An ALMA view of the Galactic super star cluster
RCW 38 at 270-AU resolution

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Abstract
We report radio continuum and molecular line observations of the Galactic super star cluster
RCW 38, obtained from the Atacama Large Millimeter/Submillimeter Array with a minimum an-
gular resolution of 0′′17 × 0′′15 (≃ 289 AU × 255 AU). The C₁⁸O image reveal many massive con-
densations embedded within filamentary structures extending along the northwest-southeast
direction in the center of cluster. The condensations have sizes of 0.01–0.02 pc, H₂ column
densities of 10^{23}–10^{24} cm⁻², and H₂ masses of 10–130 M_☉. In addition, the 233-GHz contin-
umm image discovered that two dense, small millimeter-sources with radii of 460 and 200 AU
(Source A and Source B). Source A is embedded within the most massive C₁⁸O condensation,
whereas no counterpart is seen for Source B. The masses of Source A and Source B are esti-
ated as 13 and 3 M_☉ at the optically-thin limit, respectively. The C₁⁸O emission shows a
velocity gradient of 2 km s⁻¹ at the central 2000 AU of Source A, which could be interpreted as
a Keplerian rotation with a central mass of a few M_☉ or infall motion of gas. Further, the ALMA
$^{12}$CO data reveal that Source A and Source B are associated with molecular outflows exhibiting maximum velocities of $\sim 30$–$70$ km s$^{-1}$. The outflows have short dynamical timescales of $<1000$ yr and high mass outflow rates of $\sim 10^{-4}$–$10^{-3}$ $M_\odot$ yr$^{-1}$. These observational signatures suggest an early evolutionary phase of the massive star formation in Source A and Source B, although further investigation based on the high-resolution observations are needed to reach a firm conclusion.

**Key words:** ISM: clouds — ISM: molecules — radio lines: ISM — stars: formation

## 1 Introduction

The formation mechanism of massive stars is not yet thoroughly understood. A number of theoretical models invoke a scaled-up version of the low-mass model, with a disk-like structure and jets or outflows (e.g., Krumholz, Klein, and McKee 2007; Krumholz et al. 2009; Krumholz et al. 2010; Kuiper et al. 2010; Kuiper et al. 2011; Kuiper and Hosokawa 2018; Peters et al. 2010; Hosokawa and Omukai 2009; Hosokawa, Yorke, and Omukai 2010). Otherwise, massive young stellar objects (YSOs) could not accrete by overcoming the powerful radiation pressure of luminous protostars (e.g., Wolfire and Cassinelli 1986; Nakano 1989). Observations of jets and outflows associated with massive YSOs, which resemble those of low-mass YSOs, provide indirect evidence of high-mass accretion disks (Beuther et al. 2002; Maud et al. 2015). However, observations providing a 100 AU-scale resolution of the structures of massive YSOs are scarce.

Interferometric observations with an angular resolution of a few hundred AU can be anticipated to reveal fragmentation, collapse, and outflowing gas of hidden dense materials that lead to the protostar formation, as demonstrated by recent ALMA observations in nearby low- and high-mass star-forming regions (e.g., Tokuda et al. 2014; Tokuda et al. 2016; Tokuda et al. 2019; Hirota et al. 2017; Ohashi et al. 2018; Caselli et al. 2019; Matsushita et al. 2019). Several interferometric centimeter to submillimeter studies of luminous massive YSOs have resulted in the discovery of rotating structures on the order of of 100 to 1000 AU (Sánchez-Monge et al. 2013; Guzmán et al. 2014; Johnston et al. 2015; Cesaroni et al. 2017; Beuther et al. 2017; Motogi et al. 2019). However, it is still crucial to study a greater number of massive YSOs resolved at the 100 to 1000 AU scale.

In this paper, we report new observations of the Galactic super star cluster RCW 38, obtained using the Atacama Large Millimeter Array (ALMA) cycle-3 capability. RCW 38 is an outstanding super star cluster located at 1.7 kpc, and harbors $\sim 10^4$ stars, including $\sim 20$ O-type stars (and candi-
dates) within a small region of a few parsecs (Wolk et al. 2006; Winston et al. 2011; Kuhn, Getman, and Feigelson 2015, see also a review by Wolk, Bourke, and Vigil 2008). Most importantly, RCW 38 is the youngest super star cluster reported in the Milky Way, with an age of only $\sim 0.1$–$0.5$ Myrs (Fukui et al. 2016; Wolk, Bourke, and Vigil 2008). Despite strong dissipative and destructive effects caused by feedback from the formed massive stars, rich molecular gas still remains within the central $\sim 1$ pc of RCW 38, offering a unique opportunity to observe the natal gas of the super star cluster during formation.

RCW 38 has two sources that are bright in the near-infrared. The brightest feature at $2 \mu$m is known as IRS 2, an O5.5 binary located at the center of the cluster (DeRose et al. 2009), whose luminosity was measured as $7 \times 10^5 L_\odot$ (Furniss, Jennings, and Moorwood 1975). Another bright feature, labeled IRS 1, is located $0.1$ pc west of IRS 2; this feature is a dust ridge extending by $0.1$–$0.2$ pc in the north-south direction. The central $0.1$ pc of IRS 1 and IRS 2 is devoid of dust, with cavities evidenced by infrared and millimeter observations (Huchtmeier 1974; Vigil 2004; Wolk et al. 2006; Wolk, Bourke, and Vigil 2008).

Based on molecular line observations acquired with single-dish millimeter and submillimeter telescopes, Fukui et al. (2016) claimed that the formation of O stars in RCW 38 was triggered by a collision between two molecular clouds. The two identified clouds have radial velocities of $\sim 2$ and $\sim 12$ km s$^{-1}$. The former “the ring cloud”, which has a ring-like structure surrounding the cavities of IRS 1 and IRS 2, has a mass of $3 \times 10^4 M_\odot$ and is the primary body of the natal cloud of RCW 38, whereas the latter “the finger cloud”, which is elongated across the cluster, is less dense, with a mass of $2 \times 10^3 M_\odot$. The two clouds are connected in velocity space by an intermediate velocity feature (called “a bridge feature”). The bridge feature is located at $0.3$ pc north of IRS 1 and IRS 2, indicating that the collisional interaction still continues, as suggested by the cloud-cloud collision model (Torii et al. 2015; Torii et al. 2017b; Fukui et al. 2018). Izumi et al. (2019) observed these molecular clouds in the CI emission line, indicating that the abundance ratio of CO to CI is constant for visual extinction $A_v$ of a few mag to more than 10 mag. This result may be interpreted with the clumpy photodissociation region (PDR) model, in which clumpy structures with sizes of less than a few $0.1$ pc are predicted in the molecular clouds.

The ALMA observations in RCW 38 (P.I.: Fukui, Y., #2015.1.01134.S) were conducted for the central $1.5$ pc $\times$ $0.7$ pc of IRS 1 and IRS 2 in the ALMA band-6 and band-7, using the main 12-m array and the Atacama Compact Array (ACA). The minimum angular resolution of the dataset is $0''17 \times 0''.15$, which corresponds to $289 \times 255$ AU at $1.7$ kpc. This high angular resolution allowed us to detect two dense sources of $\sim 500$–$1000$ AU in the central region of RCW 38 with a small size on the order of $0.1$ pc. The sources are embedded within dense dust condensations and are associated with
high-velocity molecular outflows, suggesting massive star formation. The remainder of this paper is
organized as follows. Section 2 describes the ALMA dataset used in this study. Section 3 presents
the main results obtained by analyzing the ALMA dataset. The results are discussed in Section 4, and
finally, a summary is presented in Section 5.

2 Observations

The parameters of the ALMA observations are summarized in Table 1, whereas the datasets used in
this study are listed in Table 2. The ALMA observations were conducted using the cycle-3 band-6
(1.3 mm) and band-7 (0.87 mm) capabilities. The band-6 observations were performed using the 12-
m array and the ACA (the 7-m array and Total Power array). The target molecular lines were $^{12}\text{CO}$
$J=2–1$, $^{13}\text{CO}$ $J=2–1$, C$^{18}\text{O}$ $J=2–1$, SiO $J=5–4$, and H$3\alpha$, with spectral resolutions set to 141 kHz
($\sim0.18 \text{ km s}^{-1}$) or 244 kHz ($\sim0.31 \text{ km s}^{-1}$). A baseband with a bandwidth of 1875 MHz centered on
233 GHz was used to obtain the continuum emission. The band-7 observations, on the other hand,
were carried out with the ACA alone. Three spectral windows were used to observe molecular lines of
$^{13}\text{CO}$ $J=3–2$, C$^{18}\text{O}$ $J=3–2$, and CS $J=7–6$ at a spectral resolution of 244 kHz ($\sim0.22 \text{ km s}^{-1}$), while
the continuum emission was observed using a baseband with a bandwidth of 1875 MHz centered on
341 GHz.

In this study, only the datasets of CO lines and continuum emission were used to investigate
the several 100 to 1000 AU-scale structures of RCW 38. Herein, individual datasets are denoted by
the names listed in the “Name” column in Table 2. The obtained data were reduced using the Common
Astronomy Software Application (CASA) package (McMulline et al. 2007). In order to acquire better
sensitivities, a uv-tapering was applied to the $^{12}\text{CO}$ data, which resulted in a larger synthesized beam
of 0".5. For the C$^{18}\text{O}$ $J=2–1$ emission, two 3D images with different beam sizes (C$^{18}\text{O}_{\text{all}}$ and C$^{18}\text{O}$) were generated to illustrate the large-scale gas structures and the small-scale gas kinematics around
compact mm-sources in RCW 38 (Figures 1 and 3). The 12-m array and ACA data were combined by
the feathering technique for the C$^{18}\text{O}_{\text{all}}$ data, whereas only the 12-m array data was used for the C$^{18}\text{O}$
data.

3 Results

3.1 Large-scale C$^{18}\text{O}$ distribution

From the C$^{18}\text{O}_{\text{all}}$ data with a resolution of $\sim2''$, Figures 1(a) and (b) show the C$^{18}\text{O}$ intensity distribu-
tion integrated over $–2$ to $+14 \text{ km s}^{-1}$, which covers the velocity ranges of the ring cloud, finger
cloud, and bridge feature. The majority of the emissions arise from the ring cloud. The C$^{18}\text{O}_{\text{all}}$
map shows filamentary structures with widths of 0.1–0.2 pc, extending along the northwest-southeast direction, whose rim at the bottom side is illuminated by nearby O stars, as indicated by the bright 5.4 µm emission (Figure 1(b)). The filamentary structures include many condensations. The condensations were identified from the C^{18}O_all integrated intensity map in Figure 1(a) using the “clumpfind” algorithm (Williams, de Geus, and Blitz 1994), where the lowest detection level was set to 5σ (= 3 Jy beam^{-1} km s^{-1}). Distributions of the 21 identified condensations are indicated by the circles in Figure 1(a), whereas their physical properties are summarized in Table 3.

The condensations have typical radius $r_{C^{18}O}$ of 0.01–0.02 pc (which correspond to ~2000–4000 AU) and are separated by 0.05–0.3 pc with each others. The H$_2$ column density $N_{H_2}$ and H$_2$ mass $M_{H_2}$ of the condensations were estimated assuming Local Thermodynamic Equilibrium (LTE). These condensations show brightness temperatures $T_b$ of 30–50 K in the $^{13}$CO_all data, and these values were used for the excitation temperature $T_{ex}$ in the calculations. A $^{16}$O/$^{18}$O ratio of 550 and a [H$_2$]/[^{12}CO] ratio of $10^4$ was adopted (e.g., Frerking, Langer, and Wilson 1982; Leung, Herbst, and Huebner 1984; Wilson and Rood 1994). The derived $N_{H_2}$ are as high as an order of $10^{23}$–$10^{24}$ cm$^{-2}$ at the peak positions of the condensations, whereas the $M_{H_2}$ ranges from ~10$M_\odot$ to ~100 $M_\odot$. The $M_{H_2}$ values are greater than the virial mass $M_{vir}$ of the condensations by factors of 2–3 (Table 3), suggesting that these condensations are gravitationally unstable.

There are several C^{18}O condensations with remarkably high $N_{H_2}$ of $10^{24}$ cm$^{-2}$, i.e., #1, #9, #10, #12, #13, #16, #18, and #19. The most dense and massive condensation #13 is located immediately west of IRS 1. Figure 1(c) shows a magnified view of the C^{18}O_all map toward the condensation #13 and IRS 1, superimposed on the Very Large Telescope (VLT) near-infrared image (Wolk et al. 2006), indicating that the eastern rim of the condensation #13 follows the western rim of the bright ridge of IRS 1. This result suggests that the bright infrared emission of IRS 2 arises from the strong irradiation of the outer envelope of the condensation by the adjacent IRS 2.

3.2 Discovery of two compact mm-sources: Source A and Source B

Figure 1(d) shows distributions of the cool dust emission in the 233-GHz (image) and 341-GHzACA (contours) maps toward the corresponding region of Figure 1(c). Two very compact millimeter(mm)-sources were detected in the continuum data: Source A coincides with the condensation #13 west of IRS 1, whereas Source B is located 0.1–0.2 pc northwest of IRS 1 without any counterparts in the C$^{18}$O condensations (Figure 1(c)). As Source B is observed in the ACA map (Figure 1(c)), which covers extended emission, the possibility of resolved-out can be dismissed to interpret the absence of C$^{18}$O condensation.
Figure 2 shows an enclosed-view of Source A and Source B in the 233-GHz map with a resolution of \(~0''.16\). Both sources exhibit a single peak component. Source A shows a parallelogram-like distribution with a peak flux density of 24.9 mJy beam\(^{-1}\), whereas Source B with a peak flux density of 48.8 mJy beam\(^{-1}\) has a circular distribution, which is not fully resolved at the present spatial resolution. The obtained peak flux densities of Source A and Source B correspond to \(T_b\) of 22 and 42 K, respectively. There are no other mm-sources with significant signals in the 233-GHz map. The relatively weak, diffuse emission located east of Source A, as shown in Figure 2(a), coincides with the western rim of IRS 1, which may due to free-free emission, rather than thermal dust emission. The total fluxes obtained at the central 12'' of Source A and Source B are 0.73 and 0.17 Jy in the 233-GHz map, respectively. These figures account for approximately 24% and 13% of the total fluxes measured with the 233-GHz\(_{ACA}\) map for the same areas. This result indicates that the 233-GHz data obtained with the 12-m array overlooks a significant amount of flux from the extended dust emission toward Source A and Source B.

The VLT/ISACC and NACO \(J, H,\) and \(K_s\) images obtained by Wolk et al. (2006) and DeRose et al. (2009) indicate no significant excess of emission toward Source A and Source B. This is also the case for the four \(Spitzer/IRAC\) bands (3.4, 4.5, 5.6, and 8.0 \(\mu m\); Wolk et al. 2006). Unfortunately, there are no available data with high angular resolution at infrared wavelengths exceeding 8 \(\mu m\).

3.3 Physical properties of Source A and Source B

Tables 4 and 5 summarize the physical parameters of Source A and Source B estimated from the 233-GHz and 341-GHz\(_{ACA}\) maps.

3.3.1 341-GHz\(_{ACA}\) data

The physical parameters measured from the 341-GHz\(_{ACA}\) map, which has an angular resolution of \(~4'\), are as follows; The radii of Source A and Source B at the half maxima, \(r_{dust}\), are as small as \(~0.02\) and \(~0.03\) pc, respectively. The \(N_{H_2}\) and \(M_{H_2}\) of the sources were calculated from the peak and total fluxes of the sources \((S_{peak}\) and \(S_{int}\)) at the optically-thin limit as follows;

\[
N_{H_2} = \frac{R_{g/d}S_{peak,\nu}}{2.8m_{H_2}k_{\nu}B_{\nu}(T_{dust})\Omega_{beam}}
\]

\[
M_{H_2} = \frac{R_{g/d}S_{int,\nu}D^2}{k_{\nu}B_{\nu}(T_{dust})},
\]

where \(T_{dust}\) is the dust temperature and \(R_{g/d}\) is the gas-to-dust ratio. Here, an \(R_{g/d}\) of 100 was assumed. The dust emissivity \(k_{\nu}\) at 341-GHz was assumed to be 1.8 cm\(^{-2}\) g\(^{-1}\) (Ossenkopf and Henning 1994). \(B_{\nu}(T_d)\) is the Planck function for \(T_d\). Far-infrared and submillimeter continuum observations indicate that cold dust components embedded within the H\(\text{II}\) regions typically have a \(T_{dust}\) of 15–30 K.
Considering the proximity of the exciting stars to Source A and Source B, which may lead to higher temperatures, \( T_{\text{dust}} \) values of 20–40 K were assumed in this study. As a result, the \( N_{\text{H}_2} \) values at the peaks of the two sources were calculated to be 1.1–2.7 \( \times 10^{24} \) cm\(^{-2} \) for Source A and 0.5–1.2 \( \times 10^{24} \) cm\(^{-2} \) for Source B, whereas the \( M_{\text{H}_2} \) values were as large as 32–81 \( M_\odot \) for Source A and 16–41 \( M_\odot \) for Source B. The derived \( N_{\text{H}_2} \) and \( M_{\text{H}_2} \) values for Source A are consistent with the those estimated for the \(^{18}\text{O} \) condensation #13 (Table 3). The number densities of the condensations \( n_{\text{H}_2} \) were calculated as an order of 10\(^7 \) cm\(^{-3} \) from the \( M_{\text{H}_2} \) assuming a sphere.

### 3.3.2 233-GHz data

The physical parameters of Source A and Source B measured from the high-resolution 233-GHz data are as follows; The \( r_{\text{dust}} \) values of Source A and Source B were measured by fitting the horizontal and vertical profiles across the peaks with a Gaussian function, with values of \( \sim 460 \) and \( \sim 200 \) AU, respectively (Figure 2). Because it is difficult to measure the optical depths of the sources with the present dataset, the \( N_{\text{H}_2} \) and \( M_{\text{H}_2} \) values were estimated as lower limits with the optically-thin assumption. The observed peak \( T_{\text{b}} \) values of 22 K for Source A and 42 K for Source B in the 233-GHz data were adopted as \( T_d \) in Equations (1) and (2), and a \( \kappa_\nu \) of 0.899 cm\(^{-2} \) g\(^{-1} \), and an \( R_{\text{g/d}} \) of 100 were applied (Ossenkopf and Henning 1994). The derived \( N_{\text{H}_2} \) value is approximately \( 1 \times 10^{27} \) cm\(^{-2} \) for the two sources, with the \( M_{\text{H}_2} \) values calculated as 13 \( M_\odot \) for Source A and 3 \( M_\odot \) for Source B. Observations at lower frequencies are crucial for measuring \( N_{\text{H}_2} \) and \( M_{\text{H}_2} \) more accurately by quantifying the optical depth of the dust emission.

### 3.3.3 Velocity distribution of the \(^{18}\text{O} \) emission in Source A

The high resolution \(^{18}\text{O} \) data were analyzed to investigate the molecular gas components associated with Source A. Figure 3(a) shows the intensity distribution of the \(^{18}\text{O} \) data integrated over a velocity range of \( -2\sim+4 \) km s\(^{-1} \), in which the \(^{18}\text{O} \) emission was detected in the presented region. The \(^{18}\text{O} \) distribution is more extended than the 233-GHz distribution, and the peak position does not perfectly coincide with the peak of the 233-GHz map, as shown by the white contours.

Figure 3(b) shows a first moment map of the \(^{18}\text{O} \) data. A clear velocity gradient along the southwest-northeast direction is present, which can also be observed in the position-velocity (p-v) diagram in Figure 3(c). The p-v diagram shows two velocity components at \( \sim -1 \) and \( \sim 3 \) km s\(^{-1} \) located west and east to the 233-GHz peak, respectively, and the 233-GHz peak is located in the center of the intermediate velocity feature connecting the two velocity components. These observed signatures suggest rotational motion of the \(^{18}\text{O} \) component centered on the 233-GHz peak. The
dashed lines in Figure 3(c) indicate pure Keplerian velocities ($\propto r^{-0.5}$) with a systemic velocity of 2 km s$^{-1}$, where the masses of the central objects were assumed as 1, 3, and 8 $M_\odot$ and no inclination is considered, indicating that the 1 and 3 $M_\odot$ curves better matches the C$^{18}$O distribution. However, the directions of the outflow lobes which will be presented in the next subsection are not perpendicular to the direction of the velocity gradient (see arrows in Figure 3(b)). This is inconsistent with the hypothesis that the observed C$^{18}$O component is a protostellar disk. Infall motion of gas, whose velocity is proportional to $r^{-1}$ (e.g., Ohashi et al. 2014), is an alternative idea to explain the observed velocity gradient. It is difficult to distinguish these two possibilities with the sensitivity and velocity resolution of the observed p-v diagram. If the velocity gradient was purely attributed to the Keplerian rotation, as the C$^{18}$O distribution does not perfectly match the 233-GHz distribution, the obtained result does not immediately indicate that Source A harbors a protostar with a mass of a few $\times M_\odot$. Indeed, Zhang et al. (2019) highlighted the importance of the choice of molecular lines in investigating the rotational motion to directly determine the mass of the central object.

3.4 High-velocity molecular outflows for Source A and Source B

In this subsection we report the discovery of high-velocity molecular outflows associated with Source A and Source B. The physical properties of the outflow lobes are summarized in Table 6. Figure 4 shows the spectra obtained from the $^{12}$CO$_{ACA}$ and C$^{18}$O$_{ACA}$ toward the 341-GHz$_{ACA}$ peaks of Source A and Source B (Figure 1(d)). Wing features with velocity widths of $\sim$30–70 km s$^{-1}$ are clearly present in the $^{12}$CO spectra for both the blueshifted and redshifted velocity ranges of Source A and Source B.

Figure 5(a) shows the spatial distributions of the outflow lobes in Source A from the high-resolution $^{12}$CO data, whereas Figure 5(b) presents velocity distributions of the outflow lobes, defined as $|v_{\text{mom1}} - v_{\text{sys}}|$, where $v_{\text{mom1}}$ and $v_{\text{sys}}$ are the first moment and systemic velocity of the source, respectively. The $v_{\text{sys}}$ value was determined from the C$^{18}$O$_{ACA}$ spectra in Figure 4 as 2 km s$^{-1}$.

As shown in Figure 5(a), the blueshifted and redshifted lobes are elongated from Source A toward the northeast-southwest direction by $\sim$3200 and $\sim$9100 AU, respectively. These two lobes are not perfectly aligned with each other, and the outflow axis does not correspond to the rotational axis of the C$^{18}$O component (see arrows in Figure 3(b)). In the blueshifted velocity range, other weak emissions are observed north and south of the lobe, but it is difficult to determine whether these features are associated with Source A, as the signal-to-noise (S/N) ratio of the present ALMA molecular line data is not high. The triangle in Figure 5(a) depicts the position of the H$_2$ emission at 2.12 $\mu$m reported by DeRose et al. (2009) using VLT/NACO, which is located near the tip of the
blueshifted lobe, suggesting the presence of shocked molecular gas caused by the outflow.

As shown in Figure 5(b), the redshifted lobe has a velocity gradient along the lobe, whereas such a gradient is not clear in the blueshifted lobe. Given the maximum velocities $v_{\text{max}}$ of 27 and 38 km s$^{-1}$, the dynamical timescales of the blueshifted and redshifted lobes $t_{\text{dyn}}$ were estimated as 560 and 1100 yr, respectively, where the inclination of the lobes is not considered. It is not simple to measure the H$_2$ masses of the outflow lobe $M_{\text{lobe}}$, because this value strongly depends on the line opacity, excitation temperature, inclination, etc; moreover it is difficult to distinguish the effects of these parameters for the relatively low-S/N ratio of the line data obtained with the 12-m array. However, using the synthetic observation technique, Offner et al. (2011) demonstrated that the CO-to-H$_2$ conversion factor can be used to track the actual mass of the outflow over different epochs, although the derived $M_{\text{lobe}}$ is generally a factor of 5–10 smaller than the actual mass due to the opacity effect. Therefore, in this study we adopt a CO-to-H$_2$ conversion factor of $2 \times 10^{20}$ (K km s$^{-1}$)$^{-1}$ cm$^{-2}$ (Bolatto, Wolfire, and Leroy 2013), as a conservative way to estimate the lower-limit of $M_{\text{lobe}}$. The derived $M_{\text{lobe}}$ values of the blueshifted and redshifted lobes were 0.06 and 0.4 $M_\odot$, respectively. Then, the mass outflow rates $\dot{M}_{\text{lobe}}$ of the two lobes were derived as $\sim 1.1 \times 10^{-4}$ and $\sim 3.6 \times 10^{-4}$ $M_\odot$ yr$^{-1}$, respectively (Table 6).

Compared with the lobes in Source A, the blueshifted lobe in Source B is relatively expanded, showing a cocoon-like shape. The $v_{\text{max}}$ of the blueshifted lobe is found to be as high as 67 km s$^{-1}$, and the velocity increases within the cocoon (Figure 6(b)). In contrast, the redshifted lobe does not show a clear shape; rather a weak, diffuse component is observed toward Source A. Although two other weak features are observed northwest of Source B in the redshifted velocity range, the association of these features with the redshifted lobe cannot be confirmed at this time. The projected length of the blueshifted lobe is $\sim 10000$ AU, providing a short $t_{\text{dyn}}$ of 750 yr (Table 6). Then, the $M_{\text{lobe}}$ and $\dot{M}_{\text{lobe}}$ values were derived as 1.3 $M_\odot$ and $1.7 \times 10^{-3} M_\odot$ yr$^{-1}$, respectively.

4 Discussion

4.1 Source A and Source B; nurseries of massive protostars?

The present ALMA data revealed two compact mm-sources at the center of the young super star cluster RCW 38. The two sources are embedded within dust condensations with $r_{\text{dust}}$ of $\sim 0.02$–0.03 pc and $M_{\text{H}_2}$ greater than $\sim 20$–30 $M_\odot$ (Table 5). These massive condensations seem to satisfy the initial conditions for the massive star formation (e.g., Tan et al. 2014). Associations with the high-velocity molecular outflows also support the hypothesis of massive star formation. Since the mass accretion rate $\dot{M}_{\text{acc}}$ correlates with the outflow mass rate ($\dot{M}_{\text{acc}} \approx$ a few $\times$ $\dot{M}_{\text{lobe}}$) (Beuther
et al. 2002; Maud et al. 2015), the observed high $\dot{M}_{\text{lobe}}$ values suggest a high $\dot{M}_{\text{acc}}$ on the order of $10^{-4}$–$10^{-3} \, M_\odot \, \text{yr}^{-1}$ for Source A and Source B, which is consistent with the values obtained with massive star formation models (e.g., McKee and Tan 2003; Hosokawa and Omukai 2009; Hosokawa, Yorke, and Omukai 2010). These observational signatures imply that Source A and Source B harbor a massive protostar that can drive high-velocity outflows. Note that the two sources exhibit a single peak at the 270 AU resolution, indicating no signs of fragmentation.

Further, the short $t_{\text{dyn}}$ values of the outflow lobes in Source A and Source B suggest that these protostars are in an early evolutionary stage. If $t_{\text{dyn}}$ is interpreted as the age of the protostar driving the outflow, it should coincide with the accretion time $t_{\text{acc}}$, suggesting that the total $M_{\text{lobe}}$ of the outflow lobes, $\sim 0.5 \, M_\odot$ for Source A and $\sim 1.6 \, M_\odot$ for Source B, would be similar to the current masses of the protostars. Although the present ALMA C$^{18}$O data presents a velocity gradient that can be possibly interpreted as a Keplerian rotation, which suggests a mass of the central object to be a few $M_\odot$, the sensitivity and velocity resolution of the ALMA data are not enough to distinguish from the infall motion of gas, as mentioned in Section 3.3.3.

4.2 Infrared-quiet sources

Measuring the luminosity at infrared wavelength is another way to constrain the evolutionary stage of the protostars. However, infrared images above 8.0 $\mu$m are not available in RCW 38 at an angular resolution of a few arcsecond. Further, no significant emission was detected for Source A and Source B in the near- and mid-infrared wavelengths below 8.0 $\mu$m; The VLT and Spitzer/IRAC images do not show any excess toward these two sources. Here, the Spitzer/IRAC 3.6, 4.5, 5.6, and 8.0 $\mu$m archival images (Wolk et al. 2006) were used to estimate the upper-limit of the luminosity at 3.6–8.0 $\mu$m ($L_{3.6-8.0}$) for Source A and Source B, by integrating the upper-limits of the flux in the four bands. The upper-limit of the flux in each band was measured as the standard deviation of the flux density distribution around a 4″ area of the source, and the derived upper-limits range $\sim 100$–400 MJy str$^{-1}$ for the four bands. The $L_{3.6-8.0}$ values were then calculated as small as 3.0 $L_\odot$ for Source A and 1.6 $L_\odot$ for Source B. Inclusion of the $J$, $H$, and $K_s$ bands does not strongly change these values.

In these wavelengths, accreting gas as well as the protostar itself should be the major sources of the emission. The accretion luminosity $L_{\text{acc}}$ can be calculated as follows;

$$L_{\text{acc}} = \frac{G M_\star \dot{M}_{\text{acc}}}{R_\star} \simeq 1219 \left( \frac{M_\star}{1 \, M_\odot} \right) \times \left( \frac{\dot{M}_{\text{acc}}}{10^{-3} \, M_\odot \, \text{yr}^{-1}} \right) \times \left( \frac{26 R_\odot}{R_\star} \right) \, [L_\odot],$$

(3)

where $G$ is the gravitational constant, and $M_\star$ is the stellar mass. The stellar radius $R_\star$ can be given as a function of $M_\star$ and $\dot{M}_{\text{acc}}$ (Stahler, Palla, and Salpeter 1986; Hosokawa and Omukai 2009):
\[ R_s \simeq 26 \left( \frac{M_*}{M_\odot} \right)^{0.27} \times \left( \frac{\dot{M}_{\text{acc}}}{10^{-3} M_\odot \text{yr}^{-1}} \right)^{0.41} [R_\odot]. \] (4)

Assuming that \( \dot{M}_{\text{acc}} \) is equal to the total \( \dot{M}_{\text{lobe}} \) of the redshifted and blueshifted lobes, the expected \( L_{\text{acc}} \) for \( M_* \) of 0.1 and 1 \( M_\odot \) is calculated as 140 and 770 \( L_\odot \) for Source A and 310 and 1700 \( L_\odot \) for Source B, respectively. Even for a small \( M_* \) of 0.1 \( M_\odot \), the derived \( L_{\text{acc}} \) is approximately two order of magnitude larger than the derived upper-limits of \( L_{3.6-8.0} \) for Source A and Source B.

A reasonable interpretation of the small \( L_{3.6-8.0} \) is that the accreting gas that is luminous in the near- and mid-infrared is veiled by the Source A and Source B. The two dust condensations have \( N_{\text{H}_2} \) of higher than \( 10^{24} \text{ cm}^{-2} \) (see Figure 1(d) and Table 5). If dust opacity model in Ossenkopf and Henning (1994) is assumed, the optical depths of the dust emission at 3.6–8/0 µm can be calculated to be \( \sim 50–100 \) at \( N_{\text{H}_2} = 10^{24} \text{ cm}^{-2} \). The emission of the accreting gas cannot be observed at these high optical depths. However, the opacity effect strongly depends on the three-dimensional inner-structures of the sources. If there is a hole created by the outflows in the condensation and if the inclination of the hole is not perpendicular to us, the emission from the accreting gas could be detected through the hole (e.g., Motogi et al. 2017; Motogi et al. 2019).

Another idea is “episodic accretion”. This idea was originally studied in low-mass star formation, followed by recent studies on the massive star formation models (e.g., Meyer et al. 2017; Meyer et al. 2018; Hosokawa et al. 2016). In the episodic accretion scenario, protostars spend most of their time in the quiescent phase with a low \( \dot{M}_{\text{acc}} \), interspersed with short but intense accretion bursts caused by disc gravitational fragmentation followed by rapid migration of the fragments onto the protostar (e.g., Dunham and Vorobyov 2012; Hosokawa et al. 2016). Therefore, the quiescent phase with a low \( L_{\text{acc}}(\propto \dot{M}_{\text{acc}}) \) has a high probability of detection, whereas the \( \dot{M}_{\text{lobe}} \) of the outflows may be high, as it is calculated as a time-averaged value.

Further investigation of these scenarios for Source A and Source B should be performed based on high-resolution observations. Observations at lower frequencies, where dust opacity is less influential, for instance, for ALMA band 3, are important accurately measuring the source masses. A high angular resolution, increased by a factor of two or three, is crucial to obtain detailed mass distributions of the sources. Observations with various molecular lines are also important for investigating the rotational motion of Source A and Source B. If Keplerian motion can be confirmed, the mass of the protostellar object can be measured. Molecular line observations are also important to investigate the possibility of CO depletion in Source B.
4.3 Formation of massive condensations in RCW 38

Source A and Source B are found inside molecular condensations embedded within the filamentary structures, with a width of $\sim 0.1$–$0.2$ pc, extending along the northeast-southwest direction in RCW 38 (Figure 1). The filamentary structures include twenty-one C$^{18}$O condensations with large $N_{\text{H}_2}$ of $>10^{23}$ cm$^{-2}$ and $M_{\text{H}_2}$ of $>10 M_\odot$ (Table 3). Although no 233-GHz continuum sources were detected in all the condensations except for #13, which harbors Source A, these condensations are possibly precursors of massive stars.

The formation of the filamentary structures and massive condensations may be attributed to strong compression caused by feedback from adjacent O stars through a process known as “collect and collapse” (Elmegreen and Lada 1977). In this model, an expanding HII region sweeps the surrounding medium, forming a dense molecular shell, which is followed by the fragmentation and formation of new stars. In the case of RCW 38, however, the distance between the massive condensations and exciting source (IRS 2) is too small for the accumulated gas to induce fragmentation. Because the distance of $\sim 0.2$–$0.3$ pc is roughly the same as the width of the filamentary structures, the gas density $n_{\text{H}_2}$ in the accumulated layer can increase by a factor of only $\sim 2$ from the initial gas density, if a plane-parallel is assumed; however, the model calculation requires that $n_{\text{H}_2}$ be increased by one or two orders of magnitude (e.g., Hosokawa and Inutsuka 2006). Thus, it is more likely that the seeds of the massive condensations holding Source A and Source B were formed prior to the onset of ionization of the O stars, although it is still possible that the feedback from nearby O stars enhanced the accretion of the condensations.

On the other hand, as summarized in the Introduction, it is suggested that the formation of massive stars in RCW 38 was triggered by a collision between two molecular clouds with a velocity separation of $\sim 10$ km s$^{-1}$ (Fukui et al. 2016). Recent ALMA observations of giant molecular clouds in the Large Magellanic Cloud found hub-filamentary structures (Myers 2009), in which massive stars are being formed, and these structures were likely formed by a large-scale colliding flow (Fukui et al. 2018; Tokuda et al. 2018; see also Andrè et al. 2016 for the case of NGC6334 in the Milky Way). Numerical calculations indicate that such a supersonic collision would create a network of filaments with widths of a few 0.1 pc at the interface of the collision (Inoue and Fukui 2013; Inoue et al. 2018). Fukui et al. (2019) analyzed the data of the numerical simulations of cloud-cloud collision in Inoue and Fukui (2013), finding that the massive cores are efficiently formed within the filaments created through the cloud-cloud collision. These massive cores are separated with each others by $\sim 0.05$–$0.2$ pc, which are consistent with the separations of the observed condensations in RCW 38 (Figure 1(a)). The observed filamentary structures and massive condensations in RCW 38 may have
been formed via a cloud-cloud collision.

To investigate this possibility, a statistical study of the physical and dynamical properties of the condensations embedded within the filamentary structures is needed, which will be reported elsewhere with the present ALMA data. The obtained information will be compared with the results of numerical models to investigate the background physics of the massive condensations formation.

5 Summary

The conclusions of the present study are summarized as follows.

1. The molecular gas associated with the Galactic super star cluster RCW 38 is resolved at the 270-AU scale using the new ALMA cycle-3 band-6 and band-7 data. The C$^{18}$O image was used to identify the filamentary structures with a width of 0.1–0.2 pc, which contains 21 condensations with $r_{\text{C}^{18}\text{O}}$ of 0.01–0.02 pc, peak $N_{\text{H}_2}$ of $10^{21}$–$10^{24}$ cm$^{-2}$, and $M_{\text{H}_2}$ of $10$–$130 M_\odot$.

2. In addition, the high-resolution 233-GHz continuum data revealed two dense, compact mm-sources (Source A and Source B) with radii of $\sim$460 and $\sim$200 AU. The $N_{\text{H}_2}$ of the two sources was derived as an order of $10^{27}$ cm$^{-2}$, whereas the $M_{\text{H}_2}$ were estimated as $13 M_\odot$ for Source A and $3 M_\odot$ for Source B at the optically-thin limit. Source A is coincident with one of the C$^{18}$O condensations, whereas no counterpart is found for Source B. The C$^{18}$O condensation holding Source A is located immediately west of IRS 1, suggesting that the bright infrared ridge of IRS 1 arises from irradiation of the eastern side of the condensation surface by IRS 2.

3. The high-resolution C$^{18}$O image shows a velocity gradient of gas toward Source A, which can be interpreted as the Keplerian rotation with a central mass of $\sim 1 M_\odot$, although no robust evidence was obtained to indicate the C$^{18}$O emission directly traces the motion of Source A. Infall motion of gas is an alternative idea to interpret the velocity gradient. High resolution and high sensitivity data are needed for further investigation.

4. The ALMA $^{12}$CO data detected molecular outflows associated with Source A and Source B. The outflows have high velocities of $\sim 30$–$70$ km s$^{-1}$ and large mass outflow rate of $\sim 10^{-4}$ $M_\odot$ yr$^{-1}$ for Source A and $\sim 10^{-3}$ $M_\odot$ yr$^{-1}$ for Source B. The derived values correspond to those expected for massive star formation models. The short dynamical timescales of the outflows, less than 1000 yr, suggest that the protostars in Source A and Source B may be massive stars in the creation stage.

5. Despite of the large $\dot{M}_{\text{lobe}}$ which imply large $\dot{M}_{\text{acc}}$ for Source A and Source, no significant excess was observed in the two sources at the near- and mid-infrared wavelengths. One idea is attenuation of the emission by dust in Source A and Source B. Another idea is the episodic accretion scenario, in which protostars spend most of their time in the quiescent phase, interspersed with short ac-
cretion bursts. Further observations with high angular resolution are needed to investigate these possibilities.

6. The formation of the filamentary structures and massive condensations was also discussed. The possibility of gas compression by the feedback from nearby O stars was eliminated. A collision between two molecular clouds may have triggered the formation of the filamentary structures in which the massive condensations were formed.

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Table 1. Spectral parameters of the ALMA observations

| Line/Continuum | Band | Frequency (GHz) | Resolution (kHz) | Array     |
|----------------|------|-----------------|------------------|-----------|
| Continuum      | 6    | 233.000         | 1.875 (GHz)      | 12-m, ACA |
| Continuum      | 7    | 341.000         | 1.875 (GHz)      | ACA       |
| $^{12}$CO $J=2$–$1$ | 6    | 230.538         | 141              | 12-m, ACA |
| $^{13}$CO $J=2$–$1$ | 6    | 220.399         | 141              | 12-m, ACA |
| $^{13}$CO $J=3$–$2$ | 7    | 330.588         | 244              | ACA       |
| $^{18}$O $J=3$–$2$ | 7    | 329.331         | 244              | ACA       |
| CS $J=7$–$6$   | 7    | 342.883         | 244              | ACA       |

Table 2. List of the ALMA datasets used in this paper

| Image             | Array | Resolution (km s$^{-1}$) | Beam (″)       | Noise$^a$ (mJy beam$^{-1}$) | Name$^b$     |
|-------------------|-------|--------------------------|----------------|------------------------------|--------------|
| Continuum (233-GHz) | 12-m  | ...                      | 0.17 × 0.15    | 0.45                         | 233-GHz     |
| $^{12}$CO $J=2$–$1$ | 12-m  | 1.0                      | 0.50 × 0.49    | 4.3                          | $^{12}$CO    |
| $^{13}$CO $J=2$–$1$ | 12-m  | 0.5                      | 0.23 × 0.21    | 19.6                         | $^{13}$CO    |
| $^{18}$O $J=2$–$1$ | 12-m  | 0.2                      | 1.90 × 1.55    | 123.8                        | $^{18}$O     |
| $^{12}$CO $J=3$–$2$ | 12-m  | 0.25                     | 7.25 × 5.29    | 15.3                         | $^{12}$CO    |
| $^{18}$O $J=3$–$2$ | 12-m  | 0.25                     | 7.3 × 5.2      | 167                          | $^{18}$O     |

$^a$ The noise is given per channel for line data cubes. $^b$ The shortened name of the dataset used in this paper.
### Table 3. Physical properties of the C$^{18}$O condensations

| # | R.A. (J2000)   | decl. (J2000) | $r_{C^{18}O}$ (pc)/AU | $dv$ (km s$^{-1}$) | $N_{H_2}$ ($\times 10^{23}$ cm$^{-2}$) | $M_{H_2}$ ($M_\odot$) | $n_{H_2}$ ($cm^{-3}$) | $M_{vir}$ ($M_\odot$) |
|---|----------------|---------------|------------------------|-------------------|-----------------------------|-------------------|----------------|------------------|
| 1 | 8:59:6.598     | -47:29:27.749 | 0.021/4365             | 1.1               | 12.8–13.9                   | 65–89             | 2.4–3.3         | 28               |
| 2 | 8:59:6.129     | -47:29:37.749 | 0.019/4012             | 1.2               | 5.3–6.8                     | 47–64             | 2.2–3.1         | 33               |
| 3 | 8:59:4.699     | -47:29:58.250 | 0.015/3093             | 0.8               | 8.5–9.7                     | 30–40             | 3.2–4.2         | 11               |
| 4 | 8:59:8.350     | -47:30:12.996 | 0.006/1335             | 0.8               | 6.3–6.8                     | 5–6               | 6.7–8.7         | 4                |
| 5 | 8:59:1.417     | -47:30:12.997 | 0.014/2979             | 1.0               | 2.4–3.3                     | 10–15             | 1.3–1.8         | 16               |
| 6 | 8:59:2.330     | -47:30:19.499 | 0.019/4085             | 1.6               | 5.9–9.1                     | 52–72             | 2.5–3.5         | 60               |
| 7 | 8:59:3.194     | -47:30:22.999 | 0.020/4210             | 1.1               | 7.6–9.1                     | 61–82             | 2.5–3.4         | 30               |
| 8 | 8:59:1.343     | -47:30:29.747 | 0.017/3441             | 0.9               | 7.2–8.6                     | 40–52             | 3.0–3.9         | 17               |
| 9 | 8:59:1.540     | -47:30:37.997 | 0.024/4876             | 1.0               | 11.0–11.5                   | 105–136           | 2.8–3.6         | 30               |
| 10| 8:59:2.577     | -47:30:41.499 | 0.016/3279             | 1.3               | 9.8–12.3                    | 39–51             | 3.4–4.5         | 30               |
| 11| 8:58:59.862    | -47:30:41.744 | 0.019/4001             | 1.3               | 6.5–9.1                     | 43–58             | 2.1–2.8         | 36               |
| 12| 8:59:2.897     | -47:30:44.249 | 0.014/2784             | 1.0               | 11.5–12.9                   | 39–47             | 5.6–6.7         | 14               |
| 13| 8:59:3.687     | -47:30:44.750 | 0.015/3158             | 1.6               | 24.6–26.8                   | 64–90             | 6.2–8.7         | 44               |
| 14| 8:59:2.478     | -47:30:47.749 | 0.012/2405             | 0.7               | 7.3–8.6                     | 18–23             | 4.0–5.1         | 6                |
| 15| 8:59:0.553     | -47:30:53.246 | 0.018/3790             | 1.2               | 9.6–10.7                    | 54–70             | 3.0–4.0         | 30               |
| 16| 8:58:59.961    | -47:30:56.994 | 0.013/2746             | 1.4               | 11.3–11.4                   | 34–43             | 5.1–6.5         | 29               |
| 17| 8:59:1.293     | -47:30:57.247 | 0.012/2553             | 0.8               | 5.6–6.5                     | 21–27             | 3.9–5.0         | 8                |
| 18| 8:59:0.084     | -47:30:59.994 | 0.011/2247             | 1.3               | 12.2–19.9                   | 24–39             | 6.7–10.6        | 21               |
| 19| 8:59:0.627     | -47:31:0.746  | 0.011/2256             | 0.9               | 10.1–10.8                   | 23–29             | 6.2–7.8         | 11               |
| 20| 8:59:1.120     | -47:31:2.497  | 0.010/2117             | 0.8               | 8.3–14.4                    | 18–27             | 5.9–9.0         | 7                |
| 21| 8:59:0.405     | -47:31:5.995  | 0.010/2070             | 1.4               | 8.2–24.0                    | 14–30             | 5.1–10.6        | 22               |

(a) $n_{H_2}$ was calculated from $M_{H_2}$ assuming a sphere with a radius of $r$.

### Table 4. Measured parameters of Source A and Source B

| Source | R.A. (J2000)   | decl. (J2000) | $S_{peak}$ (Jy beam$^{-1}$) | $S_{int}$ (Jy) | $S_{peak}$ (mJy beam$^{-1}$) | $S_{int}$ (Jy) |
|--------|----------------|---------------|-----------------------------|----------------|-----------------------------|----------------|
| A      | 8:59:3.740     | -47:30:44.832 | 3.1                         | 4.9(0.6)       | 24.9                        | 0.24(0.07)     |
| B      | 8:59:3.013     | -47:30:21.982 | 1.4                         | 2.5(0.8)       | 48.8                        | 0.11(0.05)     |

(a) The aperture radii of the photometry for measuring $S_{int}$ were set to 6$''$.5 and 0$''$.5 for the 341-GHz ACA image and the 233-GHz image, respectively. In the 341-GHz ACA image, the local background level of each source was estimated around the source using a circular annulus with inner and outer radii of 6$''$.5 and 1.5 $\times$ 6$''$.5 = 9$''$.8, respectively. The median value of the pixels within the annulus was applied as the local background level, with the standard deviation applied as the uncertainty of the photometry. The derived uncertainty is shown in parentheses.
Table 5. Physical properties of Source A and Source B

| Source | 341-GHz ACA (4′′.75 × 3′′.65) | 233-GHz (0′′.17 × 0′′.15) |
|-------|-------------------------------|---------------------------|
|       | $r_{dust}^a$ | peak $N_{H_2}^b$ | $M_{H_2}^b$ | $r_{dust}^b$ | peak $N_{H_2}^b$ | $M_{H_2}^b$ |
| A     | 0.02 | 10.7 – 26.8 | 32(3.9) – 81(9.9) | 460 | 4.8 | 13.0(3.8) |
| B     | 0.03 | 4.9 – 12.2 | 16(5.1) – 41(13.1) | 200 | 4.4 | 2.7(1.2) |

$^a$ $r_{dust}$ was measured at the half maximum. $^b$ The $N_{H_2}$ and $M_{H_2}$ were estimated at the optically-thin limit. The $T_{d}$ of 20 and 40 K were assumed in the $N_{H_2}$ and $M_{H_2}$ estimated from the 341-GHz ACA image to constrain $M_{H_2}$ ranges of the sources, whereas in the 233-GHz image the peak $T_b$ of 22 and 42 K were used as $T_d$ for Source A and Source B, respectively (Figure 2). The uncertainty of the derived $M_{H_2}$ is shown in parentheses.

Table 6. Physical properties of the outflow lobes

| Lobes           | $v_{max}$ | $l_{max}$ | $t_{dyn}$ | $M_{lobe}$ | $\dot{M}_{lobe}$ |
|-----------------|-----------|-----------|-----------|------------|------------------|
| (Source A: $v_{sys} = 2$ km s$^{-1}$) |           |           |           |            |                  |
| Blueshifted lobe| 24        | 3200      | 630       | 0.06       | 0.10 × 10$^{-3}$ |
| Redshifted lobe | 38        | 9100      | 1100      | 0.4        | 0.36 × 10$^{-3}$ |
| (Source B: $v_{sys} = 5$ km s$^{-1}$) |           |           |           |            |                  |
| Blueshifted lobe| 67        | 10600     | 750       | 1.3        | 1.7 × 10$^{-3}$  |
| Redshifted lobe | 45        | ...       | ...       | 0.3        |                  |

$v_{max}$ is the maximum velocity of the outflow lobe measured from the systemic velocity $v_{sys}$ of the source, whereas $l_{max}$ is the physical length of the lobes measured from the 233-GHz peak of the source. The dynamical timescale of the outflow $t_{dyn}$ was calculated as $t_{dyn} = l_{max}/v_{max}$. The $H_2$ mass of the outflow lobe was calculated using a CO-to-$H_2$ conversion factor of $2 \times 10^{20}$ (K km s$^{-1}$)$^{-1}$ cm$^{-2}$ (Bolatto, Wolfire, and Leroy 2013). The mass flow rate $M_{lobe}$ was measured as $M_{flow}/t_{dyn}$. The $l_{max}$ of the redshifted lobe in Source B could not be measured.
Fig. 1. (a) Intensity distributions of the C$^{18}$O$_{all}$ data integrated over a velocity range of $-2-+12$ km s$^{-1}$. Circles indicate the positions of the C$^{18}$O condensations. (b) Contour map of the C$^{18}$O$_{all}$ image in (a) superimposed on the Spitzer/IRAC 5.4 μm image (Wolk, Bourke, and Vigil 2008). Contours start at 1 mJy beam$^{-1}$ km s$^{-1}$ with steps of 2 mJy beam$^{-1}$ km s$^{-1}$. In (a) and (b), the large cross indicates the central O5.5 star IRS 2, whereas small crosses indicate the O star candidates (Winston et al. 2011). (c) A VLT near-infrared image (Wolk et al. 2006) shown in the region indicated by the white box in (b). Contours show the C$^{18}$O$_{all}$ distribution plotted in (b). (d) A 233-GHz image of the same area in (c). Contours show the 341-GHz$_{ACA}$ distribution, starting at 5σ with steps of 10σ, which correspond to 185 and 370 mJy beam$^{-1}$. The two boxes marked by red lines in (c) and (d) indicate the regions of Source A and Source B shown in Figures 2(a) and (b), respectively.
Fig. 2. (a, b) Magnified views of the 233-GHz image for Source A and Source B. The contours in (a) and (b) start at half of the peak intensities, 24.9 and 48.8 mJy beam$^{-1}$, with steps of 4 and 8 mJy beam$^{-1}$, respectively. Intensity profiles along the dashed lines across the peaks of the 233-GHz emission are plotted in black lines at the upper- and right-sides of the panels in units of $T_b$, with the best-fit Gaussian curves overlaid in dashed red lines.
Fig. 3. (a) Intensity distribution of the C$^{18}$O data (color and black contours) and the 233-GHz map (white contour) for Source A. The velocity integration range is $-2$ to $+4$ km s$^{-1}$. The black contours start at $3\sigma$ with steps of $1\sigma$, which correspond to 135 and 45 mJy beam$^{-1}$ km s$^{-1}$, respectively, whereas the white contours are plotted at the same levels as those in Figure 2(a). (b) First moment map of the C$^{18}$O data (color) superimposed with the contour map of the C$^{18}$O data in (a). The cross indicates the peak position of the 233-GHz image. The two arrows indicate the directions of the blueshifted and redshifted outflow lobes shown in Figure 5. (c) Position-velocity diagram of the C$^{18}$O data. The vertical white line indicates the direction of the 233-GHz peak of Source A, and the dashed lines show the Keplerian velocities calculated for a central mass of 1 (white), 3 (red), and 8 $M_\odot$ (yellow). Here, the C$^{18}$O data were smoothed to be a velocity resolution of 1.5 km s$^{-1}$. 
Fig. 4. Spectra of the $^{12}$CO$_{ACA}$ and C$^{18}$O$_{ACA}$ data near the peaks of the 233-GHz map for Source A and Source B. The intensities of the $^{12}$CO$_{ACA}$ profiles were doubled.

Fig. 5. (a) $^{12}$CO intensity distributions of the blueshifted and redshifted outflow lobes shown in blue and red contours, respectively, with the 233-GHz background image. The velocity ranges of the lobes are shown in parentheses in units of km s$^{-1}$. The contours stars at 3$\sigma$ with steps of 1.5$\sigma$, where the 1$\sigma$ value of the blueshifted and redshifted maps of Source A are 30 and 65 mJy beam$^{-1}$ km s$^{-1}$, respectively. The triangle depicts the approximate position of the vibrational transition of the H$_2$ emission detected by VLT (DeRose et al. 2009). (b) Color map of $|v_{\text{mom1}} - v_{\text{sys}}|$ for the lobes, with the $^{12}$CO contour maps plotted in (a), where $v_{\text{mom1}}$ is the first moment generated from the $^{12}$CO data for the velocity ranges shown in panel (a), whereas the systemic velocity of the source $v_{\text{sys}}$ was measured from the C$^{18}$O$_{ACA}$ data as 2 km s$^{-1}$ (Figure 4). The cross indicates the 233-GHz peak for Source A.
Fig. 6. The same plots shown in Figure 5 are presented here, but for Source B. In (a), the 1σ levels of the $^{12}$CO maps are 90 and 100 mJy beam$^{-1}$ km s$^{-1}$ for the blueshifted and redshifted lobes, respectively. In (b), only the blueshifted lobe is plotted.