Cloud–cloud collision in the Galactic Center Arc

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Abstract

We performed a search of cloud–cloud collision (CCC) sites in the Sagittarius A molecular cloud (SgrAMC) based on the survey observations using the Nobeyama 45 m telescope in the C32S J = 1–0 and SiO ν = 0 J = 2–1 emission lines. We found candidates abundant in shocked molecular gas in the Galactic Center Arc (GCA). One of them, M0.014−0.054, is located in the mapping area of our previous ALMA mosaic observation. We explored the structure and kinematics of M0.014−0.054 in the C32S J = 2–1, C34S J = 2–1, SiO ν = 0 J = 2–1, H13CO+ J = 1–0, and SO N, J = 2, 2–1, 1 emission lines and fainter emission lines. M0.014−0.054 is likely formed by the CCC between the vertical molecular filaments (the “vertical part,” or VP) of the GCA, and other molecular filaments along Galactic longitude. The bridging features between these colliding filaments on the PV diagram are found, which are the characteristics expected in CCC sites. We also found continuum compact objects in M0.014−0.054, which have no counterpart in the H42α recombination line. They are detected in the SO emission line, and would be “hot molecular cores” (HMCs). Because the local thermodynamic equilibrium mass of one HMC is larger than the virial mass, it is bound gravitationally. This is also detected in the CCS emission line. The embedded star would be too young to ionize the surrounding molecular cloud. The VP is traced by a poloidal magnetic field. Because the strength of the magnetic field is estimated to be ∼mgauss using the Chandrasekhar–Fermi method, the VP is supported against fragmentation. The star formation in the HMC of M0.014−0.054 is likely induced by the CCC between the stable filaments, which may be a common mechanism in the SgrAMC.

Key words: Galaxy: center — ISM: magnetic fields — ISM: molecules — stars: formation — stars: massive

1 Introduction

The Galactic center region is the nucleus of the nearest spiral galaxy. The Central Molecular Zone (CMZ) (Morris & Serabyn 1996) is a large molecular cloud reservoir in the galaxy, which extends along the galactic plane up to l ∼ ±1°. The mass of the CMZ is estimated to be ∼5 × 107 M⊙...
(e.g., Morris & Serabyn 1996; Tsuboi et al. 1999). The molecular clouds in the CMZ are much denser, warmer, and more turbulent than those in the Galactic disk region. The CMZ is recognized to be a laboratory for peculiar phenomena, which will be found in central molecular cloud reservoirs of normal external galaxies by future telescopes. Young and luminous star clusters which contain over several tens of OB stars, for example the Arches cluster and the Quintuplet cluster, have been found in the CMZ by IR observations (e.g., Genzel et al. 1996; Figer et al. 1999, 2002). They are as luminous as those which are nearly hard to be found in the Galactic disk region. These star clusters presumably have been formed in the cradle molecular clouds in the CMZ. The star formation would be influenced by external factors, such as interactions with supernova remnants (SNRs) and/or cloud–cloud collisions (CCC) because they are crowded in the region (e.g., Morris 1993; Hasegawa et al. 1994, 2008). However, it is difficult to demonstrate observationally how the cradle molecular clouds produce such massive clusters because these clusters have already almost lost the surrounding molecular materials. The Galactic Center 50 km s\(^{-1}\) molecular cloud (50MC) is an exception, as it still has abundant molecular gas and several compact H\(\text{II}\) regions. In the previous observations, we have found a half-shell structure filled with shocked molecular gas, which would be made by CCC (Tsuboi et al. 2011, 2015, 2019). As is known widely, the dense molecular clouds in the CMZ seem to exist as molecular ridges along the galactic plane, which are bundles of the molecular filaments (Bally et al. 1987; Oka et al. 1998; Tsuboi et al. 1999). The molecular filaments would collide with each other, where star formation would be activated. It is an open issue whether CCCs usually induce star formation in the CMZ or not.

First, we searched CCC sites based on the survey observations for the Sagittarius A molecular cloud complex (SgrAMC) with the Nobeyama 45 m telescope (Tsuboi et al. 1999, 2011). The SgrAMC is one of the most conspicuous molecular cloud complexes in the CMZ. One of the candidates, M0.014–0.054 near the 50MC, is located serendipitously in the mosaic observation area using ALMA of the 50MC, although the observation itself had another science objective (Uehara et al. 2019). Then we looked for the signs of CCCs and induced star formation in the ALMA science objective (Uehara et al. 2019). Then we looked for the signs of CCCs and induced star formation in the ALMA science objective (Uehara et al. 2019).

2 Search for the cloud–cloud collision candidates

We searched the CCC candidates in the SgrAMC based on the existing survey observations with the Nobeyama 45 m telescope in the \(^{32}\text{S} J = 1–0\) (48.990957 GHz) and SiO \(v = 0, J = 2–1\) (86.846995 GHz) emission lines (\(^{32}\text{S}:\) Tsuboi et al. 1999; SiO: Tsuboi et al. 2011). These surveys have the highest angular resolutions among single dish observations. The \(^{32}\text{S}\) emission line is a tracer of medium dense molecular cloud, \(n(\text{H}_2) > 10^4\ cm^{-3}\). Because this emission line is moderately optically thick, \(\tau \sim 0.5–3\), in the SgrAMC (e.g., Tsuboi et al. 1999), this emission shows mainly the location of the medium dense molecular cloud. On the other hand, the SiO emission line is a famous tracer of strong C-shock waves (\(\Delta V > 30\ km\ s^{-1}\)) which propagated in the region within 10\(^5\) yr (e.g., Gusdorf et al. 2008; Jiménez-Serra et al. 2008). Because the emission line is often detected in the CCC sites, the detection indicates the CCC candidates.

Figure 1a is the integrated intensity map of the SgrAMC in the \(^{32}\text{S} J = 1–0\) emission line with the velocity range of \(V_{\text{LSR}} = -30\ to\ 0\ km\ s^{-1}\). The contours in the figure show the Galactic Center Arc (GCA) in the 20 cm continuum emission for comparison (Yusef-Zadeh et al. 1984). The molecular cloud is identified as two curved ridges along the GCA (e.g., Serabyn & Güsten 1987). Moreover, a large molecular cloud connecting with the curved ridges is located apparently in the “continuum gap” between the GCA and Sagittarius A east SNR. This cloud extends vertically north, \(l \sim -0.02, b \sim 0.05\), and south, \(l \sim 0.03, b \sim -0.12\). We call it the “Vertical Part” (VP) here. M0.014–0.054 is identified as a strong compact feature which is apparently located on the VP in the \(^{32}\text{S}\) integrated intensity map. Figure 1b is the position–velocity (PV) diagram in the \(^{32}\text{S} J = 1–0\) emission line along the VP. We identified the VP as a ridge-like feature with no noticeable velocity gradient on the PV diagram. M0.014–0.054 is also seen as a compact feature on the ridge.

Figure 1c is the integrated intensity map in the SiO \(v = 0, J = 2–1\) emission line with the same area and velocity range as in figure 1a. Almost all molecular clouds in the area become faint or disappear in the SiO map. This shows that no strong C-shock wave propagated in the area except for several compact components including M0.014–0.054. M0.014–0.054 extends roughly east to west. The east–west extent of M0.014–0.054 seems to correspond with the width of the VP seen in the \(^{32}\text{S}\) emission line. M0.014–0.054 is more prominent in the SiO emission line than in the \(^{32}\text{S}\) emission line. This shows that shocked molecular gas originated by the C-shock wave within 10\(^5\) yr is abundant in M0.014–0.054. This suggests that the object would be made by some historical event including CCC.

In addition, figure 1d shows the continuum emission map at 330 MHz (LaRosa et al. 2000). Well-known continuum features, “threads,” are identified (yellow arrows). There is also a emission extending from the Sagittarius A east SNR to the east, which crosses threads and reaches...
Fig. 1. (a) Integrated intensity map of the Galactic Center Arc (GCA) in the C$^{32}$S $J = 1$–0 emission line with the Nobeyama 45 m telescope (Tsuboi et al. 1999). The velocity range is $V_{\text{LSR}} = -30$ to 0 km s$^{-1}$. The angular resolution is 45\,′′ in FWHM, which is indicated by a white circle in the lower left-hand corner. A red arrow indicates a candidate of the CCC site; M0.014$-$0.054. The contours show the 1.44 GHz (20 cm) continuum emission for comparison (Yusef-Zadeh et al. 1984). The contour levels are (1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 15, 20, 30, and 50) × 95 K in $T_B$. The angular resolution is 19\,′′ × 15\,′′, PA = 105\,° in FWHM. (b) Position–velocity diagram along “Vertical Part (VP)” of the GCA extending roughly north and south. The sampling area is shown as a white rectangle in panel (a). A red arrow indicates M0.014$-$0.054. (c) Integrated intensity map of the GCA in the SiO $v = 0$, $J = 2$–1 emission line with the Nobeyama 45 m telescope (Tsuboi et al. 2011). The velocity range is the same as that of panel (a). The angular resolution is 26\,′′ in FWHM, which is indicated by a white circle in the lower left-hand corner. A red arrow indicates M0.014$-$0.054. The red dashed square indicates the mapping area of the ALMA Cycle 1 observation (2012.1.00080.S., PI M. Tsuboi). (d) The 330 MHz (90 cm) continuum emission for comparison (LaRosa et al. 2000). The angular resolution is 43\,′′ × 44\,′′, PA = 65\,° in FWHM. The yellow arrows show “threads.” (Color online)

up to $l \sim 0:10$, $b \sim -0.06$. Because M0.014$-$0.054 is adjacent to these continuum features, this would be associated physically with them.

3 ALMA observation

We have performed the observation of a 330″ × 330″ area covering the 50MC in the C$^{32}$S $J = 2$–1 (97.980953 GHz), C$^{34}$S $J = 2$–1 (96.412950 GHz), H$^{13}$CO$^+$ $J = 1$–0 (86.754288 GHz), SiO $v = 0$ $J = 2$–1 (86.846995 GHz), CH$_3$OH (96.739363, 96.741377, and 96.745494 GHz), C$_2$H (87.316925 and 87.328624 GHz), c-C$_3$H$_2$ $J_{K_a, K_c} = 2_{1,2}$–1$_{0,1}$ (85.33896 GHz), and SO N, $J = 2$, 2–1, 1 (86.093983 GHz) emission lines and many fainter emission lines as ALMA Cycle 1 observation (2012.1.00080.S., PI M. Tsuboi). We also have observed the continuum emission at 86 GHz, simultaneously. The entire ALMA observation consists of a 137-pointing mosaic of the 12 m array and a 52-pointing mosaic of the 7 m array (ACA). Additionally, the single-dish data has been obtained using the Total Power Array. The red dashed square in figure 1c indicates the mapping area. It is fortunate that M0.014$-$0.054 is located in the mapping area of the ALMA observation by chance. The molecular emission lines used for imaging here are summarized in table 1.
The C$^{34}$S and H$^{13}$CO$^+$ emission lines are tracers of dense molecular cloud, n(H$_2$)$_{cl}$ $\sim$ 10$^5$ cm$^{-3}$. These emission lines are thought to be optically thin even in the SgrAMC. The optical thickness of the C$^{34}$S emission line will be demonstrated to be thin for the typical case in the subsection 4.4. That of the H$^{13}$CO$^+$ emission line is estimated to be $\tau < 0.2$ based on the observed mean temperature ratio, $T_B$(H$^{12}$CO$^+$)/$T_B$(H$^{13}$CO$^+$) $\sim$ 7 (e.g., Armijos-Abendaño et al. 2015). As mentioned previously, the SiO emission line is a well-known tracer of strong C-shock waves, while the CH$_3$OH molecules are enhanced even by mild C-shock (D$V \sim$ 10 km s$^{-1}$; e.g., Hartquist et al. 1995). The C$_2$H and c-C$_3$H$_2$ emission lines are well-known tracers of photodissociation regions (PDRs). The abundance of both radicals was found to increase close to the dissociation front (e.g., Jansen et al. 1995; Fuente et al. 1996). The HN$^{13}$C and HC$^{15}$N emission lines have critical densities in the environment of the SgrAMC as high as n(H$_2$)$_{cl}$ $\sim$ 10$^5$ cm$^{-3}$ and n(H$_2$)$_{cl}$ $\sim$ 10$^7$ cm$^{-3}$, respectively. These intensities can vary widely by their path length, abundance, and isotope ratio. The SO and $^{34}$SO emission lines are usually emitted from “hot molecular cores” (HMCs) where the molecular cloud is heated up to 100 K by newborn stars. The H42$\alpha$ recombination line and continuum emission at 86 GHz are simultaneously observed. The H42$\alpha$ recombination line traces ionized gas. The continuum emission at 86 GHz is usually emitted by ionized gas. However, there is a possibility that the emission is originated by warm dust or non-thermal mechanism in the Galactic center region. In addition, the CCS emission line is partly in the observation frequency range. The CCS molecule is abundant in the early stage of star formation but decreases with increasing time (e.g., Hirahara et al. 1992).

The resultant maps have FWHM angular resolutions of $\sim 2.5 \times 1.8$, PA $\sim -30^\circ$ and $\sim 1.9 \times 1.3$, PA $\sim -37^\circ$ using “natural weighting” and “Briggs weighting” as $u$-$v$ sampling, respectively. The original velocity resolution is 1.7 km s$^{-1}$ (488 kHz). The typical rms noise levels in the emission free areas of the resultant maps using natural weighting and Briggs weighting are $\sim$0.003 Jy beam$^{-1}$/1.7 km s$^{-1}$ or $\sim$0.11 K in $T_B$ and $\sim$0.005 Jy beam$^{-1}$/1.7 km s$^{-1}$ or $\sim$0.17 K in $T_B$, respectively. J0066–0623, J1517–2422, J1717–3342, J1733–1304, J1743–3058, J1744–3116, and J2148+0657 were used as phase calibrators. The flux density scale was determined using Titan, Neptune, and

| Name | Transition$^*$ | Rest frequency$^*$ [GHz] | Remarks |
|------|--------------|-----------------|---------|
| C$^{32}$S | J = 2–1 | 97.980953 | Medium dense molecular cloud |
| $^{34}$SO | $N, J = 2, 3 – 1, 2$ | 97.715401 | Moderately optically thick |
| CH$_3$OH | $J_{K_a, K_c} = 2_{1,1}–1_{0,0} A_{–}–$ | 97.582808 | Mild C-shock |
| CH$_3$OH | $J_{K_a, K_c} = 2_{–1,2}–1_{–1,1} E$ | 96.739363 | Mild C-shock |
| CH$_3$OH | $J_{K_a, K_c} = 2_{0,2}–1_{0,1} A_{+}+$ | 96.741377 | Mild C-shock |
| CH$_3$OH | $J_{K_a, K_c} = 2_{0,2}–1_{0,1} E$ | 96.744549 | Mild C-shock |
| CH$_3$CHO | $J_{K_a, K_c} = 5_{2,3}–4_{2,2} E$ | 96.475523 | |
| C$^{34}$S | J = 2–1 | 96.412950 | |
| C$_2$H | $N = 1–0, F = 3/2–1/2, F = 2–1$ | 87.316925 | Dense molecular cloud (opt. thin) |
| C$_2$H | N = 1–0 | 87.328624 | Dense regions exposed to UV radiation$^+$ |
| HN$^{13}$C | J = 1–0 | 87.090735 | Dense molecular cloud (opt. thin) |
| HN$^{13}$C | J = 1–0 | 87.090859 | Dense molecular cloud (opt. thin) |
| HN$^{13}$C | J = 1–0 | 87.090942 | Dense molecular cloud (opt. thin) |
| $^{28}$SiO | $v = 0, J = 2–1$ | 86.846995 | Strong C-shock |
| H$^{13}$CO$^+$ | J = 1–0 | 86.752488 | Dense molecular cloud (opt. thin) |
| CCS | $N, J = 7, 6–6, 5$ | 86.181413 | Early stage of star formation |
| $^{32}$SO | $N, J = 2, 2–1, 1$ | 86.093983 | “Hot molecular core” |
| HC$^{15}$N | J = 1–0 | 86.054967 | Dense molecular cloud (opt. thin) |
| $^{29}$SiO | $v = 0, J = 2–1$ | 85.759188 | Strong C-shock |
| HOCO$^+$ | $J_{K_a, K_c} = 4_{2,4}–3_{2,3}$ | 85.513480 | Dense molecular cloud (opt. thin) |
| c-C$_3$H$_2$ | $J_{K_a, K_c} = 2_{1,2}–1_{0,1}$ ortho | 85.338906 | Dense regions exposed to UV radiation |
| Hydrogen atom | H42$\alpha$ | 85.6884 | Ionized gas |

$^*$The values referred from [https://physics.nist.gov/cgi-bin/micro/table5/start.pl](https://physics.nist.gov/cgi-bin/micro/table5/start.pl).

$^+$See, e.g., Nagy et al. (2015).
Figures 2a–2e show the integrated intensity maps with ALMA of M0.014−0.054 and the VP in the C32S, C34S, H13CO+, SiO, and CH3OH (blended lines around 96.741 GHz) emission lines, respectively. Note that the data for the C32S and C34S maps are not combined with the single-dish data. The velocity range of each map is \(V_{\text{LSR}} = -25 \text{ to } 0 \text{ km s}^{-1}\). The velocity range was determined from figures 1b and 1c.

M0.014−0.054 and the VP are clearly detected in the map of the C32S emission line. The VP is resolved into the bundles of the molecular filaments extending roughly from north to south. M0.014−0.054 is extended roughly from west to east and over the filaments. The filaments line up nearly at a right angle to M0.014−0.054 in the far-distance area. However, they become disordered and tangled in the vicinity of M0.014−0.054. The positions of the peaks in the C2H emission line do not correspond to those in the maps of the other emission lines which will be mentioned in the following part. This is probably because the C2H emission line is partially optically thick in the region. M0.014−0.054 is also clearly detected in the maps of the C34S and H13CO+ emission lines. They resemble each other very well, and show a dense molecular cloud with \(n(H_2)_{\text{tot}} \sim 10^5 \text{ cm}^{-3}\) is abundant in M0.014−0.054. In contrast, the molecular filaments in the C34S and H13CO+ emission lines are fainter than those in the C32S emission line, suggesting that the molecular cloud in the filaments is less dense than that in M0.014−0.054.

M0.014−0.054 is clearly detected in the maps of the SiO and CH3OH emission lines. The detection in the SiO emission line shows that a strong C-shock wave (\(AV > 30 \text{ km s}^{-1}\)) propagated within 10^5 yr over the entirety of M0.014−0.054. Although the molecular filaments of the VP are also detected in the maps of these emission lines, they are faint on the whole. For example, the prominent parts are located around \(l \sim 0.010, b \sim -0.060, l \sim 0.015, b \sim -0.087, \) and \(l \sim 0.025, b \sim -0.035\) in the maps of the C32S and H13CO+ emission lines. However, they almost disappear in the SiO emission line.

The C2H (87.317 GHz) and C34S emission lines show a similar distribution in M0.014−0.054 (see figures 2f and 2g). The other C2H (87.329 GHz) emission line is also detected although this line is fainter. The VP almost disappears in the C34S emission line. It has been reported that the N[C2H]/N[c-C3H2] column density ratio increases by the UV radiation (\(\sim 32\) at the PDR edge; Cuadrado et al. 2015, up to \(\sim 80\) at planetary nebulae; Schmidt et al. 2018). Because the VP is less dense than M0.014−0.054, even the interior of the VP should have a high ratio. The c-C3H2 and HN13C emission lines show a similar distribution in M0.014−0.054 but the latter is faint (see figures 2g and 2h). The HC15N and SO emission lines show a similar distribution (see figures 2i and 2j). M0.014−0.054 is identified as a faint extended feature with a single compact peak in the maps of the HC15N and SO emission lines. The peak of the feature is located in the vicinity of the strongest peaks in the other emission lines except for the C32S emission line. The filaments of the VP disappear in the HC15N and SO emission lines.

The structures mentioned above including M0.014−0.054 and the filaments of the VP have no ionized gas counterparts which appear in the H42α recombination line (see figure 2k). However, two distinct components in M0.014−0.054 are identified in the continuum emission at 86 GHz (see figure 2l). The east one corresponds to the peak in the SO emission line. As mentioned previously, the SO emission line is a tracer of HMCs. Then the peaks would involve HMCs. The map of the 850 \(\mu\)m continuum with the James Clerk Maxwell Telescope (JCMT; Pierce-Price et al. 2000) is shown for comparison. The whole of M0.014−0.054 is identified in the 850 \(\mu\)m continuum although the VP is not identified. Two peaks detected at 850 \(\mu\)m are associated with the peaks detected at 86 GHz.

4.2 Kinematics along the vertical part

Figures 3a and 4a show the integrated intensity maps with \(V_{\text{LSR}} = -25 \text{ to } 0 \text{ km s}^{-1}\) in the C32S \(J = 2–1\) and C34S \(J = 2–1\) emission lines, respectively. Because the data of these maps are combined with the single-dish data, the mapping areas become slightly narrow. The appearances of the VP in these emission lines resemble each other very well. Figures 3b and 4b show the PV diagrams along the VP in the C32S \(J = 2–1\)
Fig. 2. Integrated intensity maps of M0.014−0.054 and the “Vertical Part” in the C$^{32}$S $J = 2–1$ (a), C$^{34}$S $J = 2–1$ (b), H$^{13}$CO$^+$ $J = 1–0$ (c), SiO $v = 0 J = 2–1$ (d), CH$_3$OH (96.741 GHz) (e), C$_2$H (87.317 GHz) (f), c-C$_3$H$_2$ (g), HN$^{13}$C (h), HC$_{15}$N (i), SO $N J = 2, 2–1, 1 (l)$, and H$^{42}$α (k) emission lines with ALMA. The C$^{32}$S map is before the combining with the single-dish data. The velocity range is $V_{LSR} = −25$ to 0 km s$^{-1}$. The angular resolutions are $\sim 2.5′′ \times 1.8′′$ in FWHM and $PA \sim −30°$, which indicate as white ovals in the lower left-hand corners. The rms noise of these maps is $\sim 0.036$ K or 0.9 K km s$^{-1}$. The panel (l) shows the map of the 850 μm continuum with JCMT is also shown for comparison (pseudo-color; Pierce-Price et al. 2000). The overlaid contours show the continuum emission at 86 GHz with ALMA. The contour levels are $\{1, 2, 4, 8, 16\} \times 0.023$ K. The angular resolution of JCMT is $−17′′$ in FWHM.
Fig. 2. (Continued)

and C$^{18}$S $J = 2–1$ emission lines, respectively. The sampling areas are shown as rectangles in figures 3a and 4a. In the PV diagrams, the VP is identified as a long feature with $V_{\text{LSR}} \sim -30$ to 0 km s$^{-1}$. There is no clear velocity gradient in the feature. The appearance and velocity gradient are consistent with those of the corresponding feature shown in figure 1b. On the other hand, M0.014−0.054 is identified as a compact curved feature on the filaments of the VP (figures 3b and 4b). This feature suggests that M0.014−0.054 had been affected by external interaction (e.g., Haworth et al. 2015a, 2015b). Additionally, a large extended feature with $V_{\text{LSR}} \sim 30$ to 80 km s$^{-1}$ is also identified. The appearances and kinematics of these features are consistent with those of the corresponding features shown in figure 1b.

In the PV diagrams, there are two compact components with $V_{\text{LSR}} \sim 20$ km s$^{-1}$ adjoining the extended feature mentioned above. In order to clarify the angular extension...
of these components, the integrated intensity maps with $V_{\text{LSR}} = 10$ to $35 \text{ km s}^{-1}$ are shown in figures 3c and 4c. These features are resolved into two molecular filaments which are almost parallel to each other in the maps. The two components in the PV diagrams are thought to be a part of the molecular filament bundle, which will be discussed in the following subsection.

In addition, a faint feature is also identified around the angular offset of M0.014−0.054 and velocity of $V_{\text{LSR}} \sim -50 \text{ km s}^{-1}$ in the $C^{14}S J = 2–1$ emission line (see figure 4b).
Fig. 5. (a) Integrated intensity maps around the MFB with $V_{\text{LSR}}$ = −40 to 10 km s$^{-1}$ (pseudo-color) and $V_{\text{LSR}}$ = 10 to 35 km s$^{-1}$ (contours) in the C$^{32}$S $J = 2–1$ emission line. These are after the combining with the single-dish data. The angular resolution is $\sim 1.9\prime\times 1.3\prime$ in FWHM and PA $\sim -37^\circ$, which is indicated by an oval in the lower left-hand corner. The contour levels are 32, 48, 64, and 80 K km s$^{-1}$. (b) Integrated intensity maps around the “Molecular Filaments Bundle” with $V_{\text{LSR}}$ = −40 to 10 km s$^{-1}$ (pseudo-color) and $V_{\text{LSR}}$ = 10 to 35 km s$^{-1}$ (contours) in the C$^{34}$S $J = 2–1$ emission line. These are after the combining with the single-dish data. The angular resolution is $\sim 1.9\prime\times 1.3\prime$ in FWHM and PA $\sim -37^\circ$, which is indicated by an oval in the lower left-hand corner. The contour levels are 4, 6, 8, and 10 K km s$^{-1}$. (Color online)

The feature is the contamination by the CH$_3$CHO $J_{K_a,K_c} = 5_{2,4}-4_{2,3}E$ emission line (96.425620 GHz) because this feature is not detected in figure 3b.

4.3 The “molecular filament bundle”

Another molecular cloud ridge extends roughly east and west over this area (see figures 5a and 5b). The western and eastern parts of this structure are seen in the negative and positive LSR velocities, respectively. We call this structure the “molecular filament bundle” (MFB). Figures 4a and 5b show the integrated intensity maps around the MFB with $V_{\text{LSR}}$ = −40 to 10 km s$^{-1}$ (pseudo-color) and $V_{\text{LSR}}$ = 10 to 35 km s$^{-1}$ (contours) in the C$^{32}$S $J = 2–1$ and C$^{34}$S $J = 2–1$ emission lines, respectively. The MFB would be extended over the mapping area. The MFB is almost along the
Galactic longitude but curved slightly. The MFB is resolved into the bundle of a few thin molecular filaments in these maps. The width of the MFB is changed periodically from \(\sim 40''\) around \(l \sim -0.035\) and \(l \sim 0.005\) to \(\sim 20''\) around \(l \sim -0.050\) and \(l \sim -0.025\). These filaments seem to be twisted each other. The appearance of the MFB is similar in both the emission lines. M0.014–0.054 is located around the apparent intersection of the MFB and VP. There is abundant shocked molecular gas in M0.014–0.054, as shown in subsection 4.1. Although the velocity of M0.014 is similar to that of the VP, it is \(V_{\text{LSR}} \sim 40\) km s\(^{-1}\) different from that of the MFB. As will be discussed in detail later, M0.014–0.054 is connected to the MFB by the “bridge” on the PV diagram and a collisionally excited maser spot is also located in M0.014–0.054. These features demonstrate that the MFB and VP collided with each other within \(10^5\) yr and M0.014–0.054 was consequently made in the interaction by CCC. In addition, M0.014–0.054 is resolved into a series of compact features in these figures. The strongest feature (labeled A) and second one (labeled B) in the CS emission line maps are centered at \(l \sim 0.021\), \(b \sim -0.051\) (the left-hand circle) and \(l \sim 0.014\), \(b \sim -0.052\) (the right-hand circle), respectively.

4.4 Molecular gas masses of M0.014–0.054, VP, and MFB

The derivation of molecular cloud mass should suffer from the optical brightness of the observed emission line. The ratio of the observed brightness temperatures of the \(C^{32}\text{S}\) and \(C^{34}\text{S}\) emission lines is given by

\[
R = \frac{T_b(C^{32}\text{S})}{T_b(C^{34}\text{S})} = \frac{f(C^{32}\text{S})T_{\text{ex}}(C^{32}\text{S})(1 - e^{-\tau})}{f(C^{34}\text{S})T_{\text{ex}}(C^{34}\text{S})(1 - e^{-\tau})},
\]

where \(T_{\text{ex}}\) and \(f\) are the excitation temperature and the beam-filling factor of the emission line, respectively. The isotope abundance ratio of \(^{32}\text{S}\) and \(^{34}\text{S}\) in the molecular cloud is assumed to be equal to the natural abundance ratio of 22.35.\(^1\)

The mean line intensity ratio in M0.014–0.054 is calculated to be \(R \sim 9.4\). Therefore the mean optical thickness of the \(C^{32}\text{S}\) emission line toward M0.014–0.054 is estimated to be \(\tau \sim 2.1\) assuming that \(T_{\text{ex}}(C^{32}\text{S}) = T_{\text{ex}}(C^{34}\text{S})\) and \(f(C^{32}\text{S}) = f(C^{34}\text{S})\). The correction factor for the optical thickness of the \(C^{32}\text{S}\) emission line is \(\tau/(1 - e^{-\tau}) \sim 2.4\). The corrected integrated intensity of the object in the CS \(J = 2-1\) emission line is given by

\[
I_{\text{corr}}(\text{CS}) = \frac{\tau}{1 - e^{-\tau}} \int_{\text{object}} \int T_b(C^{32}\text{S})dvdv.
\]

The total number of the \(\text{H}_2\) molecules in the object is given by

\[
\int_{\text{object}} N_{\text{LTE}}(\text{H}_2)dv = \frac{4.56 \times 10^{31} I_{\text{corr}}(\text{CS})}{X(\text{CS})(1 - e^{-4.7/T_{\text{ex}}(\text{CS})})},
\]

where \(N_{\text{LTE}}(\text{H}_2)\) is the local thermodynamic equilibrium (LTE) molecular column density. Here the Einstein A coefficient of the CS \(J = 2-1\) emission line is assumed to be \(A_{21} = 2.2 \times 10^{-3} \text{ s}^{-1}\).

The excitation temperature of the CS \(J = 2-1\) emission line is assumed to be \(T_{\text{ex}} = 80\) K \((T_K = 80\) K in Ao et al. 2013). The fractional abundance of the CS molecule is assumed to be \(X(\text{CS}) = N(\text{CS})/N(\text{H}_2) = 1 \times 10^{-8}\), which is usually used for molecular clouds in the disk region. The LTE molecular cloud mass is given by

\[
M_{\text{LTE}}(M_\odot) = \mu \int_{\text{object}} N_{\text{LTE}}(\text{H}_2)dv,
\]

\[
\simeq 2.4 \times 10^{-38} T_{\text{ex}} I_{\text{corr}}(\text{CS}),
\]

where \(\mu\) is the mean molecular weight per \(\text{H}_2\) molecule: \(\mu = 2.8\) in amu = \(2.4 \times 10^{-37} M_\odot\). The integrated intensity of the whole of M0.014–0.054 in the \(C^{32}\text{S}\) emission line is \(I_{\text{object}} = \int_{-40}^{10} T_b(C^{32}\text{S})(dvds = 1.15 \times 10^{40}\) [K km s\(^{-1}\) cm\(^2\)]. The LTE molecular cloud mass is estimated to be \(M_{C^{32}\text{S},\text{LTE}} \approx 5.3 \times 10^4(T_{\text{ex}}/80)\) [M_\odot].

Although the mean optical thickness of the \(C^{32}\text{S}\) emission line is fairly high in M0.014–0.054, that of the \(C^{34}\text{S}\) emission line is estimated to be as small as \(\tau \sim 2.1/22.35 \sim 0.09\). We can estimate the molecular cloud mass using the \(C^{34}\text{S}\) emission line data without the correction for the optical thickness. The integrated intensity of the whole of M0.014–0.054 in the \(C^{34}\text{S}\) emission line is \(I_{\text{object}} = \int_{-40}^{10} T_b(C^{34}\text{S})(dvds = 1.22 \times 10^{39}\) [K km s\(^{-1}\) cm\(^2\)]. The LTE molecular cloud mass is estimated to be \(M_{C^{34}\text{S},\text{LTE}} \approx 5.3 \times 10^4(T_{\text{ex}}/80)\) [M_\odot]. The LTE molecular cloud mass is consistent with that from the \(C^{32}\text{S}\) emission line observation. These are summarized in table 2.

Using the same procedure and the \(C^{32}\text{S}\) emission line data, the LTE molecular cloud masses of the VP and MFB are \(M_{C^{32}\text{S},\text{LTE}} \approx 4.3 \times 10^4(T_{\text{ex}}/80)\) [M_\odot] and \(M_{C^{34}\text{S},\text{LTE}} \approx 8.4 \times 10^4(T_{\text{ex}}/80)\) [M_\odot], respectively. Meanwhile, using the \(C^{34}\text{S}\) emission line data, the LTE molecular cloud masses of the VP and MFB are \(M_{C^{34}\text{S},\text{LTE}} \approx 4.2 \times 10^4(T_{\text{ex}}/80)\) [M_\odot] and \(M_{C^{34}\text{S},\text{LTE}} \approx 8.1 \times 10^4(T_{\text{ex}}/80)\) [M_\odot], respectively. These are also summarized in table 2.

5 The cloud–cloud collision between the VP and the MFB

As mentioned in the previous section, the MFB, VP, and M0.014–0.054 are clearly seen in figures 5a and 5b.
Table 2. Molecular gas masses.

| Object                     | τ (C$^{32}$S) | $M_{C^{32}S, LTE}$ | $M_{C^{34}S, LTE}$ | $M_{vir}$ | $M_{LTE}$ |
|---------------------------|--------------|--------------------|--------------------|-----------|-----------|
| M0.014–0.054             | 2.1          | $5.3 \times 10^4$ | $5.3 \times 10^4$ | —         | —         |
| Vertical Part             | 1.3          | $4.3 \times 10^4$ | $4.2 \times 10^4$ | —         | —         |
| Molecular Filament Bundle| 1.8          | $8.4 \times 10^4$ | $8.1 \times 10^4$ | —         | —         |
| Object A                  | 3.8          | —                  | $1.3 \times 10^4$ | $5.0 \times 10^4$ | 0.4       |
| Object B                  | 2.7          | —                  | $1.2 \times 10^4$ | —         | —         |

*Typical error of these masses is estimated to be $\sim 30\%$.

M0.014–0.054 is located positionally in the interacting area between the MFB and VP. Figures 6a, 6c, and 6e show the enlarged integrated intensity maps around the interacting area in the C$^{32}$S $J = 2–1$, CH$_3$OH (blended lines around 96.741 GHz), and $^{28}$SiO $J = 2–1$ emission lines with the velocity ranges of $V_{LSR} = 10$ to 35 km s$^{-1}$, respectively. The velocity ranges include that of the MFB. The C$^{32}$S data includes the single-dish data. On the other hand, figures 7a, 7c, and 7e show the enlarged integrated intensity maps of the same area in the C$^{32}$S $J = 2–1$, CH$_3$OH, and $^{28}$SiO $J = 2–1$ emission lines with the velocity ranges of $V_{LSR} = –25$ to 0 km s$^{-1}$, respectively. The velocity ranges include those of the VP and M0.014–0.054. As mentioned previously, the SiO and CH$_3$OH emission lines are good tracers of hard ($\Delta V \simeq 30$ km s$^{-1}$) and mild ($\Delta V \simeq 10$ km s$^{-1}$) C-shock waves, respectively. Although the filaments of the MFB are clearly seen in figure 6a, they almost disappear in figures 6c and 6e except for several faint features. The appearances in both shock tracer lines quite resemble each other. On the other hand, M0.014–0.054 is prominent in figures 7a, 7c, and 7e. The VP is faint in figures 7c and 7e although it is identified clearly in figure 7a. This indicates...
that the no part of the MFB or VP suffered from any C-shock wave with $\Delta V \gtrsim 10$ km s$^{-1}$ but a hard C-shock wave is propagating in M0.014−0.054.

Figures 6b, 6d, and 6f show the PV diagrams along the MFB in the $^{12}$CO $J = 2-1$, CH$_3$OH, and $^{28}$SiO $J = 2-1$ emission lines, respectively. The sampling area is shown as the rectangles in figures 6a, 6c, and 6e. In figure 6b, the MFB is clearly identified as a long inclined ridge with $V_{\text{LSR}} \sim -20$ at the western end to 30–50 km s$^{-1}$ at the eastern end. The MFB almost disappears in the SiO and CH$_3$OH emission lines except for the following several faint features. In these PV diagrams, M0.014−0.054 is identified around the angular offset of $-80''$. Figures 7b, 7d, and 7f show the PV diagrams along M0.014−0.054 in the $^{12}$CO $J = 2-1$, CH$_3$OH, and $^{28}$SiO $J = 2-1$ emission lines, respectively. The sampling area is along M0.014−0.054, which is shown as the rectangles in figures 7a, 7c, and 7e. In these PV diagrams, M0.014−0.054 is clearly identified as a long feature with no clear velocity gradient although the velocity width becomes large around the eastern end. The radial velocity difference between M0.014−0.054 on the VP and the MFB is $\Delta V_{\text{rad}} = \Delta V \cos \phi \sim 40$ km s$^{-1}$, where $\Delta V$ is the collision velocity in 3D space and $\phi$ is the angle between the line-of-sight and the axis of the collision. The shock wave induced by the CCC between the VP and MFB is as strong as bringing the enhancement of the SiO molecule in M0.014−0.054.

The “bridge” features, connecting between M0.014−0.054 on the VP and the MFB, are identified in these PV diagrams of figures 6 and 7 (arrows, also see a red arrow in figure 3b). The bridges also correspond to the faint features seen in figures 6c and 6e. They contain shocked molecular gas made by hard C-shock wave. Recent hydrodynamical simulation studies have shown that such connecting features in PV diagrams are reproduced as a characteristic feature of a CCC (e.g., Haworth et al. 2015a, 2015b). Therefore the bridge features support the scenario that the MFB and VP collided each other and made the bridge with the intermediate velocity between
those of the MFB and VP, which should be caused by the momentum exchange of the molecular cloud in them. Especially, the feature around the angular offset of $-60^\circ$ is more prominent than that around the angular offset of $-80^\circ$ in these emission lines. SiO molecules have been known to be taken in the mantle of interstellar dusts within 10$^5$ years and disappear from interstellar gas as mentioned previously. If the CCC occurred in such a way once in the past, the difference between the bridges may be a result of the time that has elapsed since the collision.

However, if the MFB and VP collided with the proper motion velocity of $V = 40 \times \tan \phi$ km/s before 10$^5$ yr, one molecular cloud is now separated from another molecular cloud by $\Delta d \sim 4.1 \times \tan \phi$ pc. The separation corresponds to the angular separation of $\Delta \theta \sim 0.03 \times \tan \phi$ at the distance of 8 kpc, which can be easily distinguished in this observation although $\phi$ is unknown. However, such large angular separations are not observed in the bridges connecting two clouds. There are at least two possibilities that can explain this. As will be mentioned in section 7, mGauss magnetic fields run along these filaments. In this case, the molecular cloud can move along the filaments but cannot move across them. Therefore, the molecular cloud in the bridge would be fixed around the collision area by the magnetic field which is probably tangled by the collision. On the other hand, 10$^5$ yr is the upper limit of the SiO molecules surviving in the interstellar space before re-absorption into dust and not the elapsed time from the CCC. Therefore, this may suggest the possibility that the HMCs are formed in a shorter time than the surviving upper limit of the SiO molecule, although this requires that the angle $\phi$ is somewhat small.

The crosses in figures 7a, 7c, and 7e show the position, $l = 0.02055 b = -0.05013$, of the CH$_3$OH $J = 4_{1}-3_{0}$ maser emission spot at 36.2 GHz in the velocity range of $V = 0.0 \pm 8.3$ km s$^{-1}$ (Yusef-Zadeh et al. 2013). The maser emission spot is located in the vicinity of the strongest intensity peak of the maps. The crosses in figures 7b, 7d, and 7f show the position and velocity of the CH$_3$OH $J = 4_{1}-3_{0}$ maser emission spot in the PV diagrams. The velocity range of the maser emission spot overlaps with the positive velocity edge of M0.014$-$0.054. Because the CH$_3$OH maser emission is known to be excited collisionally by a shock wave propagating in molecular cloud, these facts indicate that the CCC between the MFB and VP is on-going.

Figures 6b and 7b also shows the large feature with $V_{\text{LSR}} \sim 30$ to 80 km s$^{-1}$, which has been mentioned in subsection 4.2. This feature seems to be made of several ridge-like features. Although the ridge-like features are also identified in figures 6d, 6f, 7d, and 7f, the spines of the ridges seem to be enhanced. In addition, a faint feature is also identified around the angular extent of M0.014$-$0.054 and velocity range of $V_{\text{LSR}} = -50$ to $-70$ km s$^{-1}$ in the PV diagrams of the CH$_3$OH emission line (see figures 6d and 7d). The feature is the contamination by the CH$_3$OH $J = 2_{1}-1_{0}$, $E$ emission line (96.755507 GHz) because this feature is not detected in the C$^{15}$S $J = 2$ to 1 emission line (see figures 6b and 7b).

6 Hot molecular cores in the interacting area

6.1 Identification of HMCs in M0.014$-$0.054

Figure 8a shows the continuum map at 86 GHz of M0.014$-$0.054. The noise level of the map is $1 \sigma = 0.01$ K in $T_{\text{B}}$. M0.014$-$0.054 is detected as a series of the compact objects A, B, C, D, and E. The eastern two objects are prominent, which correspond to “A” and “B” shown in figures 5a and 5b. The cross in the map indicates the position, $l = 0.02055 b = -0.05013$, of the CH$_3$OH $J = 4_{1}-3_{0}$ maser emission spot at 36.2 GHz in the velocity range of $V = 0.0 \pm 8.3$ km s$^{-1}$ (Yusef-Zadeh et al. 2013). This is located in object A. The mean brightness temperatures of the continuum emission in objects A and B are $T_{\text{B,cont}} \sim 0.030 \pm 0.002$ K and $T_{\text{B,cont}} \sim 0.020 \pm 0.001$ K, respectively. The integration areas are shown as the circles in the map. The brightness temperature ratio of the recombination line to continuum emission is given by the formula $T_{\text{B,cont}}/T_{\text{B,cont}} \sim 3 \times 10^{-4}(T_{\text{B,cont}} K^{-1.65}(V/$GHz$)^{-1}$ on the assumption of LTE and optically thin conditions (e.g., Mezger & Henderson 1967). Therefore, the ratio at 86 GHz of ionized gas with up to $T_{e} \lesssim 1 \times 10^4$ K is estimated to be larger than unity; $T_{\text{B}}(H42\alpha)/T_{\text{B,cont}} > 1$. The mean brightness temperatures of the H42α recombination line expected to be $T_{\text{B}}(H42\alpha) > 0.030$ K in object A and $T_{\text{B}}(H42\alpha) > 0.020$ K in object B, respectively. Figure 8b shows the integrated intensity map with the velocity range of $-25$ to $0$ km s$^{-1}$ of the H42α recombination line. The velocity width is as large as that of the recombination line from the ionized gas at $T_{e} \sim 1 \times 10^4$ K. The upper limits of the mean brightness temperatures in the H42α recombination line are $5 \sigma = 0.019$ K at object A and $5 \sigma = 0.019$ K at object B, respectively. The integration areas are the same as those mentioned above. Objects A and B are not detected in the map. There is no ionized gas in objects A and B of M0.014$-$0.054 above the detection limit of our observation. In the cases of objects C, D, and E, we cannot exclude the existence of ionized gas by this procedure because of their weak intensities. However, the low $T_{\text{B}}(C_2H)/T_{\text{B}}(c-C_2H_2)$ ratios suggest that objects C, D, and E have no ionized gas, as will be discussed in subsection 6.4.

There are two possibilities to explain the situation that the ionized gas does not exist although the mm-wave continuum is detected. One possibility is that these continuum
emissions are made by the low-frequency extension of the dust emission shown in the JCMT map of figure 21. As mentioned previously, the continuum emissions of objects A and B at 86 GHz correspond to “double peaks” of the 850 μm dust emission with $T_B \sim 0.3$ K (see figure 21). If the dust $\beta$ is $\sim 2$, the mean brightness temperatures at 86 GHz of objects A and B are consistent with the dust emission at the low frequency. In addition, objects C, D, and E also have the corresponding components in the 850 μm dust emission (see figure 21). Another possibility is that this emission is an artifact of contamination from other molecular emission lines. If so, the appearance of the 86 GHz continuum emission in figure 8a should resemble those in the other molecular emission lines. However, they do not always resemble that of the 86 GHz continuum emission. Therefore, the second possibility seems unlikely. This will be discussed in what follows.

Figures 8c and 8d show the enlarged integrated intensity maps of M0.014−0.054 in the SO and $^{34}$SO emission lines.
with the velocity ranges of $V_{\text{LSR}} = -25$ to $0 \text{ km s}^{-1}$, respectively. As mentioned previously, the SO and $^{34}$SO emission lines are good tracers of the HMC. A compact feature in the SO and $^{34}$SO emission lines is located in object A. In contrast, these emissions are associated with object B but not centered in it. Or rather, these emissions traces the southern limb of the object. This suggests that object B has a hollow structure in these molecules. Objects A and B would be HMCs despite some different structures. The appearances in these emission lines resemble those in the HC$^{15}$N emission line which is shown in figure 9(e). Chemical models of HMCs suggest that the HC$^{15}$N emission line is enhanced in HMCs with the age of $\gtrsim 10^5 \text{ yr}$ (e.g., see figure 11 in Stéphan et al. 2018). Therefore star formation activity may have fairly advanced in the HMCs. In addition, faint features in the SO, $^{34}$SO and HC$^{15}$N emission lines are also

**Fig. 9.** Enlarged integrated intensity map of M0.014−0.054 of the C$^{32}$S $J = 2–1$ emission line with the velocity ranges of $V_{\text{LSR}} = -25$ to $0 \text{ km s}^{-1}$. Contours show the continuum map at 86 GHz. The first contour level and contour interval are both 0.014 K. (b) Map of the C$^{34}$S $J = 2–1$ emission line. (c) Map of the H$^{13}$CO$^+$ $J = 1–0$ emission line. (d) Enlarged integrated intensity map of the HN$^{13}$C $J = 1–0$ $F = 1–1$ emission line. (e) Map of the HC$^{15}$N $J = 1–0$ emission line. (f) Map of the HOCO$^+$ $J_{Ka,Kc} = 4_0,4–3_0,3$ emission line. (g) Map of the CH$_3$OH blended emission lines around 96.741 GHz. Contours show the continuum map at 86 GHz. The first contour level and contour interval are both 0.014 K. (h) Map of the CH$_3$OH emission lines at 96.583 GHz. (i) Map of the $^{28}$SiO $J = 2–1$ emission line. (j) Map of the $^{29}$SiO $J = 2–1$ emission line. (Color online)
detected around objects C, D, and E. This may suggest that these objects are in a similar evolutionary stage to objects A and B.

Figures 8e and 8f show the enlarged integrated intensity maps of M0.014−0.054 in the HCOOH and CH$_3$CHO (96.475523 GHz) emission lines with the velocity range of $V_{\text{LSR}} = -25$ to 0 km s$^{-1}$, respectively. Although the emissions of the HCOOH and CH$_3$CHO emission lines are very weak, they are also centered in object A. The association with the other objects is marginal. Figure 10c shows the wide field peak intensity map of the whole area in the HCOOH emission line. The emissions of HCOOH are identified only on several spots in the 50MC except for in M0.014−0.054. These spots seem to correspond to HMCs identified by Miyawaki et al. (2020). The concentration of the HCOOH emission to HMCs should be remarkable. The HCOOH emission line may be a good tracer of HMCs. Although the distribution in the CH$_3$CHO emission line is not clear in the 50MC because of the contamination of the C$^{34}$S emission line, similar concentration might be seen.

6.2 Physical properties of HMCs

Figures 9a–9d show the enlarged integrated intensity maps of M0.014−0.054 in the C$^{32}$S, C$^{34}$S, H$^{13}$CO$^+$, and HN$^{13}$C emission lines with the velocity ranges of $V_{\text{LSR}} = -25$ to 0 km s$^{-1}$. The image in the C$^{32}$S emission line has a ridge-like feature along the distribution of objects A–E in the continuum map, which does not resemble the images in the other emission lines as mentioned previously. The image would suffer from the large optical thickness of the C$^{32}$S emission line. The images in the C$^{34}$S, H$^{13}$CO$^+$, and HN$^{13}$C emission lines resemble each other. These emissions have strong intensity peaks centered at object A. Meanwhile, the emissions trace the southern limb of object B rather than the continuum emission peak. There are also the C$^{34}$S, H$^{13}$CO$^+$, and HN$^{13}$C emissions associated with objects C, D, and E. These similar images would be caused by tracing the similar number density of hydrogen molecules, $n$(H$_2$) $\sim$ 10$^5$ cm$^{-3}$. Figure 9e shows the map in the HC$^{15}$N emission line with the same velocity range. The critical density of this emission line, $n$(H$_2$)$_{\text{crit}}$ $\sim$ 10$^7$ cm$^{-3}$, is higher than those of the others. This emission becomes strong at object A, indicating that the object is filled by a very dense molecular cloud. Although there is the emission along the south limb of object B, it is not centered at the object. The center part of object B is not filled by such a dense molecular cloud.

The LTE molecular cloud masses of objects A and B are estimated from the C$^{32}$S and C$^{34}$S emission line.
Fig. 10. (a), (b) Peak intensity maps of the field including the 50MC and Sgr A in the HOCO$^+$ emission line. (c), (d), (e) Peak intensity maps in the HCOOH, C$^{34}$S, and H$^{13}$CO$^+$ emission lines, respectively. The velocity range of the maps is $V_{\text{LSR}} = -150$ to $150$ km s$^{-1}$. The FWHM beam sizes are shown in the lower left-hand corners. The contours in panels (a), (c), (d), and (e) show the continuum emission at 86 GHz for comparison. The contour levels are $(1, 2, 8, \text{ and } 32) \times 3.5$ K. The contours in panel (b) show the continuum emission at 1.44 GHz for comparison (Yusef-Zadeh et al. 1984). The contour levels are $(1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 15, 20, 30, 40, \text{ and } 50) \times 24$ K. (Color online)
observations using the procedure shown in subsection 4.4. The mean intensity ratios are calculated to be $R \sim 6.3$ in object A and $R \sim 8.1$ in object B. Then the optical thicknesses of the C$^{32}$S emission line are $\tau \sim 3.8$ in object A and $\tau \sim 2.7$ in object B. Those of the C$^{34}$S emission line are $\tau \sim 3.8/22.35 = 0.17$ in object A and $\tau \sim 2.7/22.35 = 0.12$ in object B. Because the C$^{32}$S emission line of both objects A and B is fairly thick, the LTE molecular cloud masses of objects A and B are estimated from the C$^{34}$S emission line data using the optical thickness correction factors of $\tau/(1 - e^{-\tau}) \sim 1.09$ and $\sim 1.06$, respectively. The integration velocity range is $V_{\text{LSR}} \sim 40$ to $10$ km s$^{-1}$. The LTE molecular cloud masses of objects A and B are $M_{\text{LTE}} = 1.3 \times 10^4 (T_{\text{ex}}/80) M_\odot$ and $M_{\text{LTE}} = 1.2 \times 10^4 (T_{\text{ex}}/80) M_\odot$, respectively. Although these masses are consistent with the LTE masses of the HMCs detected in the 50MC, $M_{\text{LTE}} \sim 8 \times 10^3 (T_{\text{ex}}/80) M_\odot$ (Miyawaki et al. 2020), they are much larger than those of the molecular cloud cores detected in the 50MC, $M_{\text{LTE}} \sim 2 \times 10^4 (T_{\text{ex}}/50) M_\odot$ (Uehara et al. 2019).

The mean physical radius of object A is estimated to be $R_{\text{FWHM}} = 0.33$ pc as the half width at half maximum (FWHM) by two-dimensional Gaussian fit for the C$^{34}$S image. The FWHM velocity width is estimated to be $\Delta V_{\text{FWHM}} = 8.5 \pm 0.7$ km s$^{-1}$ by one-dimensional Gaussian fit for the C$^{34}$S line profile. Using the following formula for a spherical object,

$$M_{\text{vir}}[M_\odot] = 210 \times \Delta V_{\text{FWHM}}[\text{km s}^{-1}]^2 R[\text{pc}]. \quad (5)$$

the virial mass of object A is estimated to be $M_{\text{vir}} = 5.0 \times 10^4 M_\odot$. It is difficult to estimate the virial mass of object B using this formula since the shape of the C$^{34}$S image is not spherical (see figure 9b). Because the CCC is ongoing around object A as mentioned previously, the observed velocity width may be widened, and the derived virial mass should be on the upper limit. Therefore, the virial parameter of object A is estimated to be $M_{\text{vir}}/M_{\text{LTE}} \lesssim 1$. Although the fractional abundance of the CS molecule and the excitation temperature of the CS emission line have large ambiguity, object A could be bound gravitationally. These masses are also summarized in table 2.

The flux density at 850 $\mu$m in object A is $S_\nu \sim 240$ Jy (see figure 2). Because the beam size of JCMT is not sufficiently small to resolve the structure seen in the map and there are other components in the line of sight (see figures 3 and 4), the flux density should be the upper limit. Assuming that the dust temperature is 33 K (see figure 3 in Etxaluze et al. 2016) and the gas-to-dust ratio is 100, the gas mass is estimated to be $M \sim 7 \times 10^3 M_\odot$. This mass is consistent with the LTE molecular cloud mass and larger than the virial mass. This also indicates that object A is bound gravitationally.

### 6.3 Chemical properties of HMCs

#### 6.3.1 HOCO$^+$ ion

The HOCO$^+$ emission line has been detected toward the molecular clouds in the CMZ including the 50MC (e.g., Minh et al. 1991). Figure 9f shows the map of $M_{0.014} = 0.054$ in the HOCO$^+$ emission line with the velocity range of $V_{\text{LSR}} = -25$ to 0 km s$^{-1}$. This emission is clearly centered on object A. The distribution closely resembles those of the C$^{34}$S and H$^{13}$CO$^+$ emission lines (see figures 9b and 9c). The C$^{34}$S emission line is considered to be a faithful tracer of the dense molecular cloud with $n(H_2)_{\text{crit}} \sim 10^{17}$ cm$^{-3}$. The effective critical density of the H$^{13}$CO$^+$ emission line is similar to that of the C$^{34}$S emission line. Although this similarity is probably why the distribution of the C$^{34}$S and H$^{13}$CO$^+$ emission lines resemble each other, it cannot explain why that of the HOCO$^+$ emission line resembles them.

Figure 10a shows the wide field peak intensity map of the whole area of this observation, which includes the 50MC and Sgr A*. The HOCO$^+$ emission line. The velocity range is $V_{\text{LSR}} = -150$ to 150 km s$^{-1}$. The emission in $M_{0.014} = 0.054$, especially object A, is the most prominent in the velocity range and area although some emissions are identified in the 50MC. The distribution might originate with the spatial variation of the fractional abundance of the HOCO$^+$ ion. Figures 10d and 10e show the wide field peak intensity maps in the C$^{34}$S and H$^{13}$CO$^+$ emission lines, respectively. In the C$^{34}$S emission line, the 50MC is the most prominent molecular cloud in the area, although $M_{0.014} = 0.054$ is relatively inconspicuous (also see figure 5 in Uehara et al. 2019). On the other hand, the distribution of the H$^{13}$CO$^+$ emission line in $M_{0.014} = 0.054$ is more conspicuous than that in the 50MC. Although the effective critical densities of these emission lines are similar, the distributions have a distinctive difference. The distribution of the HOCO$^+$ emission line relatively resembles that of the H$^{13}$CO$^+$ emission line.

There are some possibilities of the formation of the HOCO$^+$ ion which could cause the distributions mentioned above. An ion–molecule reaction;

$$\text{HCO}^+ + \text{OH} \rightarrow \text{HOCO}^+ + \text{H}, \quad (6)$$

might be possible (e.g., Fontani, et al. 2018) because OH radicals should be abundant and the gas kinetic temperature...
is high in the Sgr A region. Because CO molecules are also abundant in the region, the reaction consuming the HOCO$^+$ ion,
\[
\text{HOCO}^+ + \text{CO} \rightarrow \text{HCO}^+ + \text{CO}_2, \tag{7}
\]
is also expected in the region (e.g., Sakai et al. 2008). In this case, the distribution of the HOCO$^+$ emission line would resemble that of the H$^{13}$CO$^+$ emission line.

The HOCO$^+$ ion may be formed by the protonated reaction of the CO$_2$ molecule. The H$_2^+$ ion is abundant by the abundant cosmic ray in the Sgr A region (e.g., Oka et al. 2019). CO$_2$ molecules are evaporated extensively from the dust mantle by the high gas kinetic temperature in M0.014–0.054 (\(T_k \simeq 80\) K in Ao et al. 2013). Therefore an ion–molecule reaction forming the HOCO$^+$ ion,
\[
\text{H}_2^+ + \text{CO}_2 \rightarrow \text{HOCO}^+ + \text{H}_2, \tag{8}
\]
is also expected in the region (e.g., Sakai et al. 2008). In this case, it is not necessary that the distribution of the HOCO$^+$ emission line resemble that of the H$^{13}$CO$^+$ emission line. Note that these reactions are not mutually exclusive and other reactions forming and destroying HOCO$^+$ ion are also possible.

Figure 10b shows the comparison between the peak intensity map of the HOCO$^+$ emission line and 1.44 GHz continuum emission (Yusef-Zadeh et al. 1984). The features in the 50MC observed in the HOCO$^+$ emission line are located only along the southeastern edge of Sgr A East SNR. This suggests that the physical interaction between the 50MC and Sgr A East SNR forms the HOCO$^+$ ions or at least assists the formation. There are two possibilities explaining the scenario. The first one may be concerned in shock chemistry by the SNR. However, it is hard to specify the mechanism of the formation immediately. In the second one, abundant OH radicals made by cosmic rays of the SNR or at least assists the formation. There are two possibilities explaining the scenario. The first one may be concerned in SNRs because there is no known SNR around it. However, the low-frequency continuum emission associated with the southern edge of M0.014–0.054 is seen. This is identified more clearly at 330 MHz as mentioned in section 2 (see figure 1d). A possibility explaining the continuum emission would be that the CCC between the VP and MFB accelerates cosmic rays. The strong magnetic field (see section 7) and large collision velocity (see section 5) may enable such acceleration around M0.014–0.054, although it has not been observed in the disk region. The accelerated cosmic ray would increase the abundance of OH radicals simultaneously (also see Tielens 2013). Therefore the HOCO$^+$ ions would be formed through the second scenario mentioned above.

### 6.3.2 CH$_3$OH and SiO molecules

As mentioned previously, the C-type shock wave propagating in the molecular cloud enhances the abundances of the CH$_3$OH and SiO molecules. Figures 9g and 9h show the enlarged integrated intensity maps of M0.014–0.054 in the CH$_3$OH (blended lines around 96.741 GHz) and CH$_3$OH (97.583 GHz) emission lines with the velocity ranges of \(V_{\text{LSR}} = -25\) to 0 km s$^{-1}$, respectively. However, the higher \(J\) transition lines of the CH$_3$OH molecule, \(J_{K_a,K_c} = 6 - 2.5 - 7 - 1.7\) E at 85.568 GHz, \(J_{K_a,K_c} = 7.5 - 6, 3\) A... at 86.616 GHz, \(J_{K_a,K_c} = 21.6 - 22.5, 17\) A... and 21.6, 15–22.5, 18 A... at 97.679 GHz, \(J_{K_a,K_c} = 24, 19 - 23.7, 16\) A... and 24, 18–23.7, 17 A... at 98.030 GHz, are not detected in this observation. Figures 9g and 9h do not resemble each other well although these are the maps in the CH$_3$OH emission lines with \(j = 2\).

Figures 9i and 9j show the enlarged integrated intensity maps in the $^{28}$SiO and $^{29}$SiO emission lines with the velocity ranges of \(V_{\text{LSR}} = -25\) to 0 km s$^{-1}$, respectively. These do not resemble each other well. On the other hand, figures 9g and 9i resemble each other and figures 9h and 9j resemble each other in spite of different molecules. The intensity ratio between object A and the others in figure 9g is smaller than that in figure 9h, although the intensity in the former is larger than that in the latter. The difference between the two CH$_3$OH maps is similar to that between the maps of the $^{28}$SiO and $^{29}$SiO emission lines, which are the major and minor isotopes (see figures 9i and 9j). These would be explained by that the CH$_3$OH (96.741 GHz) and $^{28}$SiO emission lines are fairly optically thick around object A but the CH$_3$OH (97.583 GHz) and $^{29}$SiO emission lines are optically thin. Figures 9h and 9i would indicate faithfully the abundance enhancements of these molecules. Therefore, we conclude that the shocked molecular gas is enhanced strongly in object A although it is somewhat enhanced in other components. This is consistent with the detection of the Class-I methanol maser only in object A as mentioned above.

### 6.4 Embedded stars in the HMCs

The C$_2$H and c-C$_3$H$_2$ molecules would survive for longer time even in the molecular clouds exposed to UV radiation than others (e.g., Cuadrado et al. 2015). Figures 11a and 11b show the integrated intensity maps of M0.014–0.054 in the C$_2$H $N = 1 - 0$ \(J = 3/2-1/2\) \(F = 2-1\) and c-C$_3$H$_2$ \(J_{K_a,K_c} = 2, 1 - 1, 0, 1\) emission lines. The velocity ranges are both \(V_{\text{LSR}} = -25\) to 0 km s$^{-1}$. The distributions
in these emission lines resemble those in the C$^{18}$S, H$^{13}$CO$^+$, and HN$^{13}$C emission lines. The higher $J$ emission line, c-C$_3$H $J_{K_a,K_c} = 4_{1,2} - 4_{2,3}$, at 85.6564 GHz is not detected. Other small hydrocarbon molecules, l-C$_3$H (97.996 GHz and 98.012 GHz), C$_4$H (96.478 GHz), and C$_5$H (97.863 GHz) emission lines are not also detected.

The transition of c-C$_3$H is not in our observation frequency range.

Figure 11c shows the ratio map of $T_B[C_2H]/T_B[c$-C$_3$H$_2]$ in M0.014−0.054. In addition, figures 12a and 12b show the spectra of the C$_2$H $N = 1$−0 $J = 3/2$−1/2 $F = 1$−0 emission line on objects A and B, respectively. The sampling areas are shown in figures 11a and 11b as circles. The ratio in object A is $T_B[C_2H]/T_B[c$-C$_3$H$_2] = 1.73 \pm 0.03$. However, the ratio is seen to be inhomogeneous in the object. The ratio of the southeastern half is $T_B[C_2H]/T_B[c$-C$_3$H$_2] = 2.06 \pm 0.05$ (see figure 11c). The ratio of the northwestern half is $T_B[C_2H]/T_B[c$-C$_3$H$_2] = 1.47 \pm 0.04$ (see figure 11c). On the other hand, the ratio in object B is $T_B[C_2H]/T_B[c$-C$_3$H$_2] = 1.53 \pm 0.02$ (see figure 11c). The ratios of the southern half and northern half are $T_B[C_2H]/T_B[c$-C$_3$H$_2] = 1.31 \pm 0.03$ and $1.96 \pm 0.05$. Although the integrated intensities of the emission lines in the northern half are weaker than those in the southern half, the ratio in the northern half is larger than that in the southern half. The ratios in objects C, D, and E are $T_B[C_2H]/T_B[c$-C$_3$H$_2] = 1.40 \pm 0.04, 1.84 \pm 0.04, and 1.47 \pm 0.04$, respectively (see figure 11c). The ratios in objects C and E are about ~1.5. These are located on the intensity ridge of the molecular cloud in M0.014−0.054 (see figures 11a and 11b). The ratio of the object D is slightly higher than the others.

Although the photodissociation potential of the C$_2$H molecule, 4.9 eV (C$_2$H $\rightarrow$ C$_2$ + H), is similar to that of the c-C$_3$H$_2$ molecule, 4.4 eV (c-C$_3$H$_2$ $\rightarrow$ C$_3$H + H), the ionization potential of the C$_2$H molecule, 11.4 eV, is moderately higher than that of the c-C$_3$H$_2$ molecule, 9.2 eV (van Hemert & van Dishoeck 2008). The difference between the ionization potentials may raise the viability of the C$_2$H molecule in the UV irradiated condition compared with that of the c-C$_3$H$_2$ molecule and increase the abundance ratio of $X[C_2H]/X[c$-C$_3$H$_2]$. Consequently, the $T_B[C_2H]/T_B[c$-C$_3$H$_2]$ ratio would increase.
The high ratios measured in the southeastern half of object A and the northern half of object B are distinct from those in the northwestern half of object A, the southern half of object B, and objects C and E. The $T_B[C_2H]/T_B[c-C_3H_2]$ ratios have been reported to be increased in UV irradiated regions, for example, ~3 at the Horsehead PDR (Teysier et al. 2004). The measured high ratios may be consistent with that of the Horsehead PDR. Similar UV irradiated condition is expected in both M0.014−0.054 and the Horsehead PDR. Because object B is adjacent to object A, they are expected to be in a similar UV irradiated condition. If the UV photons with softer spectra, for example $h\nu_{typ} \sim 4$–5 eV, are dominant in the objects, a slight difference between the photodissociation potentials of these molecules would decrease the abundance ratio between $X[C_2H]$ and $X[c-C_3H_2]$. Consequently, $T_B[C_2H]/T_B[c-C_3H_2]$ ratio is decreased. This suggests that the lower ratios of ~1.5 are mainly determined by the embedded stars or protostars.

Figure 11d shows the enlarged integrated intensity map of M0.014−0.054 in the CCS $N, J = 7, 6$–6, 5 (86.181413 GHz) emission line with the velocity range of $V_{LSR} = -18$ to −8 km s$^{-1}$. The same velocity range as in other panels cannot be set because this emission line is at the edge of the observation frequency range. The faint emission is centered in object A. The emission in object B is not centered but the southern part of the object. The faint emission is probably associated with objects C, D, and E. Objects A and B are detected in the dust continuum emission but not in the recombination line, as shown in subsection 6.1. The star formation activities had started and the surfaces of the embedded stars had been heated to at least several 100 K. However, the existence of CCS molecules suggests that the chemical evolution by the star formation activity in object A is still in the early stage (e.g., Hirahara et al. 1992).

On the other hand, the molecular emission lines including the CCS emission line are not centered in object B. The observed features suggest that CCS molecules still remain in the hollow structure of the molecular cloud around the embedded star. The star would emit soft UV radiation sufficient to dissociate the surrounding molecular cloud. This means that the chemical evolution in object B is advanced compared with that in object A. If the star has already been in the main sequence stage, it may be a less massive star than B1 because it does not emit enough vast Lyman continuum emission to ionize the surrounding gas. In addition, if the faint features seen around objects C, D, and E in the molecular emission lines including the CCS emission line are the remnants of the cradle molecular clouds, the chemical evolutions in these objects may be more advanced compared with that in object B.

7 Magnetic field in the VP

7.1 Direction of the magnetic field

We used polarization data at 350 $\mu$m with the Caltech Submillimeter Observatory 10 m telescope (CSO) to obtain the direction of the magnetic field, $\phi_{int}$, in the VP (table 4 in Chuss et al. 2003). Figure 13 shows the submillimeter polarization ($B$ vector) overlaid on the velocity integrated intensity map with the velocity ranges of $-150$ to
150 km s\(^{-1}\) (pseudo-color) and \(-40\) to \(10\) km s\(^{-1}\) (contours) in the C\(_{32}\)S \(J = 2-1\) emission line. There are two molecular cloud components on the line of sight, one of which belongs to the VP and the other is seen in the velocity range of \(30\) to \(70\) km s\(^{-1}\) (see figures 3b and 4b). The observed polarization vectors are the sum of the intrinsic polarization vectors originated by these components. Although the 50MC is dominant in the western half of the area, the VP could be identified as the bundle of filaments in the eastern half. Therefore the observed \(B\) vectors in the eastern half are expected to be originated mainly by the VP. We consider that the observed \(B\) vectors trace the magnetic field lines well through the classical Davis–Greenstein mechanism, in which the observed \(B\) vectors are thought to be parallel to the magnetic field lines. The well-ordered \(B\) vectors suggest that the magnetic field lines run along the filaments of the VP.

Such a poloidal magnetic field (or perpendicular to the Galactic plane) has usually been observed in the nonthermal structures in the Galactic center region (e.g., Yusef-Zadeh et al. 1984; Tsuboi et al. 1986). Meanwhile, the magnetic field in the Galactic center molecular clouds has been unveiled to be mainly toroidal (or parallel to the Galactic plane) by IR observations (e.g., Nishiyama et al. 2010). The poloidal magnetic field in the molecular cloud is a unique case in the Galactic center region.

### 7.2 Strength of the magnetic field

The Chandrasekhar–Fermi method is used to estimate the magnetic field strength from the direction fluctuation of the magnetic field line and internal gas kinematics (Chandrasekhar & Fermi 1953). The magnetic field strength on the plane of sight is given by

\[
B_\parallel = \sqrt{4\pi \rho \frac{\delta v}{\delta \phi}},
\]

where \(\rho\), \(\delta v\), and \(\delta \phi\) are gas density, velocity dispersion, and direction fluctuation of the magnetic field, respectively. This is converted to the following formula for molecular clouds (Crutcher et al. 2004);

\[
B_\parallel [\mu \text{Gauss}] \simeq 9.3 \times \sqrt{n(H_2) \frac{\Delta \nu_{\text{int}}}{\Delta \phi_{\text{int}}}}.
\]

where \(\Delta \phi_{\text{int}}\) [degrees] is the direction fluctuation of the magnetic field, \(n(H_2)\) [cm\(^{-3}\)] is the molecular gas density, which can be estimated by the critical density of the observed molecular line, and \(\Delta \nu_{\text{int}}\) [km s\(^{-1}\)] is the FWHM velocity width of the line profile integrated in the area. The relation between the observed fluctuation, \(\Delta \phi_{\text{obs}}\), and \(\Delta \phi_{\text{int}}\), is given by

\[
\Delta \phi_{\text{int}} = \sqrt{\Delta \phi_{\text{obs}}^2 - \Delta \phi_{\text{err}}^2},
\]

where \(\Delta \phi_{\text{err}}\) is the mean error of the observation. \(\Delta \phi_{\text{obs}}\) is calculated from the observed magnetic field directions (Chuss et al. 2003) as the standard deviation. The intrinsic fluctuation of the direction of the magnetic field is estimated to be \(\Delta \phi_{\text{int}} \sim 9^\circ\) in the VP (Chuss et al. 2003). The FWHM velocity width of the C\(^{34}\)S emission line is derived to be \(\Delta \nu_{\text{int}} = 13.8 \pm 0.8\) km s\(^{-1}\) by Gaussian fitting. The emission line is optically thin in the VP as mentioned previously. The sound velocity of C\(^{34}\)S molecules is estimated to be \(c_{\text{s,C}^{34}\text{S}} = \sqrt{(k_B T_K)/\rho_{\text{C}^{34}\text{S}} m_{\text{H}})} \approx 0.1\) km s\(^{-1}\) at \(T_K = 80\) K, where \(\rho_{\text{C}^{34}\text{S}} = \text{the molecular weight of a C}^{34}\text{S molecule, }\mu_{\text{C}^{34}\text{S}} = 46, \text{ and } m_{\text{H}} = \text{the mass of a hydrogen atom. The broadening of the FWHM velocity width by the sound velocity is negligible. The effective critical density of the C}^{34}\text{S emission line is assumed to be } n(H_2) \sim 5 \times 10^4\text{ cm}^{-3}\)
at $T_K = 80$ K. Consequently, the magnetic field strength in the VP is estimated to be $B_{\parallel} \sim 3$ mGauss.

The Chandrasekhar-Fermi method is not valid when the magnetic field line is significantly fluctuated by the external perturbations such as H\,ii regions and/or SNRs because the fluctuation of the magnetic field is assumed to be originated only by the Alfvén wave in this method. Because the CMZ is generally filled with the external perturbations, the magnetic field must suffer from such perturbations to varying degrees. The estimated value of the magnetic field strength should have a large ambiguity.

### 7.3 Stability of molecular cloud filaments

The critical mass per unit length of molecular filaments is given by

$$M_{\text{line, crit}} = \frac{2\sigma_{\text{tot}}^2}{G},$$

where $\sigma_{\text{tot}}$ is the total velocity dispersion which is given by $\sigma_{\text{tot}} = \sqrt{\sigma_{\text{nonth}}^2 + c_s^2 + (1/2)\left(V_A^2\right)}$ for a magnetized molecular cloud filament (e.g., Fiege & Pudritz 2000; Arzoumanian et al. 2013). When the LTE mass per unit length of the filament is larger than this limit, the filament can fragment into molecular cores along the axis of the filament (e.g., Inutsuka & Miyama 1997). In the case of the VP, the velocity dispersion of the nonthermal motion is calculated to be $\sigma_{\text{nonth}} = \sqrt{(\Delta v_{\text{int}}^2 - c_s^2_{\text{C34S}})/8\ln 2} = 5.9 \pm 0.3$ km s$^{-1}$. The sound velocity in the VP is estimated to be $c_s = (k_B T_K)/(\mu m_H) \simeq 0.5$ km s$^{-1}$ at $T_K = 80$ K where $\mu$ is the mean molecular weight, $\mu = 2.8$. While the Alfvén velocity is estimated to be $V_A = 1300 B/\left(\sqrt{n(H_2)}\right) \simeq 17$ km s$^{-1}$ at the magnetic field strength of $B \sim 3$ mGauss and the molecular gas density of $n(H_2) \sim 5 \times 10^{4}$ cm$^{-3}$ as mentioned in the previous subsection. The sound velocity is much smaller than the Alfvén velocity and the velocity dispersion of the nonthermal motion. Therefore, the critical mass per unit length of the VP is estimated to be

$$M_{\text{line, crit}} \sim 2\sigma_{\text{tot}}^2/G \sim 8 \times 10^4 M_\odot \text{pc}^{-1}.$$ 

Because the magnetic field strength is not observed in the MFB, the critical mass per unit length cannot be derived. However, the lower limit can be estimated when the magnetic field is ignored. In the case of the MFB, the velocity dispersion of the nonthermal motion is calculated to be $\sigma_{\text{nonth}} = 5.1 \pm 0.3$ km s$^{-1}$. The critical mass per unit length of the MFB is

$$M_{\text{line, crit}} \gtrsim 1 \times 10^4 M_\odot \text{pc}^{-1}.$$ 

On the other hand, the LTE mass per unit length of the VP is given by

$$M_{\text{line, LTE}} \sim \frac{M_{\text{LTE}}}{nL},$$

where $M_{\text{LTE}}$ is the LTE molecular cloud mass estimated in subsection 4.4, $M_{\text{LTE}} \sim 4 \times 10^4 (T_{\text{ex}} / 80) M_\odot$, $L$ is the length of the VP, $L \sim 8$ pc, and $n$ is the number of the observed filaments, $n \sim 3$ (see figures 3a and 4a). Therefore, the LTE mass per unit length of the VP is estimated to be $M_{\text{line, LTE}} \sim 2 \times 10^4 (T_{\text{ex}} / 80) M_\odot \text{pc}^{-1}$. Using the same procedure, the LTE mass per unit length of the MFB is estimated to be $M_{\text{line, LTE}} \sim 3 \times 10^4 (T_{\text{ex}} / 80) M_\odot \text{pc}^{-1}$. Because the inclination angles of the VP and MFB are not known, these LTE masses per unit length are the upper limits. Both the LTE masses per unit length of the VP and MFB are much smaller than their critical masses per unit length, respectively. The filaments are stable for the fragmentation along the filaments. The star formation activity in the VP and MFB cannot start without any external trigger. In this observation, we found evidence of the CCC including the bridges between the VP and MFB, and also found evidence of the star formation including HMCs in M0.014–0.054, which is located at the intersection between the colliding filaments. Even for stable molecular filaments, the CCC presumably has a role in the star formation as the external trigger (see also figure 1 in Inoue & Fukui 2013). Although there are still many issues in massive star formation, the star formation induced by CCC would be a promising mechanism in the SgrAMC.

### 8 Spatial structure of the CCC and its possible scenario

Based on the observation results and discussion mentioned above, we would like to depict the spatial structure of the CCC between the VP and MFB and infer a possible scenario. As mentioned in the previous section, the VP and MFB, except for the colliding area, are stable molecular filaments against gravitational fragmentation and are approximately perpendicular to the Galactic plane and parallel to it, respectively. Their stability is secured by the strong magnetic field and/or large velocity dispersion in the filaments.

Figure 14a shows the schematic display of the VP and MFB before the collision. The viewpoint of the panel is along the MFB. The directions of the magnetic fields observed by CSO is considered to indicate the large-scale structure of the magnetic fields in the VP because the effective angular resolution is as large as $\sqrt{\text{FWHM}^2 + \text{Grid}^2} \sim 27''$ (Chuss et al. 2003). The magnetic field in the VP is approximately perpendicular to the Galactic plane (see figure 13). The molecular filaments depicted in the CS emission line are along the magnetic field. Note that it has not been clear how the vertical magnetic field originates and how molecular clouds are taken into the VP. On the other hand, the magnetic field in the MFB is not observed...
Although the molecular filaments are approximately parallel to the Galactic plane (see figure 5). However, because the magnetic field along the Galactic plane is observed in the neighboring molecular clouds (e.g., Nishiyama et al. 2010), such a magnetic field may exist also in the MFB. The molecular clouds in them are thought to be along the magnetic fields. The molecular clouds in the VP are considered to be confined around the Galactic plane by the gravity although the molecular clouds in the MFB are considered to be able to move along the magnetic fields. (b) Schematic display of the VP and MFB after the collision. The viewpoints of the left- and right-hand panels are along the MFB and VP, respectively. The collision velocity should be larger than $\Delta \gtrsim 40 \text{ km s}^{-1}$ because the SiO molecules seem to be abundant in the colliding area, which are confined in the tangled magnetic field there. In the VP, the molecular clouds should converge kinematically along the magnetic fields and form massive molecular cloud cores around the collision area. Successively, they form high-mass protostars in their insides and evolve into HMCs. On the other hand, the molecular clouds in the MFB can move from the colliding area along the magnetic field because there is no confined molecular cloud like in the VP. Therefore the molecular clouds around the colliding area would become less dense than those in the VP and cannot form high-mass protostars in their insides. (Color online)

Figure 14b shows the schematic display of the VP and MFB after the collision. The viewpoint of the left-hand panel is along the MFB, which is the same as that in figure 14a, while that of the right-hand panel is perpendicular to the Galactic plane, which is along the VP. The collision velocity should be larger than $\Delta \gtrsim 40 \text{ km s}^{-1}$ because the SiO emission line is enhanced around the expected colliding area. The molecular filaments in the VP are seen to get tangled up around M0.014–0.054 although they are lined up perpendicular to the Galactic plane in the area farther from it (see figures 2 and 3). This probably shows that the molecular field in the VP got tangled up in the colliding area because the filaments trace the magnetic field. In the VP, the molecular clouds should converge kinematically along the magnetic fields because the magnetic fields are deformed, as shown in figure 14b (cf. Inoue & Fukui 2013), and form massive molecular cloud cores around the collision area. Because the shocked molecular gas made by the collision cannot expand crossing the filaments, this should be confined around the colliding area. The molecular cloud cores were massive enough to be bound gravitationally as mentioned in subsection 6.2. Therefore, they form high-mass protostars in their insides and evolve into HMCs. On the other hand, the molecular clouds in the MFB can escape from the colliding area along the magnetic field because there is no confined molecular cloud like in the VP as shown...
the right-hand panel of figure 14b. Therefore the molecular clouds around the colliding area would become less dense than those in the VP and cannot form high-mass protostars in their insides. This scenario explains why the HMCs are observed only in the VP.

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References

Ao, Y., et al. 2013, A&A, 550, A135
Armijo-Abdanado, J., Martin-Pintado, J., Requena-Torres, M. A., Martin, S., & Rodriguez-Franco, A. 2015, MNRAS, 446, 3842
Arzoumanian, D., Andr´e, P., Peretto, N., & K¨onyves, V. 2013, A&A, 553, A119
Bally, J., Stark, A. A., Wilson, R. W., & Henkel, C. 1987, ApJS, 65, 13
Boehle, A., et al. 2016, ApJ, 830, 17
Chandrasekhar, S., & Fermi, E. 1953, ApJ, 118, 113
Chuss, D. T., Davidson, J. A., Dotson, J. L., Dowell, C. D., Hildebrand, R. H., Novak, G., & Vaillancourt, J. E. 2003, ApJ, 599, 1116
Crutcher, R. M., Nutter, D. J., Ward-Thompson, D., & Kirk, J. M. 2004, ApJ, 600, 279
Cuadrado, S., Goicoechea, J. R., Pilleri, P., Cernicharo, J., Fuente, A., & Joblin, C. 2015, A&A, 575, A82
Etxaluze, M., Smith, H. A., Tolls, V., Stark, A. A., & González-Alfonso, E. 2011, AJ, 142, 134
Fiege, J. D., & Pudritz, R. E. 2000, MNRAS, 311, 85
Figer, D. F., et al. 2002, ApJ, 581, 258
Figer, D. F., McLean, I. S., & Morris, M. 1999, ApJ, 514, 202
Fontani, F., Vagnoli, A., Padovani, M., Colzi, L., Caselli, P., & Rivilla, V. M. 2018, MNRAS, 481, 79
Fuente, A., Rodriguez-Franco, A., & Martin-Pintado, J. 1996, A&A, 312, 599
Genzel, R., Thatte, N., Krabbe, A., Kroker, H., & Tacconi-Garman, L. E. 1996, ApJ, 472, 153
Gudofsky, A., Cabrit, S., Flower, D. R., & Pineau Des Forêts, G. 2008, A&A, 482, 809
Hartquist, T. W., Menten, K. M., Lepp, S., & Dalgarno, A. 1995, MNRAS, 272, 184
Hasegawa, T., Arau, T., Yamaguchi, N., & Sato, F. 2008, Ap&SS, 313, 91
Hasegawa, T., Sato, F., Whiteoak, J. B., & Miyawaki, R. 1994, ApJ, 429, L77
Haworth, T. J., et al. 2015a, MNRAS, 450, 10
Haworth, T. J., Shima, K., Tasker, E. J., Fukui, Y., Torii, K., Dale, J. E., Takahira, K., & Habe, A. 2015b, MNRAS, 454, 1634
Hirahara, Y., et al. 1992, ApJ, 394, 539
Inoue, T., & Fukui, Y. 2013, ApJ, 774, L31
Inutsuka, S., & Miyama, S. M. 1997, ApJ, 480, 681
Jansen, D. J., Spaans, M., Hogerheijde, M. R., & van Dishoeck, E. F. 1995, A&A, 303, 541
Jiménez-Serra, I., Caselli, P., Martin-Pintado, J., & Hartquist, T. W. 2008, A&A, 482, 549
LaRosa, T. N., Cassim, N. E., Lazio, T. J. W., & Hyman, S. D. 2000, AJ, 119, 207
McMullin, J. P., Waters, B., Schiebel, D., Young, W., & Golap, K. 2007, in ASP Conf. Ser., 376, Astronomical Data Analysis Software and Systems XVI, ed. Shaw R. A. (San Francisco: ASP), 127
Mezger, P. G., & Henderson, A. P. 1967, ApJ, 147, 471
Minh, Y. C., Brewer, M. K., Irvine, W. M., Friberg, P., & Johansson, L. E. B. 1991, A&A, 244, 470
Miyawaki, R., Tsuibo, M., Kitamura, Y., Uehara, K., & Miyazaki, A. 2020, PASJ, submitted
Morris, M., & Serabyn, E. 1996, ARA&A, 34, 645
Morris, M. R. 1993, ApJ, 408, 496
Nagy, Z., Ossenkopf, V., Van der Tak, F. S., Faure, A., Makai, Z., & Bergin, E. A. 2015, A&A, 578, A124
Nishiyama, S., et al. 2010, ApJ, 722, L23
Oka, T., Gahalle, T. R., Goto, M., Usuda, T., McCall, B. J., & Indriolo, N. 2019, ApJ, 883, 54
Oka, T., Hasegawa, T., Sato, F., Tsuibo, M., & Miyazaki, A. 1998, ApJS, 118, 455
Pierce-Price, D., et al. 2000, ApJ, 545, L121
Sakai, N., Sakai, T., Aikawa, Y., & Yamamoto, S. 2008, ApJ, 675, L89
Schmidt, D. R., Zack, L. N., & Ziurys, L. M. 2018, ApJ, 864, L31
Serabyn, E., & Güsten, R. 1987, A&A, 184, 133
Stéphan, G., Schilke, P., Le Bourlot, J., Schmiedeke, A., Choudhury, R., Godard, B., & Sánchez-Monge, Á. 2018, A&A, 617, A60
Teyssier, D., Fossé, D., Gerin, M., Pety, J., Abergel, A., & Roueff, E. 2004, A&A, 417, 135
Tielens, A. G. G. M. 2013, Rev. Mod. Phys., 85, 1021
Tsuboi, M., Handa, T., & Ukita, N. 1999, ApJS, 120, 1
Tsuboi, M., Inoue, M., Handa, T., Tabara, H., Kato, T., Sofue, Y., & Kusaka, N. 1999, ApJ, 514, 202
Tsuboi, M., Kitamura, Y., Uehara, K., Miyazaki, A., Miyawaki, R., Tsutsu, T., & Miyoshi, M. 2019, PASJ, 71, 128
Tsuboi, M., Miyazaki, A., & Uehara, K. 2015, PASJ, 67, 109
Tsuboi, M., Tadaki, K., Miyazaki, A., & Handa, T. 2011, PASJ, 63, 763
Uehara, K., Tsuboi, M., Kitamura, Y., Miyawaki, R., & Miyazaki, A. 2019, ApJ, 872, 121
van Hemert, M. C., & van Dishoeck, E. F. 2008, Chem. Phys., 343, 292
Yusef-Zadeh, F., Cotton, W., Viti, S., Wardle, M., & Royster, M. 2013, ApJ, 764, L19
Yusef-Zadeh, F., Morris, M., & Chance, D. 1984, Nature, 310, 557