\)CO and \(^{13}\)CO \(J = 1–0\), respectively. The cloud distribution outlines the bubble shape of the 8 \(\mu\)m emission, and the southern part (Figures 3d, 3e, 4d, and 4e) is more intense than the northern part of the bubble (Figures 3b, 3c, 4b, and 4c). The \(^{13}\)CO emission coincides with the most intense parts of the \(^{12}\)CO \(J = 1–0\) emission. We obtain the velocity difference between the northern and southern parts of the bubble from the velocity range of \(-86.4\) to \(-77.8\) km s\(^{-1}\) (Figures 3b-e and 4b-e). Figure 5 shows the first-moment map of \(^{13}\)CO \(J = 1–0\) and several spectra. The \(^{13}\)CO map is useful for investigating velocity gradients because it delineates the denser regions of the parent clouds. From the first-moment map (Figure 5a) and the spectra (Figure 5b, 5c, and 5d), we can see that two velocity components exist around the bubble. Focusing on the eastern side of the bubble, we can clearly identify both velocity components in the same region (Figure 5c). We therefore suggest that these velocity differences do not represent a velocity gradient of a single cloud but instead are two independent components around the bubble. Because of their velocities, we hereafter designate these two clouds as the \(-84\) km s\(^{-1}\) cloud” and the \(-79\) km s\(^{-1}\) cloud”, respectively, and they are most likely to be associated with the bubble.

Figure 6a shows the two \(^{13}\)CO \(J = 1–0\) clouds superposed on the Spitzer 8 \(\mu\)m image. The \(-84\) km s\(^{-1}\) and \(-79\) km s\(^{-1}\) clouds overlap on the eastern side of the bubble. Figures 6b and 6c present position-velocity diagrams for which the integration ranges focus on the overlapping parts of the two clouds. The velocity of the radio recombination line \((-77\) km s\(^{-1}\) from Caswell and Haynes 1987) is also shown in the position-velocity diagram (Figures 6b and 6c). We note the cavity-like structure around the bubble, and we find that the two clouds are connected to each other by a bridging feature at intermediate velocities. The cavity-like structures (a few km s\(^{-1}\)) around the radio-recombination-line velocity may be caused by ionization from the exciting star(s), and the bridging feature indicates that these two clouds may be interacting with each other around the bubble.

#### 3.2 Physical properties of the two clouds

We calculated the physical properties of the two molecular clouds using the \(^{12}\)CO and \(^{13}\)CO lines assuming local thermodynamical equilibrium (LTE). We used the following procedures (e.g., Wilson et al. 2009) to derive them above the 3\(\sigma\) noise level. First, we obtained the excitation temperature \(T_{\text{ex}}\) from the \(^{12}\)CO peak intensity \(T_{\text{mb}}(^{12}\text{COpeak})\), assuming that the \(^{12}\)CO \(J = 1–0\) line is optically thick:

\[
T_{\text{ex}} = 5.5 \left(\ln \left(1 + \frac{5.5}{T_{\text{mb}}(^{12}\text{COpeak}) + 0.82}\right)\right) \text{[K].}
\]

The excitation temperatures of the \(-84\) km s\(^{-1}\) and \(-79\) km s\(^{-1}\) clouds are estimated to be 8 - 13 K and 8-25 K, respectively. The optical depths \(\tau_{13}\) of the \(^{13}\)CO emission at each velocity channel are calculated from the following equation for the \(^{13}\)CO brightness temperature \([T_{\text{mb}}(v)]\):

\[
\tau_{13} = \frac{T_{\text{mb}}(v)}{T_{\text{ex}}}. 
\]
\[ \tau_\lambda(v) = -\ln \left[ 1 - \frac{T_{\text{mb}}(v)}{0.5} \left\{ \frac{1}{\exp \left( \frac{v}{T_{\text{mb}}} \right)} - 1 \right\}^{-1} \right] . \]  

We then calculated the \(^{13}\text{CO}\) column density \(N(^{13}\text{CO})\) for all the velocity channels for which the resolution \(\Delta v\) is 0.43 km s\(^{-1}\):

\[ N(^{13}\text{CO}) = 2.4 \times 10^{14} \sum_v \frac{T_{\text{mb}}^{13}(v) \Delta v}{1 - \exp \left( - \frac{2.2}{T_{\text{mb}}} \right)} \text{ [cm}^{-2}]. \]

We converted \(N(^{13}\text{CO})\) into \(\text{H}_2\) column densities \(N(\text{H}_2)\) assuming the CO abundance ratio to be \([^{12}\text{CO}] / [\text{H}_2] = 10^{-4}\) (e.g., Frerking et al. 1982; Pineda et al. 2010) and the isotopic abundance ratio to be \([^{13}\text{C}] / [^{12}\text{C}] = 77\) (Wilson & Rood 1994). We find the peak column densities of the \(-84\) km s\(^{-1}\) and \(-79\) km s\(^{-1}\) clouds to be \(\times 10^{22}\) cm\(^{-2}\) and \(\times 10^{22}\) cm\(^{-2}\), respectively. Finally, we estimated the masses of the two clouds using the following equation:

\[ M = \mu_{\text{H}_2} m_{\text{H}} D^2 \Omega \sum N(\text{H}_2), \]

where \(\mu_{\text{H}_2} = 2.8\) is the mean molecular weight of molecular hydrogen, \(m_{\text{H}} = 1.67 \times 10^{-24}\) g is the proton mass, \(D = 4.6\) kpc is the adopted distance, and \(\Omega\) is the solid angle subtended by the cloud. The molecular masses of the \(-84\) km s\(^{-1}\) and \(-79\) km s\(^{-1}\) clouds are thus estimated to be \(\times 10^3\) \(M_\odot\) and \(\times 10^4\) \(M_\odot\), respectively. We also calculated the total masses and column densities from the \(^{12}\text{CO}\) \(J = 1\rightarrow0\) integrated intensity, assuming the conversion factor to be \(N_{\text{H}_2} / W(\text{CO}) = 2 \times 10^{20}\) (K km s\(^{-1}\))\(^{-1}\) cm\(^{-2}\), with \(\pm30\%\) uncertainty, where \(W(\text{CO})\) is the integrated intensity of the \(^{12}\text{CO}\) \(J = 1\rightarrow0\) line (Bolatto et al. 2013). The cloud masses estimated from the \(^{12}\text{CO}\) and \(^{13}\text{CO}\) emissions differ by a factor of 3 for the \(-84\) km s\(^{-1}\) cloud. This may be an effect of the low-density gas traced by \(^{12}\text{CO}\) \(J = 1\rightarrow0\). We summarize the physical properties of the two clouds in Table 2.

### 3.3 \(^{12}\text{CO} \ J = 3\rightarrow2\) distributions and \(^{12}\text{CO} \ J = 3\rightarrow2/1\rightarrow0\) intensity ratios

Figure 7 shows the velocity-channel map for \(^{12}\text{CO} \ J = 3\rightarrow2\) obtained with ASTE. The \(^{12}\text{CO} \ J = 3\rightarrow2\) distribution more clearly shows the ring features associated with the 8 \(\mu\)m emission from the bubble. We also find two clumps, at \((l,b) = (334^\circ495,0^\circ835)\) and \((l,b) = (334^\circ505,0^\circ845)\), at the western side of the bubble in the velocity range of \(-84.2\) to \(-82.1\) km s\(^{-1}\) (Figure 7c), and a clumpy structure at \((l,b) = (334^\circ53,0^\circ80)\) in Figure 7d. Figures 8a, and 8b show the \(^{12}\text{CO} \ J = 3\rightarrow2/^{12}\text{CO} \ J = 1\rightarrow0\) (\(R_{3\rightarrow2/1\rightarrow0}\)) intensity ratio maps for (a) the \(-84\) km s\(^{-1}\) and (b) the \(-79\) km s\(^{-1}\) cloud, respectively. We convolved the \(^{12}\text{CO} \ J = 3\rightarrow2\) map with a Gaussian kernel of \(45''\), which is the final beam size of the \(^{12}\text{CO} \ J = 1\rightarrow0\) Mopra data. The 5\(\sigma\) (\(\sim 1.5\) K km s\(^{-1}\)) clipping level we adopted is shown by the white dotted contour of \(^{12}\text{CO} \ J = 3\rightarrow2\). The intensity ratio between the different rotational transition levels of the CO lines provides the excitation conditions in the CO gas, and a high intensity ratio is a good indicator of a physical association with the H \(\Pi\) region. The \(-84\) km s\(^{-1}\) cloud has high ratios \((R_{3\rightarrow2/1\rightarrow0} \sim 1.0\sim1.2)\) at the western edge \((l,b) = (334^\circ400,0^\circ825)\) and the northeastern edge \((l,b) = (334^\circ555,0^\circ830)\) of the bubble (Figure 8a). The \(-79\) km s\(^{-1}\) cloud also has enhanced \(R_{3\rightarrow2/1\rightarrow0} \sim 1.0\sim1.2\), but around the southern and western edges of the bubble. The distributions of the intensity ratio \(R_{3\rightarrow2/1\rightarrow0}\) delineate the 8 \(\mu\)m ring structure, showing a steep increase of temperature inside the bubble. These results indicate that the two clouds are likely to be physically associated with the bubble.

### 3.4 Comparison with the ionized gas and cold dust emissions

Figures 9a, and 9b show comparisons of the \(-84\) km s\(^{-1}\) and \(-79\) km s\(^{-1}\) clouds, respectively, with SUMSS 843 MHz (36 cm) continuum images. The continuum image traces the free-free emission from the ionized gas heated by the high-mass stars. The 843 MHz intensity is enhanced at the southern side of the bubble, having an arc-like structure. We note that the ionized gas is not spread uniformly inside the 8 \(\mu\)m shell structure, which is different from other bubbles (e.g., N10 and N21, Watson et al. 2008). The \(-84\) km s\(^{-1}\) cloud is distributed along the northern edge of the bubble. (Figure 9a). The \(-79\) km s\(^{-1}\) cloud surrounds the ionized gas at the southern side of the bubble (Figure 9b). Figures 9c, and 9d show the comparisons of the \(-84\) km s\(^{-1}\) and \(-79\) km s\(^{-1}\) clouds, respectively, with the 870 \(\mu\)m continuum images obtained with APEX. The 870 \(\mu\)m continuum image shows the distribution of the thermal emission from the cold dust (Schuller et al. 2009). The distribution of the cold dust outlines the shape of the bubble, with some peaks coinciding with the peaks of the \(-84\) km s\(^{-1}\) and \(-79\) km s\(^{-1}\) clouds. The \(-84\) km s\(^{-1}\) cloud is distributed along the edge of the cold dust emission at \((l,b) \sim (334^\circ555,0^\circ825)\) (Figure 9c). The peak in the 870 \(\mu\)m emission at \((l,b) = (334^\circ52,0.077)\) on the southern side of the bubble corresponds to the compact source AGAL G334.521+00.769 cataloged by the ATLASGAL survey (Contreras et al. 2013, Urquhart et al. 2014). Figure 9d shows that AGAL G334.521+00.769 is embedded in one of the peaks of the \(-79\) km s\(^{-1}\) cloud. We note that the peaks of the radio continuum, CO, and 870 \(\mu\)m emission have ordered distributions moving to
3.5 Estimation of the spectral type of the exciting star(s)

We investigated the spectral type of the exciting star(s) embedded in the bubble from the radio continuum flux. If we assume the 843 MHz (36 cm) emission from the bubble to be optically thin, we can estimate the number of Lyman continuum photons $N_{L,\gamma}$ from the 843 MHz radio continuum flux $S_\nu$ by using the following equation (Rubin 1968c, Mezger et al. 1974):

$$
\left[ \frac{N_{L,\gamma}}{s^{-1}} \right] \sim 4.761 \times 10^{48} a(\nu, T_e)^{-1} \left[ \frac{\nu}{\text{GHz}} \right]^{0.1} \left[ \frac{T_e}{\text{K}} \right]^{-0.45} \left[ \frac{S_\nu}{\text{Jy}} \right] \left[ \frac{D}{\text{kpc}} \right]^2,
$$

where $a(\nu, T_e)^{-1}$ is the ratio of the optical path length for free-free emission from Oster (1961) and Altenhoff et al. (1960), which for most cases is $a(\nu, T_e)^{-1} \sim 1$ (Mezger & Henderson 1967a). The radio continuum flux $S_\nu$ is estimated by drawing contours at intensities of 0.015 Jy/beam ($\sim 5\sigma$). If we assume the electron temperature to be $T_e = 10^4 \text{ K}$ in the H II region (Ward-Thompson & Whitworth 2011), the numbers of photons is $N_{L,\gamma} \sim 10^{48.08} \text{ s}^{-1}$. If we assume a single object, this figure suggests that the exciting star in S44 has a spectral type of O8.5-9, which corresponds to an 18–19$M_\odot$ star, from the stellar parameters for Galactic O stars (Martins et al. 2005, Table 4). In this paper, we assume that the ionizing O-star is embedded around the peak of the radio-continuum image.

3.6 Color-color diagram of the 24 $\mu$m sources

We constructed a color-color diagram to distinguish between YSOs and other objects toward the 24 $\mu$m sources cataloged around this bubble by Robert & Heyer (2015). They obtained a radius of 7 pc ($\sim 5.25$) around the geometric center position at $(l, b) = (334.5, 253, 0.5823)$. Figure 10 shows the result of the [3.6]-[5.8] versus [8.0]-[24] diagram toward the 24 $\mu$m sources. We adopted the YSO criteria from Muzerolle et al. (2004), who carried out this classification toward the embedded star-forming region NGC 7129 in the Milky Way. We identified the #1 source in S44 as a Class II YSO at the southern edge of the bubble (Figures 11 c, and d). Taking account of its error bars, the #2 source located outside the bubble also is possibly a Class II YSO. The photometric parameters of these sources (#1 and #2) are summarized in Table 3. Many of the other 24 $\mu$m sources are categorized as Class III/stellar objects. We will not argue these Class III/stellar objects in this paper, because it is not clear whether they are physically related to the bubble.

4 Discussion

4.1 Star formation around the bubble and the origin of the isolated O star(s)

From previous studies of bubbles, the C&C and/or RDI processes have been discussed as mechanisms for star formation at the edge of a bubble created by expanding an H II region (e.g., Deharveng et al. 2010, Zavagno et al. 2006, 2007). In the case of S44, we find a cold-dust condensation at 870 $\mu$m at the southern edge of the bubble (AGAL G334.521+00.769). Figure 11a shows the H$_2$ column density derived from $^{13}$CO $J = 1-0$, together with the contours of cold-dust emission from 870 $\mu$m. There is clearly good spatial correspondence between the high molecular column densities and the peaks of cold-dust emission, which suggests that star formation around the bubble is likely to be happenig at the southern edge, while such cold and dense dust condensations are not detected at the northern side of the bubble. These observational results are common to other bubbles (e.g., RCW 120, Deharveng et al. 2009; Figueira et al. 2017; RCW 79, Zavagno et al. 2006, Liu et al. 2017).

Our observations show two velocity components associated with the bubble at the northern and southern sides of the 8 $\mu$m emission (Figure 6a), together with a bridging feature connecting the two clouds (Figures 6b and 6c). These signatures suggest that the two clouds are interacting with each other at the bridging feature, and they are similar to the properties of other bubbles that are formed by cloud-cloud collisions (RCW 120, Torii et al. 2015; RCW 79, Ohama et al. 2018b; N4, S.Fujita et al. 2018 submitted). Numerical simulations of a cloud-cloud collision reproduce the broad-line bridging feature at the interface between the two clouds in the position-velocity diagram (Haworth et al. 2015a, 2015b; see also the review by Haworth et al. 2017) based on the model from Takahira et al. (2014, 2018) and Shimaj et al. (2017). From synthetic CO observations, they showed that the bridging feature is caused by turbulent motions in the compressed layer between the two colliding clouds.

Stellar feedback from the exciting star may be an alternative explanation for the bridging feature. If expanding motions dominate the kinematics of the bubble, we expect to observe a ring-like velocity distribution in the position-velocity diagram. However, in the position-velocity diagram toward the center of the bubble, we do not find expanding velocity structures from the CO data.
corresponding to the sound speed ($\sim 10 \text{ km s}^{-1}$) of the ionized gas (Figure 6c). This suggests that any acceleration caused by stellar feedback is limited, which is consistent with the case of RCW 120 (Anderson et al. 2015a, Torii et al. 2015). We note that S44 is an isolated bubble, because we do not find extended infrared emission (Figure 1a), even though the molecular clouds are distributed up to 50 pc beyond the northern and southern sides of the bubble (Figure 2a). Hence, isolated O star(s) are unlikely to be formed by stellar feedback from other high-mass stars. The formation of massive, dense cores from an O star or a star cluster require external shock compression (e.g., Zinnecker & Yorke 2007). Some numerical magneto-hydrodynamical simulations show that a cloud-cloud collision process satisfies the initial conditions for O-star formation (e.g., Inoue & Fukui 2013, Wu et al. 2015, 2017a, 2017b). We therefore hypothesize that the two clouds collided with each other and that the collision triggered the formation of an isolated, massive exciting star.

4.2 A cloud-cloud collision scenario

Based on our observational results, in this section we propose a scenario in which star formation is triggered by a cloud-cloud collision. From the similar mid-infrared bubble RCW 120 (Torii et al. 2015), and based on the numerical simulation of Habe & Ohta (1992), our proposed scenario is as follows (see our schematic picture in Figure 12):

- The $-84 \text{ km s}^{-1}$ diffuse cloud, enclosing a dense core, and the $-79 \text{ km s}^{-1}$ cloud approach each other (Figure 12, stage I).
- The two clouds collide with each other, creating a compressed layer in the dense part of the $-84 \text{ km s}^{-1}$ cloud at the interface between the two clouds and forming a cavity in the $-79 \text{ km s}^{-1}$ cloud. The two clouds mix at the boundary and form the intermediate velocity component (Figure 12, stage II).
- A High-mass star are formed in the compressed layer at the interface between the two colliding clouds. The parent cloud and the surrounding interstellar medium are then ionized, leading to the formation of a bubble-like structure (Figure 12, stage III).

Figure 11b shows the hot-dust distribution at 24 $\mu$m, together with contours of the cold-dust emission at 870 $\mu$m. The 24 $\mu$m hot-dust emission has an asymmetric distribution at the southern side of the bubble, that is more intense than that at the northern side. We also find a class II YSO at 24 $\mu$m (red arrows Figures 11c and d) that is embedded in the cold-dust condensation producing the 870 $\mu$m emission. This is similar to the distribution of YSOs emitting at 24 $\mu$m embedded in condensation 1” at the edge of RCW 120 (Deharveng et al. 2009, Figure 10). We note that it is not clear whether a cloud-cloud collision caused the formation of this class II YSO, because it may be a pre-existing star.

Torii et al. (2015) and Ohama et al. (2018b) showed that remnants of the colliding clouds exist outside the openings of the bubbles in RCW 120 and RCW 79. In the case of S44, the opening (broken) bubble seen in $8 \mu$m emission is not clearly comparable to RCW 120 or RCW 79. We suggest that this difference between the closed and broken 8 $\mu$m emission bubbles can be explained by the projection effect toward the bubble. Based on this assumption, we adopt the projection angle toward S44 as 45° in section 4.3 below.

4.3 The timescale for star formation

If we assume an inclination angle of 45°, the collisional timescale is about $20 \text{ pc}/(5 \times \sqrt{2}) \text{ km s}^{-1} \sim 3 \text{ Myr}$ from the extended cloud size and velocity difference. On the other hand, if we assume the mass-accretion rate of high-mass stars to be $2 \times 10^{-4} M_\odot \text{ yr}^{-1}$ from the numerical simulation of Inoue et al. (2018), the timescale for high-mass star formation in S44 is $(18-19 M_\odot)/2 \times 10^{-4} M_\odot \text{ yr}^{-1} \sim 0.1 \text{ Myr}$. We thus suggest that the event of a cloud-cloud collision happens on a long time scale ($\sim$ a few Myr), because the small cloud is decelerated by conserving the momentum through the collision, whereas O-star formation has a short timescale of $\sim 0.1 \text{ Myr}$. This is similar to the case of the super star cluster NGC 3603, except for the number of O stars and the high $H_2$ column density (Kudryavtseva et al. 2012, Fukui et al. 2014). We propose that S44 may be a miniature version of a super star cluster.

5 Conclusions

We summarize the conclusions of the present study as follows:

1. We made new CO observations toward the mid-infrared bubble S44 using NANTEN2, Mopra, and ASTE. We identified two clouds, at $-84 \text{ km s}^{-1}$ and $-79 \text{ km s}^{-1}$, in the direction of the bubble.

2. The $-84 \text{ km s}^{-1}$ cloud shows diffuse CO emission that extends outside of the bubble, with $R_{3-2/1-0} > 0.6$ on the northern side of the bubble. From the Mopra and ASTE data sets, the $-79 \text{ km s}^{-1}$ cloud corresponds morphologically to the $8 \mu m$
emission, with $R_{3-2/1-0}$ greater than 0.8 around the bubble. The ionized-gas and cold-dust images exhibit a spatial correlation with the bubble.

3. We estimate the spectral type of the exciting star to be O8.5-9 ($\sim 20 M_\odot$), from the SUMSS 843 MHz (36 cm) radio-continuum flux, if we assume a single object.

4. The two clouds are connected by a bridging feature at intermediate velocities that overlap on the eastern side of the bubble. These observational signatures are interpreted as being due to the interaction between the two clouds.

5. We hypothesize that the two clouds collided with each other 3 Myr ago, triggering the formation of the O star(s) and the isolated bubble. A cloud-cloud collision scenario can explain the morphology of the two clouds and the origin of the isolated O-star.

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Table 1. Observational properties of data sets.

| Telescope | Line          | HPBW | Velocity Resolution | RMS noise<sup>2</sup> |
|-----------|---------------|------|---------------------|-----------------------|
| NANTEN2   | $^{12}$CO J = 1–0 | 160″  | 0.16 km s<sup>-1</sup> | ~ 1.2 K               |
| Mopra     | $^{12}$CO J = 1–0 | 33±2′′<sup>(1)</sup> | 0.088 km s<sup>-1</sup> | ~ 0.76 K              |
|           | $^{13}$CO J = 1–0 | 33±2′′<sup>(1)</sup> | 0.092 km s<sup>-1</sup> | ~ 0.53 K              |
| ATE       | $^{12}$CO J = 3–2 | 22″   | 0.11 km s<sup>-1</sup> | ~ 0.3 K               |

Telescope/Survey | Band | Resolution | References
--- | --- | --- | ---
Spitzer/GLIMPSE | 3.6 μm | ~2″ | [1,2]
Spitzer/GLIMPSE | 8.0 μm | ~2″ | [1,2]
Spitzer/MIPSGAL | 24 μm | 6″ | [3]
APEX/ATLASGAL | 870 μm | 19″ | [4]
MOST/SUMSS | 843 MHz | ~ 60″ | [5]

<sup>1</sup> Reference : Ladd et al. (2005).
<sup>2</sup> The values of the rms noise levels after smoothing the (space and/or velocity) data sets.

References [1] Benjamin et al. (2003), [2] Churchwell et al. (2009), [3] Carey et al. (2009), [4] Schuller et al. (2009), [5] Bock et al. (1999)
Table 2. Physical properties of the two clouds

| Name               | $T_{\text{ex}}$ | $\tau_{13}$ | $N(\text{H}_2)_\text{peak}$ | $N(\text{H}_2)_\text{mean}$ | $M^{(13}\text{CO})$ | $M^{(12}\text{CO})$ |
|--------------------|-----------------|-------------|------------------------------|----------------------------|---------------------|---------------------|
| $-84$ km s$^{-1}$ cloud | 9               | 0.36        | $1 \times 10^{22}$          | $9 \times 10^{20}$         | $4 \times 10^3$     | $1 \times 10^4$     |
| $-79$ km s$^{-1}$ cloud | 12              | 0.38        | $5 \times 10^{22}$          | $7 \times 10^{21}$         | $3 \times 10^4$     | $3 \times 10^4$     |

The excitation temperature $T_{\text{ex}}$ and mean column density $N(\text{H}_2)_\text{mean}$ are the averaged values above the $3\sigma$ noise level for each cloud.

The optical depths $\tau_{13}$ the averaged values from the integrated velocity range above the $3\sigma$ noise level.

Table 3. Photometric data for the YSO candidates from the 24 µm sources (Robert & Heyer 2015) 7 pc from the center position of the bubble.

| Number | $l$   | $b$   | $\sigma_{3.6}$ | $\sigma_{5.8}$ | $\sigma_{8.0}$ | $\sigma_{24}$ | $\sigma_{24}$ |
|--------|-------|-------|----------------|----------------|----------------|---------------|---------------|
|        | [deg] | [deg] | [mag]          | [mag]          | [mag]          | [mag]         | [mag]         |
| 1      | 334.502 | 0.761 | 9.568          | 0.041          | 8.505          | 0.033         | 7.544         |
| 2      | 334.605 | 0.826 | 10.958         | 0.086          | 10.764         | 0.084         | 10.299        | 0.055         | 6.30    | 0.03 |
Spitzer, blue : 3.6 μm, green : 8.0 μm, red : 24 μm

Fig. 1. (a) Large-scale three-color composite images of S44. Blue, green, and red show the Spitzer/IRAC 3.6-μm, Spitzer/IRAC 8-μm, and Spitzer/MIPS 24-μm results. The jagged white line along the Galactic latitude at $b \sim 0.95$ shows the observing limit of Spitzer/MIPS 24-μm. (b) A close-up image of (a). The colors are the same as in (a). The pink dotted arrows indicate the pillar-like structures.
Fig. 2. (a) Integrated map of the $^{12}$CO $J = 1–0$ emission in the velocity range of $-88.5$ to $-69.2$ km s$^{-1}$. The contours show the Spitzer/IRAC 8-µm result, where the region used for the 8-µm emission is indicated by the black box. The lowest contour and contour intervals are 70 MJy/beam and 80 MJy/beam, respectively. The final beam size after convolution is $180''$. (b) Integrated intensity map of the $^{12}$CO $J = 1–0$ emission with Mopra. The final beam size after convolution is $45''$. 
Fig. 3. Velocity-channel map of the $^{12}\text{CO} J = 1-0$ emission, with a velocity step of 2.15 km s$^{-1}$, obtained by Mopra. The contours show the 8μm emission from Spitzer/IRAC. The final beam size after convolution is 45″. The 1σ noise level is $\sim 0.7$ K km s$^{-1}$ for the velocity interval of 2.15 km s$^{-1}$. 

Contour levels (8 μm) : min 70 MJy/beam, Step 80 MJy/beam
Fig. 4. Velocity-channel map of the $^{13}\text{CO} J = 1–0$ emission, with a velocity step of 2.15 km s$^{-1}$, obtained by Mopra. The contours show the 8$\mu$m emission from Spitzer/IRAC. The final beam size after convolution is 45$''$. The 1$\sigma$ noise level is $\sim$ 0.5 K km s$^{-1}$ for the velocity interval of 2.15 km s$^{-1}$.
Fig. 5. (a) The first-moment map of the $^{13}$CO $J = 1$–0 emission, which we created for the velocity range of $-87.64$ to $-77.33$ km s$^{-1}$ using the volume voxels with the intensities greater than 2.1 K ($\sigma$). The lowest contour and contour intervals were 70 MJy/beam and 80 MJy/beam for the Spitzer/IRAC 8-µm result. The boxes show the averaging areas for each profile. (b), (c), and (d) The averaged spectra for $^{12}$CO, $^{13}$CO $J = 1$–0, and $^{12}$CO $J = 3$–2. The dotted lines indicate the two velocity components at $-84$ km s$^{-1}$ and $-79$ km s$^{-1}$. The size of averaging box is $35'' \times 35''$. 
Fig. 6. (a) Integrated intensity map of $^{13}$CO $J=1-0$ obtained by Mopra for the $-84$ km s$^{-1}$ cloud (blue contours) and the $-79$ km s$^{-1}$ cloud (red contours) superposed on the Spitzer 8µm emission. The yellow dashed lines show the integration ranges in latitude and longitude. (b) Galactic latitude-velocity diagram integrated over the longitude range from 334.54 to 334.57. The 1σ noise level is $\sim 0.004$ K degree for the longitude interval of 0.03. (c) Galactic longitude-velocity diagram integrated over the latitude range from 0.81 to 0.84. The dashed lines represent the radio- recombination-line velocity ($-77$ km s$^{-1}$) from Caswell and Haynes (1987). The spatial and velocity resolution are smoothed to 52′′ and 0.18 km s$^{-1}$, respectively. The 1σ noise level is $\sim 0.004$ K degree for the latitude interval of 0.03.
Fig. 7. Velocity-channel map of the $^{12}$CO $J = 3$–2 emission, with a velocity step of 2.15 km s$^{-1}$, obtained by ASTE. The contours show the 8 μm emission from Spitzer/IRAC. The final beam size is 22$''$. The 1σ noise levels are $\sim$ 0.3 K km s$^{-1}$ for the velocity interval of 2.15 km s$^{-1}$. 
Fig. 8. (a),(b) Intensity ratio map of $^{12}$CO $J=3-2/^{12}$CO $J=1-0$ from ASTE and Mopra for the $-84$ km s$^{-1}$ cloud (a) and the $-79$ km s$^{-1}$ cloud (b). The final beam size after convolution is $\sim 45''$. The $5\sigma$ ($\sim 1.5$ K km s$^{-1}$) clipping levels adopted are shown by the dotted white contour of $^{12}$CO $J=3-2$. The lowest yellow contour and intervals are 70 MJy/beam and 80 MJy/beam for the Spitzer/IRAC 8-$\mu$m result.
Fig. 9. (a), (b) Integrated intensity map of $^{12}$CO $J = 3$–$2$ (contours) obtained with ASTE superposed on the MOST 843 MHz continuum image. (c), (d) Integrated intensity map of $^{12}$CO $J = 3$–$2$ (contours) obtained by ASTE superposed on the APEX 870 μm continuum image. The blue and red contours represent the $-84$ km s$^{-1}$ cloud and the $-79$ km s$^{-1}$ cloud, respectively.
Fig. 10. The color-color diagram ([3.6]-[5.8] versus [8.0]-[24]) for the 24 μm sources cataloged by Robert & Heyer (2015) around the bubble. The dotted boxes show the classification of YSOs from Muzerolle et al. (2004).

Fig. 11. (a) The APEX 870 μm image (contours) superposed on the H$_2$ column density image from $^{13}$CO $J=1$–0 with the velocity range of $-88.5$ to $-69.2$ km s$^{-1}$. (b) The APEX 870 μm image (contours) superposed on the Spitzer 24 μm emission. The red dotted square shows the sources detected in the 24 μm image embedded in the cold dust condensation. (c) Close-up 8 μm and (d) 24 μm images, respectively, at the southern edge of the bubble. The YSO is indicated by a red arrow in panels (c) and (d).
Fig. 12. Schematic image of a cloud-cloud collision scenario based on Habe & Ohta (1992) and Torii et al. (2015, 2017a). Stage I: a 3D image of the initial condition of the two clouds. Stage II: a 2D image of the two clouds in the X-Z plane at the time when the two clouds collide with each other. Stage III: a 2D image of the bubble in the X-Z plane. The Y-axis corresponds to the line of sight. The final panel shows the observational result for the two clouds superposed on the 24 µm image.