CO observations of the molecular gas in the galactic HII region Sh2-48; Evidence for cloud-cloud collision as a trigger of high-mass star formation

Kazufumi Torii1, Yusuke Hattori2, Mitsuhiro Matsuo1, Shinji Fujita2, Atsushi Nishimura2, Mikito Kohno2, Mika Kuriki3, Yuya Tsuda4, Tetsuhiro Minamidani1,5, Tomofumi Umemoto1,5, Nario Kuno3, Satoshi Yoshihke2, Akio Ohama2, Kengo Tachihara2, Yasuo Fukui2, Kazuhiro Shima6, Asao Habe6, Thomas J. Haworth7

1Nobeyama Radio Observatory, 462-2 Nobeyama Minamimaki-mura, Minamisaku-gun, Nagano 384-1305, Japan
2Graduate School of Science, Nagoya University, Chikusa-ku, Nagoya, Aichi 464-8601, Japan
3Department of Physics, Graduate School of Pure and Applied Sciences, University of Tsukuba, 1-1-1 Ten-nodai, Tsukuba, Ibaraki 305-8577, Japan
4Meisei University, 2-1-1 Hodokubo, Hino, Tokyo 191-0042, Japan
5Department of Astronomical Science, School of Physical Science, SOKENDAI (The Graduate University for Advanced Studies), 2-21-1, Osawa, Mitaka, Tokyo 181-8588, Japan
6Faculty of Science, Department of Physics, Hokkaido University, Kita 10 Nishi 8 Kita-ku, Sapporo 060-0810, Japan
7Astrophysics Group, Imperial College London, Blackett Laboratory, Prince Consort Road, London SW7 2AZ, UK

†E-mail: kazufumi.torii@nao.ac.jp

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Abstract

Understanding the mechanism of high-mass star formation is one of the top-priority issues in contemporary astrophysics. Sh2-48 is a galactic HII region located at 3.8 kpc from the Sun. It harbors an O9.5-type star at the center of the HII region which is extended for ~10′. As a part of the FOREST Unbiased Galactic plane Imaging survey with the Nobeyama 45-m telescope (FUGIN) project, we obtained the CO J=1−0 dataset for a large area of Sh2-48 at a spatial resolution of 21″, which corresponds to ~0.4 pc at 3.8 kpc. The CO data revealed that the molecular gas having a total molecular mass of 8.5 × 10^4 M⊙ is associated with Sh2-48, which shows a characteristic line-symmetric velocity gradient over ~4 km s^{-1}. Such a velocity gradient cannot be formed by a spherical expansion the HII region. In this paper, we discuss a cloud-cloud collision scenario to interpret the observed signatures including the velocity gradient. By comparing between the observations and simulations, we found that this line-symmetric velocity gradient is an expected outcome of a collision between a cylindrical cloud and a large spherical cloud, and we concluded that the high-mass star formation in Sh2-48 was triggered by the collision. Our results reinforce the importance of cloud-cloud collision for high-mass star formation in the Milky Way.
Key words: ISM: clouds — ISM: molecules — radio lines: ISM — stars: formation

1 Introduction

High-mass stars are influential in the galactic environment via injecting large energy in stellar winds, ultra-violet (UV) radiation, and supernova explosions. It is therefore crucial to understand formation mechanism of high-mass stars in our long-term efforts to elucidate galactic evolution.

Recent attempts to search for parental molecular clouds of high-mass stars have shown that cloud-cloud collisions (CCC) is a promising mechanism to trigger formation of high-mass stars (Furukawa et al. 2009; Ohama et al. 2010; Torii et al. 2011; Torii et al. 2015; Torii et al. 2017; Fukui et al. 2014; Fukui et al. 2015; Fukui et al. 2016; Saigo et al. 2017; Fukui et al. 2017a; Fukui et al. 2017b; Gong et al. 2017; Dewangan 2017). These studies indicated that such a collision occurs at a colliding velocity of 10–30 km s$^{-1}$ and can trigger high-mass star formation for a wide range of stellar mass, from a single O star (e.g., M20 by Torii et al. 2011; Torii et al. 2017, RCW120 by Torii et al. 2015, Young stars in N159 by Fukui et al. 2015; Saigo et al. 2017)) to super star clusters having a few tens O stars (e.g., Westerlund 2 by Furukawa et al. 2009; Ohama et al. 2010, NGC3603 by Fukui et al. 2014, and RCW38 by Fukui et al. 2016).

Among these studies, Torii et al. (2015) observed the molecular line emission in the galactic HII region RCW 120, which has a beautiful infrared ring structure surrounding an HII region. Such a ring structure is usually discussed as a “bubble” formed through expansion of an HII region (e.g., Deharveng et al. 2009; Deharveng et al. 2010; Zavagno et al. 2007). However, by analyzing the velocity distributions of the molecular gas, Torii et al. (2015) found no evidence of expansion of the ring structure in RCW 120. Based on the discovery of two distinct velocity components which are both associated with RCW 120 despite of a large velocity separation of $\sim$20 km s$^{-1}$, the authors discussed a CCC model as an alternative scenario to explain the ring structure in RCW 120. In their CCC model, the collision occurred between two molecular clouds with different sizes, and the ring structure in RCW 120 can be understood as a cavity created on the larger cloud through the collision. Formation of a cavity through CCC was presented in the numerical simulations of CCC (e.g., Habe and Ohta 1992; Anathpindika 2010; Takahira, Tasker, and Habe 2014), and the observations by Torii et al. (2015) for the first time lent credence to these calculations. Torii et al. (2015) finally concluded that the exciting O star in RCW 120 was formed in the compressed layer created at the interface of the collision.

Infrared rings in the Milky Way (MW) were extensively studied by Churchwell et al. (2006) based on the Spitzer observations. Churchwell et al. 2006 identified about 600 ring-like $8\mu$m structures including RCW 120 within $\pm60^\circ$ in the Galactic longitude, and the work was followed by an expanded catalog of $\sim$1500 ring emissions by Simpson et al. (2012). Deharveng et al. (2010) and Kendrew et al. (2012) indicated that many of the identified infrared rings enclose an HII region. It is therefore important to analyze the molecular line data for these infrared rings in order to investigate the CCC model as the mechanism of high-mass star formation. For such a purpose, in this study we focus on the galactic HII region Sh2-48 which is cataloged as the infrared ring N18 by Churchwell et al. (2006).

Sh2-48 is a galactic HII region located at $(l,b) \sim (16.6^\circ, -0.3^\circ35)$, which was first cataloged by Sharpless (1959). Figure 1 shows a composite image of the Spitzer/MIPS GAL 24 $\mu$m (red), Spitzer/IRAC 8 $\mu$m (green), and SuperCOSMOS H$\alpha$ (blue) emissions toward a large area of N18 (Benjamin et al. 2003; Parker et al. 2005; Churchwell et al. 2009; Carey et al. 2009), with the MAGPIS 20 cm radio continuum emission indicated as contours (Helfand et al. 2006). Sh2-48 has a bright ring-like structure in the $8\mu$m emission, which is attributed to polycyclic aromatic hydrocarbon (PAH) excited by strong UV radiation. The $8\mu$m ring in Sh2-48 has a diameter of about 10$'$ and is brightest at the western part of the ring. At the inside of the ring, the H$\alpha$ and 20 cm emissions from the ionized gas and the $24\mu$m emission from hot dust grains which are being heated by the HII region are excited. The star BD-14 5014 having a spectral type of O9.5V was identified at the center of the HII region (Avedisova and Kondratenko 1984; Vogt and Moffat 1975; Vijapurkar and Drilling 1993). Anderson et al. (2009) detected molecular line emission from Sh2-48 at a radial velocity of $\sim$44.6 km s$^{-1}$, which corresponds to the near and far distances of 3.8 kpc and 12.4 kpc, respectively, by assuming a flat rotation model for the Milky Way with a solar galactocentric distance $R_\odot$ of 7.6 $\pm$ 0.3 kpc and a solar rotational speed $\Theta_\odot$ of 214 $\pm$ 7 km s$^{-1}$. Based on the HII absorption studies, the authors resolved the ambiguity and favored the far distance. However, as discussed by Ortega et al. (2013), the spectroscopic observations of BD-14 5014 provided better constraints which supports for the near distance for the O star, and we therefore adopt 3.8 kpc in this study.
Spatial and velocity distributions of the molecular gas for a large area of Sh2-48 has not been studied to date. Anderson et al. (2009) analyzed the Boston University-Five College Radio Astronomy Observatory (BU-FCRAO) $^{13}$CO $J$=1–0 Galactic Ring Survey data (GRS; Jackson et al. 2006), having a beam size of 46″, but the authors did not focus on the gas distribution in Sh2-48. Ortega et al. (2013) observed a small part (2′ × 2′) of Sh2-48 in the CO $J$=3–2 and CS $J$=7–6 emissions to study a bright-rimmed cloud in Sh2-48.

In this study, we present the molecular gas distribution in the CO $J$=1–0 emissions for a large area including Sh2-48 obtained using the Nobeyama 45-m telescope at 21″ resolution, which corresponds to ∼0.39 pc at 3.8 kpc. The CO dataset having a high spatial resolution provides a wealth of information on the distribution and dynamics of the molecular gas in Sh2-48, which allows us to investigate high-mass star formation in Sh2-48. In Section 2 we describe the CO $J$=1–0 dataset used in this study, and in Section 3 we present the main results of analyses on the CO dataset and comparisons with the other wavelengths. In Section 4 we discuss the results and as summary is presented in Section 5. In this paper, we refer the four points of the compass based on the galactic coordinates.

2 Dataset

In this study, we analyzed the $^{12}$CO, $^{13}$CO, and C$^{18}$O $J$=1–0 dataset obtained as a part of FOREST Unbiased Galactic plane Imaging survey with the Nobeyama 45-m telescope (FUGIN; see Umemoto, T. et al. 2017, in preparation, for the full description of the observations and data reduction). In FUGIN, we conducted a large scale galactic plane survey using the receiver FOur-beam REceiver System on the 45-m Telescope (FOREST; Minamidani et al. 2016), which is the four beams, dual-polarizaiton, and two sideband receiver installed in the Nobeyama 45-m telescope. Typical system temperatures of FOREST were ∼250 K for $^{12}$CO and ∼150 K for $^{13}$CO and C$^{18}$O. The backend system was the digital spectrometer “SAM45”, which provided a bandwidth of 1 GHz and a resolution of 244.14 kHz. These figures correspond to 2600 km s$^{-1}$ and 1.3 km s$^{-1}$, respectively, at 115 GHz. The observations were made in the on-the-fly mode, and the output data has grid sizes of 8.5″ in space and 0.65 km s$^{-1}$ in velocity. We smoothed the output data with a 2-dimensional Gaussian function to a spatial resolution of 30″ for $^{12}$CO and $^{13}$CO and of 45″ for C$^{18}$O in order to improve the sensitivity. The final root-mean-square (r.m.s) noise fluctuations of the data were 0.5 K for $^{12}$CO, 0.3 K for $^{13}$CO, and 0.2 K for C$^{18}$O at a channel resolution of 0.65 km s$^{-1}$.
3 Results

3.1 Spatial and velocity distribution of the molecular cloud in Sh2-48

Figure 2 shows the integrated intensity distributions of the three CO emissions for a velocity range $\sim 39–51 \text{ km s}^{-1}$, in which the CO emission associated with Sh2-48 is pronounced. The molecular cloud in Sh2-48 is extended in a $l$ range of $\sim 16^\circ 4–16^\circ 7$ and a $b$ range of $\sim -0^\circ 5–-0^\circ 2$, with gas distribution consisting of network of filamentary structures having widths of $\sim 1–2 \text{ pc}$ and clumpy structures with sizes of $\sim 2–3 \text{ pc}$. Among these clumps, the one at the center of the cloud, $(l, b) \sim (16^\circ 56, -0^\circ 35)$, having a size of $3 \text{ pc}$ shows the brightest emissions in the Sh2-48 cloud in $^{12}\text{CO}$ and $^{13}\text{CO}$. The clump coincides with the bright part of the $8 \mu\text{m}$ ring (Figure 1), suggesting that the cloud is associated with the HII region in Sh2-48. We found no molecular clumps which coincide with the O star BD-14 5014 indicated as cross in Figure 2 along the line of sight, but there is a clump located just the northeast to the O star, $(l, b) \sim (16^\circ 67, -0^\circ 34)$, although association between the clump and BD-14 5014 is not clear in the present CO dataset. The $^{13}\text{CO}$ emission is widely detected in all the directions at which the $^{12}\text{CO}$ and $^{13}\text{CO}$ emission are bright. Detections of the $^{13}\text{CO}$ emission indicate the existence of dense gas having gas densities such as $10^3–10^4 \text{ cm}^{-3}$. The $^{13}\text{CO}$ emissions show smoothed intensity distribution over the cloud, and the clumpy structures, which are outstanding in the $^{12}\text{CO}$ and $^{13}\text{CO}$ maps, are not clearly identified. Note that the bright CO emission outside the Sh2-48 cloud at $(l, b) \sim (16^\circ 37, -0^\circ 21)$ corresponds to another HII region, G016.361-00.209 (Anderson et al. 2014). The molecular cloud of G016.361-00.209 is possibly connected with the Sh2-48 cloud. We do not focus on this cloud but will study high-mass star formation in the cloud in a separate paper (Ohama, A. et al. 2017, in preparation).

Figure 3 shows velocity distribution of the molecular cloud in Sh2-48 in the velocity channel maps of the $^{12}\text{CO}$ and $^{13}\text{CO}$ emissions at a velocity interval of $\sim 4 \text{ km s}^{-1}$, which indicates a systematic velocity change of the cloud from the center of the cloud to the western and eastern sides as velocity increases. At the lower velocity side at $\sim 40 \text{ km s}^{-1}$, the molecular gas is distributed around the western rim of the $8 \mu\text{m}$ ring, having a vertically elongated shape in the map, while the cloud is separated into two distinct
Fig. 3. CO three velocity components in N18. The left panels show the $^{12}$CO $J=1$–$0$ emission, while the right panels for the $^{13}$CO $J=1$–$0$ emission. The cross indicates BD-14 5014, while the circle with dashed lines depicts the 8 µm ring.

components at the higher velocity part at $\sim 49$ km s$^{-1}$, where one is distributed at $l \sim 16^\circ.4$–$16^\circ.5$ and the other is at $l \sim 16^\circ.6$–$16^\circ.7$. This velocity change appears as an line-symmetric velocity gradient in the moment 1 map of the $^{13}$CO emission shown in Figure 4. We defined new coordinates by eyes which follows the line-symmetric velocity distribution as plotted in Figure 4. The rotation angle of the new coordinates relative to the galactic coordinates is $33^\circ$ in counter-clockwise, with the origin of the new coordinates set to the peak position of the $^{13}$CO integrated intensity map in Figure 2, $(l, b.) = (16^\circ.560, -0^\circ.355)$. Using the new coordinates, in Figure 5 we present the position-velocity diagram of the $^{13}$CO emission along the X-axis, in which the line-symmetric velocity gradient is seen as a “V-shape” velocity distribution. The velocity difference between the top and bottom of the V-shape is measured as $\sim 4$ km s$^{-1}$, with the velocity gradient estimated as $\sim 4$ km s$^{-1}$/7 pc $\sim 0.6$ km s$^{-1}$ pc$^{-1}$.

3.2 Physical parameters of the molecular cloud

The total molecular mass of SH2-48 was estimated from the $^{13}$CO $J=1$–$0$ data assuming local thermodynamic equilibrium (LTE). We derived excitation temperature $T_{\text{ex}}$ of the $^{13}$CO emission at each observing point using the peak temperature of the $^{12}$CO profile. The derived $T_{\text{ex}}$ ranges 15–30 K. The abundance ratio between $^{12}$C and $^{13}$C was assumed as 77 (Wilson and Rood 1994). The H$_2$
The moment 1 map of the $^{13}$CO $J=1$–0 data. The contours indicate the $^{13}$CO $J=1$–0 distributions shown in Figure 2. The X and Y axes and labels are used for the position-velocity map shown in Figure 5.

Fig. 5. Position-velocity diagram of the $^{13}$CO emission along the X-axis of the coordinates defined in Figure 4.

The column density $N(H_2)$ was derived to be $(1–3) \times 10^{22}$ cm$^{-2}$, with the total molecular mass estimated as $8.5 \times 10^4 M_\odot$ at 3.8 kpc. The masses of the clumps embedded in the cloud ranges from 1000 to 2000 $M_\odot$, while the line masses of the filaments are $\sim 100–200 M_\odot$ pc$^{-1}$.

3.3 Comparisons with other wavelengths

We here make comparisons between the FUGIN CO dataset and images at other wavelengths. Figure 6(a) shows comparisons of the spatial distributions between $^{13}$CO and the Spitzer 8.0 $\mu$m image for the three velocity ranges presented in Figure 3, while in Figure 6(b) comparisons with the H$\alpha$ emission are shown. The positions where the spatial coincidences between $^{13}$CO and 8 $\mu$m (or absorption in H$\alpha$) are seen are indicated as red circles.

Correlations between the $^{13}$CO and 8 $\mu$m emissions indicate that the molecular gas is illuminated by the UV radiation, suggesting that the gas is located in the vicinity of the high-mass star. In Figure 6(a), as already mentioned, the brightest part of the 8 $\mu$m emission at the west of the 8 $\mu$m ring coincides with the lower velocity component of the molecular gas in Sh2-48 at $\sim 40$ km s$^{-1}$, which includes a dense clump having 1500 $M_\odot$ at $(l, b) \sim (16^\circ.56, -0^\circ.35)$. Correlation is not clear at the intermediate velocity
Fig. 6. Comparisons of the three velocity components with (a) the Spitzer/IRAC $8 \mu$m emission and (b) the H$_{\alpha}$ emission. The $^{13}$CO $J=1$–$0$ distributions are shown in the blue colored images with contours, while the infrared and H$_{\alpha}$ maps are shown in the orange colored images. The contours are plotted at every $2.5$ K km s$^{-1}$ from $7.5$ K km s$^{-1}$. The positions where the spatial coincidences between $^{13}$CO and $8 \mu$m or absorption in H$_{\alpha}$ are seen are indicated as red circles.

range, while at the higher velocity part at $\sim 49$ km s$^{-1}$, a filamentary structure at the southern part of the $8 \mu$m ring has a counterpart in a thin filament of the $^{13}$CO emission.

In Figure 6(b) spatial coincidences between $^{13}$CO and H$_{\alpha}$ are seen as anti-correlation between emission in $^{13}$CO and absorption in H$_{\alpha}$. Intensity decrease of the H$_{\alpha}$ emission indicates extinction by the dust grains, suggesting that the corresponding velocity component of the molecular gas is located in front of the nebula along the line of sight. In the lower velocity part at $\sim 40$ km s$^{-1}$, two compact molecular components at ($l, b$) $\sim (16^\circ 65, -0^\circ 28)$ and ($l, b$) $\sim (16^\circ 70, -0^\circ 42)$ coincide with gaps of the H$_{\alpha}$ emissions. The former corresponds to the bright rimmed cloud studied by Ortega et al. (2013). The authors discussed interaction between the cloud and the HII region in Sh2-48. The latter component is located at X of $\sim 0^\circ 17$ in the coordinate in Figure 4 and looks not following the line-symmetric velocity gradient, as is also seen in Figure 5. At the intermediate velocity range at $\sim 45$ km s$^{-1}$, the southern part of the filamentary structure which surround BD-14 5014 along the line of sight coincides with the dark feature against the background H$_{\alpha}$ emission, indicating that it is distributed in front of the HII region, while the northern part of the filament is located either at the inside or at the rear side of the nebula, as it shows no counterpart in the H$_{\alpha}$ image.

Figure 7 shows the intensity distributions of the $^{13}$CO, $8 \mu$m, $24 \mu$m, $20$ cm, and H$_{\alpha}$ emissions as well as $N$(H$_2$) derived using $^{13}$CO in Section 3.2 along the X-axis of the coordinates defined in Figure 4 to follows the velocity gradient. The peaks of the $^{13}$CO and $8 \mu$m emissions correspond well with each other. $N$(H$_2$) is peaked at the same position as $^{13}$CO and $8 \mu$m with a peak value a
factor of 1.5 larger than the surrounding parts. The 24 μm profile which probes warm dust grains is similar to the 20 cm profile, and these peaks are shifted to the positive direction by 0.03, which corresponds to ∼1.8 pc at 3.8 kpc. The Hα profile is much different with the 20 cm profile, although both of these trace ionized gas. This is because that the Hα emission around the 20 cm peak is absorbed by the dust grains located in front of the nebula along the line of sight, as also discussed in Figure 6(b). The 20 cm and 24 μm emissions therefore trace the ionized gas distribution better than Hα.

In Figure 8 the YSO candidates identified using the Spitzer observations (red circles, Robitaille et al. 2008) and AKARI (white circle, Tóth et al. 2014) are plotted superimposed on the 13CO intensity map shown in Figure 2(b). For the former, Robitaille et al. (2008) discussed that their catalog consist of 50–70% of YSOs and 30–50% of asymptotic giant branch (AGB) stars. Figure 8 shows that there are several YSO candidates which coincide with the clumpy structures embedded in the Sh2-48 cloud, suggesting that, if these are YSOs, the Sh2-48 cloud harbors on-going star formation, while in the present observations we found no signs of massive YSO and protostars. This is consistent with the discussion on a bright rimmed cloud in Sh2-48 by Ortega et al. (2013).

4 Discussion

In the previous section, we presented the spatial and velocity distributions of the molecular cloud in Sh2-48 and showed that the cloud has a characteristic line-symmetric velocity gradient at ∼0.6 km s\(^{-1}\) pc\(^{-1}\). The central axis of the velocity gradient corresponds to the brightest part of the 8 μm ring in Sh2-48, implying that the velocity gradient has a relationship with the high-mass star formation in Sh2-48. A comparison between the 13CO and Hα emissions indicate that the center and western parts of the molecular cloud is distributed in front of the nebula of Sh2-48, while the eastern part of the cloud, which overlaps the Hα emission without any correlation, is located at the inside or at the rear side. In this section, we discuss the origin of the line-symmetric velocity gradient of the cloud and how it is related to the O star formation in Sh2-48.

4.1 High-mass stars in Sh2-48

First we discuss the high-mass stars in Sh2-48. We estimated the flux of the Lymann continuum photons \(N_{\text{Ly}}\) in Sh2-48 using the 20 cm image shown in Figure 1 as contours. We used the flux integrated over the pixels having more than 1 mJy beam\(^{-1}\) for the estimate, and by assuming the electron temperature of 8000 K, the \(N_{\text{Ly}}\) in Sh2-48 was measured as ∼10\(^{48.92}\) photons s\(^{-1}\) (Kurtz, Churchwell, and Wood 1994). This figure corresponds to a single O6.5 star or four O9.5 stars (Panagia 1973). As described in Section 1, the O star BD-14 5014 was identified around the center of the H\(\alpha\) region in Sh2-48. The classification of BD-14 5014, O9.5V, can account for only a fraction of the total luminosity required for the O6.5-type star, suggesting that there is other O star(s)
emissions as shown in Figure 7. In Figure 7 these emissions show no significant enhancements in the direction of BD-14 5014, while peaks, which corresponds to a visual extinction $A_V$ of $\sim$16 mag, where the relations $N(H+H_2) = 5.8 \times 10^{22} E(B-V) \ cm^{-2} \ mag^{-1}$ and $A_V = 3.1 E(B-V)$ are assumed (Bohlin, Savage, and Drake 1978). Such a high $A_V$ may veil a bright O star.

4.2 Expanding motion of the H\textsc{ii} region

Next we discuss what formed the line-symmetric velocity gradient of the molecular cloud. A reasonable idea to interpret the velocity gradient of the molecular cloud associated with an H\textsc{ii} region is an expanding motion driven by the over-pressured H\textsc{ii} region. In such a case, an expanding H\textsc{ii} region accumulates the surrounding neutral material to form a dense shell structure, and by observing the molecular line emissions one would expect to see an axisymmetric velocity gradient respect to the central point which corresponds to the direction of the exciting star. However, as shown in Figures 4 and 5, the velocity gradient observed in the molecular cloud in Sh2-48 is an line-symmetric respect to the western rim of the H\textsc{ii} region, and the velocity gradient exist even at the outside the H\textsc{ii} region. Spherical expansion of an H\textsc{ii} region cannot form such a line-symmetric velocity gradient, and it is likely that the line-symmetric velocity gradient was not formed by the H\textsc{ii} region. We cannot find any other global scale velocity gradient which indicates expansion of the H\textsc{ii} region, suggesting a slow expansion of the H\textsc{ii} region in Sh2-48.

In order to investigate the slow expansion of the H\textsc{ii} region in Sh2-48, we test a simple H\textsc{ii} region model. In Figure 9 we plotted the evolutionary tracks of H\textsc{ii} regions based on the analytical model of the D-type expansion developed by Spitzer (1978) (see also Bisbas et al. 2015 for more information on this simple H\textsc{ii} region expansion model), where the radius of the H\textsc{ii} regions $r_{\text{HII}}$, the expanding velocity of the H\textsc{ii} region $v_{\text{exp}}$, and the electron density $n_e$ are plotted in (a), (b), and (c), respectively. In these plots, we assumed $N_{l_{\text{Ly}}}$ of $10^{48.92}$ photons s$^{-1}$, $T_e$ of 8000 K, and the sound speed of ionized gas $c_s$ of 10 km s$^{-1}$. Dashed lines in each panel indicates the constraint from the observations. The $r_{\text{HII}}$ of Sh2-48 is measured as $\sim$5.5 pc, while the full velocity width of the Sh2-48 cloud, $\sim$4 km s$^{-1}$, provides a safe upper-limit of $v_{\text{exp}}$. We measured the typical emission measure and $n_e$ of Sh2-48 as $\sim 1.5 \times 10^4 \ pc \ cm^{-6}$ and $\sim 40 \ cm^{-3}$, respectively, using the 20 cm data, which is nearly consistent with the estimate by Ortega et al. (2013). The black dots in (b) and (c) depict the points at which $r_{\text{HII}}$ is 5.5 pc in (a). Figure 9 indicates that the cases for densities of $10^3 \ cm^{-3}$ and $10^4 \ cm^{-3}$ satisfies the conditions required from the observations, i.e., $r_{\text{HII}} \sim 5.5 \ pc$, $v_{\text{exp}} < 4 \ km \ s^{-1}$, and $n_e \sim 80 \ cm^{-3}$. The respective expansion timescales of these two cases are $\sim 1.5 \ Myr$ and $\sim 5 \ Myr$. We here removed the high density case with $10^5 \ cm^{-3}$ because of unreasonably large timescale (\sim 15 Myr).
Fig. 9. Evolutionary tracks of expanding HII regions based on the Spitzer D-type expansion equation. Different colors indicate different initial densities. Dashed lines show the constraints given from the observations. The black dots in (b) and (c) depict the points at which $r_{\text{HII}}$ is 7 pc in (a). The tracks in (a)–(c) are calculated using the equation (9), the derivative of the equation (9), and the equation (6) of Bisbas et al. (2015), respectively.

Fig. 10. Surface density plots of the 10 km s$^{-1}$ CCC simulations by Takahira, Tasker, and Habe (2014). The clouds prior to a collision are shown in (a), while a snapshot of the collision, where the time corresponds to the maximum number of formed cores, is in (b) (see Takahira, Tasker, and Habe 2014 for details). Both of the two snapshots are at a viewing angle perpendicular to the collision axis. The labels in the $x$, $y$, and $z$ axes are normalized to the radius of the small cloud, 3.5 pc (Takahira, Tasker, and Habe 2014).
Fig. 11. Spatial distributions of the synthetic CO $J=1-0$ data of the collision model in Figure 10 are shown in (a)–(c) for three different velocity ranges. The velocity ranges are indicated as dashed lines in Figure 13. The velocity components of the small cloud and the large cloud are shown in (a) and (c), respectively, while the components at the intermediate velocity between the two clouds is in (b). The viewing angle is set to the parallel to the collisional axis. (d) The moment 1 map of the synthetic CO data. The color indicates the radial velocity of the gas normalized with the velocity separation between the large cloud and the small cloud as $4\, \text{km s}^{-1}$. Dashed lines indicate the integration range in Y shown in Figure 13.

4.3 Cloud-cloud collision (CCC) model

We here postulate a CCC model as an alternative idea to explain the observed signature of the molecular gas and formation of the O stars in Sh2-48. Torii et al. (2017) observed the molecular line emission in the galactic HII region M20, and by comparing between the observations and numerical simulations, the authors discussed that CCC is an unique interpretation that can explain the observed velocity distribution of the molecular clouds in M20. In the interpretation in Torii et al. (2017), “complementary spatial distribution between two colliding clouds” and “bridge feature which connect the two colliding clouds in the velocity space” are the signatures of the molecular gas characteristic to the young CCC region. We found that the discussion by Torii et al. (2017) can be applied to the present case in Sh2-48.

Figure 10 shows surface density plots of the CCC simulations by Takahira, Tasker, and Habe (2014), in which a collision between two dissimilar clouds at $10\, \text{km s}^{-1}$ is presented. During the collision, the small cloud forms a cavity on the large cloud, forming a dense compressed, turbulent layer at the interface of the collision as shown in Figure 10(b). Spatial distributions of the velocity components of the two colliding clouds are presented in Figure 11 using the synthetic CO $J=1-0$ observational data calculated by Haworth et al. (2015a) and Haworth et al. (2015b) based on the data of the CCC simulation shown in Figure 10(b). The line of sight of the synthetic observations was set to parallel to the colliding axis so that the two clouds coincides each other along the line of sight. As shown in Figures 11(a) and (c), the two colliding clouds can be seen in two different velocity ranges, and the large cloud has a ring-like morphology. The inner radius of the ring structure corresponds to the radius of the small cloud shown in (a), showing a complementary distribution between these. At the intermediate velocity range in (b), the turbulent gas excited through the collision is seen. This intermediate velocity component is continuously distributed in the velocity space, which corresponds to the bridge feature discussed in Torii et al. (2017). In Figure 11(d) the moment 1 map of the synthetic CO data in presented. It shows an axisymmetric velocity gradient.

Haworth et al. (2015a) discussed that during a collision, deceleration of the colliding velocity efficiently works due to the momentum conservation, and that at a latter phase of the collision, the velocity separation between two colliding clouds becomes smaller...
than the proper turbulent velocities of the clouds, making it difficult to distinguish the two colliding clouds. Their discussion suggests that the two characteristic observational signatures discussed in Torii et al. (2017), i.e., complementary distribution and bridge feature, as well as the symmetric velocity gradient shown in Figure 11(d) are observable in an early evolutionary stage of CCC.

4.4 CCC and O star formation in Sh2-48

We interpret that the line-symmetric velocity gradient of the molecular cloud in Sh2-48 presented in Figure 4 was formed by CCC. In Figure 12 we present schematics of our CCC scenario in Sh2-48. While the case shown in Figures 10(b) and 11 is a collision between two spherical clouds, we here discuss a collision between a vertically elongated, cylindrical cloud and a large spherical cloud, with a viewing angle parallel to the collisional axis. In Figure 13 the position-velocity diagram of the synthetic CO data is shown, where the Y range of the diagram is set to just cover the height of the small cloud as shown in Figure 11(d) so that the velocity gradient of the molecular gas can be approximated to line-symmetric along the X axis. The CO emission in Figure 13 shows “V-shape” velocity distribution, which resembles the CO distribution in the present observations shown in Figure 5, being consistent with the present CCC model. Since a V-shape in position-velocity diagram indicates an on-going collision between two dissimilar clouds, further star formation including massive stars will be possibly triggered in Sh2-48 in the future, although the Sh2-48 cloud currently shows no signs of massive YSOs and protostars discussed in Section 3.2. The gas motion along the filaments in the Sh2-48 cloud may provides additional information on the possibility of future high-mass star formation. Further observations with high spatial and velocity resolutions will allow us to investigate the detailed distributions and dynamics of the gas in the filaments in the Sh2-48 cloud.

In our CCC model, the region at which the line-symmetric velocity gradient is seen indicates the colliding part of gas. Detections of the C\(^{18}\)O emission throughout the line-symmetric velocity gradient is consistent with this assumption, suggesting strong compression of the gas by the collision (Figure 2(c)). The synthetic CO data shows that the colliding part of the gas has network of filaments as shown in Figure 11(b). This is also consistent with the observations, as the dense gas in the Sh2-48 has filamentary structures. Here it is noted that the simulations by Takahira, Tasker, and Habe (2014) did not include the magnetic field, and based on the magnetohydrodynamical simulations of colliding flows Inoue and Fukui (2013) pointed out that the magnetic field plays an important role on formation of filaments at the collisional layer and that these filaments are crucial on high-mass star formation. Further discussion concerning the observed filamentary structures should be done based on the future numerical simulations of CCC including the magnetic field.

The timescale of the H\(\text{II}\) region formation in Sh2-48 was measured as 1.5 and 5 Myr in Section 4.2 for model cases with initial densities of \(10^3\) and \(10^4\) cm\(^{-3}\), respectively. On the other hand, the collisional velocity in Sh2-48 at the current state can be measured to be \(\sim 4\) km s\(^{-1}\) as the velocity difference between the top and bottom of the V-shape velocity distribution shown in Figure 5. The initial collisional velocity may have been larger than 4 km s\(^{-1}\), as collisional velocity decreases during a collision. If we tentatively assume an average collisional velocity in Sh2-48 over the time of 6 km s\(^{-1}\), the travel distance of the collision can be calculated as 9 pc and 30 pc for the two density cases. Because in the latter case the travel distance is much larger than the size of the large cloud, and the collision would no longer continues in this case, we here prefer the model case with an initial density of \(10^3\) cm\(^{-3}\) and a timescale of 1.5 Myr.

We here note that if there is a hole/holes in the H\(\text{II}\) region, ionized gas streams out into the wider ISM, increasing an expanding velocity, and also an expanding timescale, slightly faster than the predicts in the models shown in Figure 9. Because ionized gas streams out through the cavity created by the collision in the CCC model, this discussion may be the case in Sh2-48. In such an H\(\text{II}\)
Fig. 13. The position-velocity diagram of the synthetic CO $J=1$–0 data of the collision model shown in Figure 11. The integration range in $Y$ is indicated as dashed lines in Figure 11(d). The labels of the $X$ and $V$ axes are normalized with the radius of the small cloud as 3.5 pc and the velocity difference between the small cloud and the large cloud as 4 km s$^{-1}$, respectively. The velocity ranges used for Figures 11(a)–(c) are indicated as dashed lines.

region, local interactions between ionized gas and molecular gas are expected to be seen around the surface of the hole(s). Based on the radiation hydrodynamic simulations of massive star feedback in a series of papers by Dale et al. (e.g., Dale, Ercolano, and Bonnell 2012 and Dale, Ercolano, and Bonnell 2013), Haworth et al. (2015b) discovered many small globules or clumps that are accelerated by the HII region, not finding global expanding motion of the neutral medium. This is because that the HII regions reproduced in these simulations were porous, losing up to 95% of the ionizing photons. The clumps at ($l, b$) $\sim$ (16$^\circ$.65, $-0^\circ$.28) and (16$^\circ$.70, $-0^\circ$.42) which coincide with the absorption in H$\alpha$ at 39–43 km s$^{-1}$ (see red circles in Figure 6(b)) are interacted with the HII region as studied by Ortega et al. (2013), and are possibly accelerated by the HII region, as these have different velocities compared with these surroundings as shown in Figure 4.

The HII region in Sh2-48 is extended to the east relative to the central axis of the line-symmetric velocity gradient. This is probably due to the positions of the O stars. As the O stars in Sh2-48 were formed in the eastern part of the colliding region as illustrated in Figure 12(b), the ionized gas excited by the O stars was prevented from streaming into the western part of the clouds probably by the dense gas in the colliding layer, and hence the HII region have been evolved toward the east. The asymmetric profiles of the 20 cm and 24 $\mu$m emissions shown in Figure 7 support for the asymmetric expansion of the ionized gas. It is important to perform numerical simulations which calculates CCC including ionization in order to better understanding of the observed properties of both the neutral and ionized components.

4.5 Comparisons with the other CCC regions

Torii et al. (2015) studied CCC in the galactic HII region RCW 120 which has a beautiful infrared ring in the 8 $\mu$m emission. The authors discussed that the ring shape in RCW 120 was created through a collision between two dissimilar clouds. A notable difference in star formation between RCW 120 and the present case in Sh2-48 is in the number of the formed high-mass stars in CCC; i.e., one in RCW 120 and more than one in Sh2-48. Based on the molecular line observations in the super star cluster RCW 38, Fukui et al. (2016) discussed that the number of high-mass stars formed through CCC is strongly affected by the column density of the colliding clouds. If at least one of two colliding clouds has a column density larger than $10^{23}$ cm$^{-2}$, massive star cluster having more than ten O stars can be formed. However, the colliding clouds in Sh2-48 has column densities of (1–2) $\times$ $10^{22}$ cm$^{-2}$, not high enough to form a massive star cluster.

A possible reason which allowed Sh2-48 to form multiple high-mass stars is a large area of the colliding layer in Sh2-48. The physical size of the CCC in RCW 120 is estimated to be less than $\sim$3 pc based on the size of the 8 $\mu$m ring in RCW 120, while the size of the line-symmetric velocity gradient in Sh2-48 (Figure 4) is as large as $\sim$13 pc $\times$ 10 pc. The O stars formed via CCC immediately begin ionization of the surrounding medium after their birth, which may halt the further mass growth in other dense cores in the surrounding region. If a collision takes place between two clouds having large sizes, such destructive effect is not
efficient and multiple O stars can form in the colliding layer. The projected distance between BD-14 5014 and the 20 cm peak, which is the candidate site of another O star(s) in Sh2-48, is measured as 2–3 pc. If the sound speed of ionized gas is 10 km s\(^{-1}\), it takes 0.2–0.3 Myr for ionized gas excited to travel 2–3 pc. Such a timescale is enough for a protostar to gain 20–30 \(M_\odot\) at a mass accretion rate of \(10^{-4} M_\odot\) yr\(^{-1}\), which is required for high-mass star formation (e.g., Wolfire and Cassinelli 1986; McKee and Tan 2003; Hosokawa and Omukai 2009; Krumholz et al. 2009).

5 Summary

The conclusions of the present study are summarized as follows;

1. We analyzed the CO \(J=1\rightarrow0\) dataset of the galactic H\(\text{II}\) region Sh2-48 obtained as a part of the FUGIN project using the Nobeyama 45-m telescope in Japan, and found that a molecular cloud having a total molecular mass of \(8.5 \times 10^4 M_\odot\) and \(H_2\) column densities of \((1–3) \times 10^{22} \text{cm}^{-2}\) is associated with Sh2-48. The molecular cloud consists of network of filamentary structures having widths of \(\sim 1–2\) pc and clumpy structures with sizes of \(\sim 2–3\) pc, with a characteristic line-symmetric velocity gradient over \(\sim 4\) km s\(^{-1}\) with the center axis corresponding to the western rim of the H\(\text{II}\) region.

2. By comparing the CO emission with the absorption in H\(\alpha\), we found that the eastern part of the molecular cloud in Sh2-48 is distributed inside or at the rear side of the H\(\text{II}\) region, whereas the central part is located in front of the nebula, although these two parts are continuously distributed both in space and velocity.

3. Based on the analysis on the 20 cm continuum data, we discussed that there may be previously unidentified O star(s) in the vicinity of the 20 cm continuum peak, which is close to the central axis of the line-symmetric velocity gradient.

4. In order to interpret the observed line-symmetric velocity gradient of the molecular cloud, we investigated two possibilities; One is expansion of the H\(\text{II}\) region, and the other is cloud-cloud collision (CCC). Since the line-symmetric velocity gradient cannot be explained by spherical expanding motion of the H\(\text{II}\) region, and since the non-detection of the spherical expanding motion of the gas in the Sh2-48 cloud can be explained with the Spitzer D-type H\(\text{II}\) region expansion model, we concluded that the CCC assumption is preferable.

5. We discussed a scenario that a collision between a vertically elongated cylindrical cloud and a spherical large cloud occurred about 1.5 Myr ago and triggered the O star formation in Sh2-48, with a viewing angle almost parallel to the collisional axis. By analyzing the numerical calculations of CCC by Takahira, Tasker, and Habe (2014) and Haworth et al. (2015b), we found that the line-symmetric velocity gradient of the molecular cloud seen in Sh2-48 can be reproduced by the present CCC model, and it is suggested that the CCC in Sh2-48 is still continuing. Investigating a possibility of the further star formation including high-mass stars in Sh2-48 triggered by the collision is an important issue for the future study.

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References

Anathpindika, S. V. 2010, MNRAS, 405, 1431
Anderson, L. D., Bania, T. M., Balser, D. S., Cunningham, V., Wenger, T. V., Johnstone, B. M., & Armentrout, W. P. 2014, ApJS, 212, 1
Anderson, L. D., Bania, T. M., Jackson, J. M., Clemens, D. P., Heyer, M., Simon, R., Shah, R. Y., & Rathborne, J. M. 2009, ApJS, 181, 255
Avdissova, V. S., & Kondratenko, G. I. 1984, Nauchnye Informatsii, 56, 59
Benjamin, R. A., et al. 2003, PASP, 115, 953
Bisbas, T. G., et al. 2015, MNRAS, 453, 1324
Bohlin, R. C., Savage, B. D., & Drake, J. F. 1978, ApJ, 224, 132
Carey, S. J., et al. 2009, PASP, 121, 76
Churchwell, E., et al. 2006, ApJ, 649, 759
Churchwell, E., et al. 2009, PASP, 121, 213
Dale, J. E., Ercolano, B., & Bonnell, I. A. 2012, MNRAS, 424, 377
Dale, J. E., Ercolano, B., & Bonnell, I. A. 2013, MNRAS, 431, 1062
Deharveng, L., Zavagno, A., Schuller, F., Caplan, J., Pomerès, M., & De Breuck, C. 2009, A&A, 496, 177
Deharveng, L., et al. 2010, A&A, 523, A6
Dewangan, L. K. 2017, ApJ, 837, 44
Fukui, Y., Tsuge, K., Sano, H., Bekki, K., Yozin, C., Tachihara, K., & Inoue, T. 2017a, ArXiv e-prints, arXiv:1703.01075
Fukui, Y., et al. 2014, ApJ, 780, 36
Fukui, Y., et al. 2015, ApJL, 807, L4
Fukui, Y., et al. 2016, ApJ, 820, 26
Fukui, Y., et al. 2017b, ArXiv e-prints, arXiv:1701.04669
Furukawa, N., Dawson, J. R., Ohama, A., Kawamura, A., Mizuno, N., Onishi, T., & Fukui, Y. 2009, ApJL, 696, L115
Gong, Y., et al. 2017, ApJL, 835, L14
Habe, A., & Ohta, K. 1992, PASJ, 44, 203
Haworth, T. J., Shima, K., Tasker, E. J., Fukui, Y., Torii, K., Dale, J. E., Takahira, K., & Habe, A. 2015a, MNRAS, 454, 1634
Haworth, T. J., et al. 2015b, MNRAS, 450, 10
Helfand, D. J., Becker, R. H., White, R. L., Fallon, A., & Tuttle, S. 2006, AJ, 131, 2525
Hosokawa, T., & Omukai, K. 2009, ApJ, 691, 823
Inoue, T., & Fukui, Y. 2013, ApJL, 774, L31
Jackson, J. M., et al. 2006, ApJS, 163, 145
Kendrew, S., et al. 2012, ApJ, 755, 71
Krumholz, M. R., Klein, R. I., McKee, C. F., Offner, S. S. R., & Cunningham, A. J. 2009, Science, 323, 754
Kurtz, S., Churchwell, E., & Wood, D. O. S. 1994, ApJS, 91, 659
McKee, C. F., & Tan, J. C. 2003, ApJ, 585, 850
Minamidani, T., et al. 2016, in Proc. SPIE, Vol. 9914, Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy VIII, 99141Z
Ohama, A., et al. 2010, ApJ, 709, 975
Ortega, M. E., Paron, S., Giacani, E., Rubio, M., & Dubner, G. 2013, A&A, 556, A105
Panagia, N. 1973, AJ, 78, 929
Parker, Q. A., et al. 2005, MNRAS, 362, 689
Robitaille, T. P., et al. 2008, AJ, 136, 2413
Saigo, K., et al. 2017, ApJ, 835, 108
Sharpless, S. 1959, ApJS, 4, 257
Simpson, R. J., et al. 2012, MNRAS, 424, 2442
Spitzer, L. 1978, Physical processes in the interstellar medium, Wiley-Interscience, New York, p. 333
Takahira, K., Tasker, E. J., & Habe, A. 2014, ApJ, 792, 63
Torii, K., et al. 2011, ApJ, 738, 46
Torii, K., et al. 2015, ApJ, 806, 7
Torii, K., et al. 2017, ApJ, 835, 142
Tóth, L. V., et al. 2014, PASJ, 66, 17
Vijapurkar, J., & Drilling, J. S. 1993, ApJS, 89, 293
Vogt, N., & Moffat, A. F. J. 1975, A&A, 45, 405
Wilson, T. L., & Rood, R. 1994, ARA&A, 32, 191
Wolfire, M. G., & Cassinelli, J. P. 1986, ApJ, 310, 207
Zavagno, A., Pomarèse, M., Deharveng, L., Hosokawa, T., Russeil, D., & Caplan, J. 2007, A&A, 472, 835