DETAILED MOLECULAR OBSERVATIONS TOWARD THE DOUBLE HELIX NEBULA

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ABSTRACT

The Double Helix Nebula (DHN), located 100 pc above Sgr A* in the Galactic center (GC), is a unique structure whose morphology suggests it is a magnetic feature. Recent molecular observations toward the DHN revealed two candidate molecular counterparts of the DHN at radial velocities of −35 km s⁻¹ and 0 km s⁻¹ and discussed the model in which the DHN has its origin at the circumnuclear disk in the GC. In this paper, new CO observations toward the DHN using the Caltech Submillimeter Observatory and Mopra telescopes are presented. The higher-resolution observations of ~1 pc scale reveal the detailed distributions and kinematics of the two CO counterparts (the 0 km s⁻¹ and −35 km s⁻¹ features) and provide new information on their physical conditions. As a result, we find that the 0 km s⁻¹ feature with a mass of 3.3 × 10⁴ M⊙ coincides with the infrared emission of the DHN, indicating clear association with the DHN. The association of the −35 km s⁻¹ feature, with a mass of 0.8 × 10⁴ M⊙, is less clear compared with the 0 km s⁻¹ feature, but the complementary distribution between the molecular gas and the DHN and velocity variation along the DHN support its association with the DHN. The two molecular features are highly excited, as shown by the relatively high CO J = 2–1/3–1 intensity ratios of ~1.0, and have kinetic temperatures of ~30 K, consistent with the typical molecular clouds in the GC.

Key words: Galaxy: center – ISM: clouds – radio lines: ISM

Online-only material: color figures

1. INTRODUCTION

The Galactic center (GC) has many outstanding structures that are not seen in the outer part of the Galaxy. In particular, several lines of evidence indicate that the magnetic field plays an important role in this region. A strong magnetic field of 50 μG has been suggested as an averaged figure within the central 400 pc (central molecular zone (CMZ; Morris & Serabyn 1996) by an analysis of the non-thermal radio spectrum (Crocker et al. 2010), and many unique astrophysical structures related to the magnetic field have been discovered so far. Many linear, non-thermal radio filaments are present in the radio arc (Yusef-Zadeh et al. 1984), in which highly ordered magnetic field lines distributed vertically to the Galactic plane are traced by their radio synchrotron emission (e.g., Lang et al. 1999; LaRosa et al. 2000; Yusef-Zadeh et al. 2004). Their origin is still elusive, though numerous ideas have been advanced (Morris 1996). On a larger scale, Fukui et al. (2006) discovered two giant molecular loops ~700 pc away from the center with a height of ~200 pc, and they propose that they are a result of magnetic buoyancy driven by the Parker instability. Follow-up studies reveal that the footpoints of the loops have highly turbulent molecular clumps with velocity dispersions of ~50 km s⁻¹, and magnetic reconnection has been discussed as the origin of these clumps (Torii et al. 2010a, 2010b; Kudo et al. 2011).

The Double Helix Nebula (hereafter DHN) was discovered ~100 pc above the GC by Morris et al. (2006) using infrared observations with Spitzer (Figure 1). It has an apparent helical morphology that can be seen in dust emission, implying that it is organized by a magnetic field. Morris et al. (2006) suggest that the DHN was created by torsional Alfven waves emitted from the circumnuclear disk (CND) which surrounds the supermassive black hole, Sgr A*. On the other hand, Tsuboi & Handa (2010) use radio polarization measurements to hypothesize that the DHN is an extension of the polarized northern lobe of the magnetic radio arc. An interesting clue that supports the magnetic nature of the DHN is the presence of non-thermal radio emission distributed along the western rim of the DHN (Law et al. 2008).

Most recently, Enokiya et al. (2014) presented the observations of a 4′′ × 2′′ area of the GC in the 12CO(J = 2–1) transition, obtained using the NANTEN2 4 m telescope with a beam size of 100″, which found that two molecular features at radial velocities of ~35 km s⁻¹ and 0 km s⁻¹ (hereafter, the −35 km s⁻¹ and 0 km s⁻¹ features) coincide with the DHN. They also found that these features are located at the tops of molecular ridges elongated vertically to the Galactic plane, having lengths of ~150 pc at the GC distance. Indeed, they estimate the distance of the ridges as 8 ± 2 kpc, which is consistent with the distance to the GC, by carrying out an analysis of the K-band stellar extinction. Therefore, it seems quite likely that the DHN and its molecular counterparts have their origin at the GC. However, a spatial resolution of 100″, which corresponds to ~4 pc at the GC, is much coarser than the typical size of the helical filaments of the DHN, ~1–2 pc, and detailed comparisons of molecular emission with the 24 μm Spitzer image have not yet been possible.

In this study, we present results of new molecular observations toward the DHN using the Caltech Submillimeter Observatory (CSO) and Mopra telescopes. The improved spatial resolutions of ~33″ (~1.3 pc) enable a more detailed description of the −35 km s⁻¹ and 0 km s⁻¹ features and help clarify whether they are physically associated with the DHN. This paper is organized as follows; Section 2 summarizes the observations and Section 3 the results. The discussion is given in Section 4 and a summary in Section 5. In this study, we adopt a GC distance of 8.0 kpc.

2. OBSERVATIONS

Observations of the 12CO(J = 2–1) and 13CO(J = 2–1) transitions were carried out with the 10.4 m telescope of the
CSO in 2011 June. The half-power beamwidth (HPBW) of the telescope was 33″ at 230 GHz, which corresponds to 1.4 pc at the distance of the GC. The 230 GHz SIS receiver provided a typical single-sideband (SSB) system temperature, $T_{\text{sys}}$, of $\sim 400$–500 K at 230 GHz and enabled us to observe the $^{12}$CO($J = 2–1$) and $^{13}$CO($J = 2–1$) transitions simultaneously. The spectrometer was a Fast Fourier Transform Spectrometer with 8192 channels, providing a velocity coverage of $\sim 1300$ km s$^{-1}$ with a velocity resolution of 0.16 km s$^{-1}$ at 230 GHz. We observed the nine 4′ × 4′ regions shown in Figure 1 with the on-the-fly (OTF) mode. The output grid of the observations is spaced by 15″. We smoothed the velocity resolution and spatial resolution to 0.16 km s$^{-1}$ and 45″, respectively, to achieve a better noise level. The pointing accuracy was checked and adjusted every hour to be better than 5′ using observations of SiO masers. The obtained spectra were converted into a $T_{\text{mb}}$ scale with a beam efficiency of 0.698. In the final maps, we obtained rms noise fluctuations of $\sim 0.08$ K per channel.

Observations of the $^{12}$CO($J = 1–0$) and $^{13}$CO($J = 1–0$) transitions were carried out using the 22 m ATNF Mopra millimeter telescope in Australia in 2011 October, which provided an HPBW of 33″ at 110 GHz, the same as that of the $J = 2–1$ lines measured at the CSO. The OTF mode was again used toward the eight 4′ × 4′ regions shown in Figure 1. The typical SSB system noise temperature was 500 K. The Mopra backend system “MOPS” provided 4096 channels across 137.5 MHz in each of the two orthogonal polarizations. The effective velocity resolution was 0.088 km s$^{-1}$ and the velocity coverage was 360 km s$^{-1}$ at 115 GHz. The pointing accuracy was checked every hour to be better than 7″ using observations of 86 GHz SiO masers. The spectra were gridded to a 15″ spacing, and smoothed to a 45″ beam size. We observed Orion-KL (R.A., decl.) = ($5^h35^m14.5^s$,$-5^\circ22'29.6''$) for the absolute intensity calibration and carried out comparisons with the results of Ladd et al. (2005). The “extended beam efficiency” in Ladd et al. (2005) was estimated to be 0.38 by dividing the observed peak antenna temperature of Orion-KL by 100 K, which is the corrected absolute intensity shown in Figure 6 of Ladd et al. (2005). After calibrating the spectra, we finally smoothed the channels in velocity to a resolution of 0.86 km s$^{-1}$. The typical rms noise levels achieved in the $^{12}$CO($J = 1–0$) and $^{13}$CO($J = 1–0$) spectra are 0.14 K and 0.07 K, respectively.

The reference position of the OTF scans used in the CSO and Mopra observations is ($l, b$) = (359°33.4, 1°800′), which is chosen to have no significant emission over a velocity range of $\pm 100$ km s$^{-1}$ at an rms noise level of $\sim 0.05$ K per channel in both transitions.

3. RESULTS

3.1. Spatial and Velocity Distribution of the Molecular Gas

In Figure 2, we present the integrated intensity distributions of the $-35$ km s$^{-1}$ feature and the $0$ km s$^{-1}$ feature in $^{12}$CO($J = 1–0$) and $^{13}$CO($J = 2–1$). The $-35$ km s$^{-1}$ feature shown in Figures 2(a) and (b) is distributed between $-36$ and $-30$ km s$^{-1}$, widely covering the whole DHN. It extends to $b \sim 0^\circ 86$, beyond the top of the DHN where the 24 μm emission becomes too faint to discern any possible continuation of the helical pattern. The $-35$ km s$^{-1}$ CO gas shows the strongest emission just to the west and north of the DHN and is spatially complementary to the western edge of the DHN, suggesting a possible association. In Figures 2(c) and (d), the $0$ km s$^{-1}$ feature shows a remarkably good coincidence with the DHN. It has brighter CO emission and traces the helical distribution of the DHN. The width of the $0$ km s$^{-1}$ feature is $\sim 0.05$ pc, comparable to that of the DHN. The $0$ km s$^{-1}$ feature is also extended to $b \sim 0^\circ 86$, where the infrared emission also fades out. The excellent spatial coincidence between the CO and infrared emission provides robust evidence that the $0$ km s$^{-1}$ feature is physically associated with the DHN, while association of the $-35$ km s$^{-1}$ feature is less clear.

In Appendix A, we show in Figure 10 the integrated intensity of the CO($J = 2–1$) emission, and in Figures 11–13, the velocity channel maps of $^{12}$CO($J = 1–0$) and $^{13}$CO($J = 2–1$) emission. Another CO feature around $8–15$ km s$^{-1}$ (hereafter the $10$ km s$^{-1}$ feature) overlaps the DHN, as seen in Figure 11, but the gas distribution does not coincide with the DHN, thus it does not seem to be associated. This feature is also seen in the large scale view of Enokiya et al. (2014) and they conclude that a relationship with the DHN is unlikely.

Figures 3(a) and (b) show the distributions of the first moment maps of the spectra in the $-35$ km s$^{-1}$ and $0$ km s$^{-1}$ features, respectively. Here $^{12}$CO($J = 2–1$) is used, which has less complicated profiles than $^{13}$CO($J = 1–0$). In the $-35$ km s$^{-1}$ feature, a velocity jump up to $2$ km s$^{-1}$ which coincides spatially with the DHN is seen at ($l, b$) = ($0^\circ 05$, $0^\circ 65–0^\circ 75$). As can be seen in Figure 12 of Appendix A, the $-35$ km s$^{-1}$ feature consists of three filamentary structures that are distributed almost parallel to the DHN; two of them occur around $-35$ km s$^{-1}$ and the third one, which coincides with the DHN, is found near $-31$ km s$^{-1}$. The apparent velocity jump seen in Figure 3(a) is due to the velocity difference between these filamentary structures. In
Figure 2. Distributions of the two CO features in $J=1\rightarrow 0$ emission. The $-35$ km s$^{-1}$ feature is shown in panels (a) and (b), and the 0 km s$^{-1}$ feature in panels (c) and (d). Panels (a) and (c) show the emission from $^{12}$CO($J=1\rightarrow 0$), and panels (b) and (d) show the $^{13}$CO($J=1\rightarrow 0$) emission. The contour levels of each panel are as follows; (a) minimum: 2 K km s$^{-1}$, step: 1.5 K km s$^{-1}$, (b) minimum: 0.8 K km s$^{-1}$, step: 0.6 K km s$^{-1}$, (c) minimum: 2 K km s$^{-1}$, step: 2 K km s$^{-1}$, (d) minimum: 0.8 K km s$^{-1}$, step: 0.6 K km s$^{-1}$.

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Figure 3. First moment maps of the $-35$ km s$^{-1}$ (left) and 0 km s$^{-1}$ features (right). Contours show the integrated $^{12}$CO($J=2\rightarrow 1$) emission shown in Figure 2(b)–(c).

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Figure 3(b), around the top of the DHN ($b \sim 0^\circ:75$–$0^\circ:80$), the 0 km s$^{-1}$ feature shows an east–west velocity gradient of 1 km s$^{-1}$ pc$^{-1}$. At the lower-latitude part of the 0 km s$^{-1}$ feature, the velocity distribution is much more complicated. We find a velocity jump of 2 km s$^{-1}$ around the intersection of the DHN strands at $b \sim 0^\circ:68$.

To show the velocity distributions of the $-35$ km s$^{-1}$ and 0 km s$^{-1}$ features in more detail, we define a new coordinate parallel to the DHN. A linear fit to the infrared emission of the DHN shows it to be tilted at a position angle of $-11^\circ:6$ relative to Galactic north. We adopt the term “DHN coordinate” to refer to positions along this axis, with the origin taken to be $(l, b) \sim (0^\circ:03, 0^\circ:72)$. Figures 4(a) and (c) show the $^{12}$CO($J=2\rightarrow 1$) distributions of the two velocity features in this DHN orientation, and Figures 4(b) and (d) show the velocity-position distributions. In Figure 4(b), the top of the $-35$ km s$^{-1}$ feature shows a velocity width of $\sim 5$ km s$^{-1}$, broader than the rest of the feature. Figure 4(d) shows a sinuous velocity variation between $-5\prime$ and $0\prime$ along the Y-axis, which results largely from the velocity jump found at $b \sim 0^\circ:68$ in Figure 3(b).

Figure 5 shows the velocity–position distributions of the $^{12}$CO($J=1\rightarrow 0$) and $^{12}$CO($J=2\rightarrow 1$) emission over a large velocity range, $-45$–$+20$ km s$^{-1}$ along the DHN coordinate. The 0 km s$^{-1}$ feature and the 10 km s$^{-1}$ feature are surrounded by diffuse molecular gas which is likely located in the foreground, and thus not necessarily associated with the DHN features. Essentially no foreground emission is seen around the $-35$ km s$^{-1}$ feature, especially in the $^{12}$CO($J=2\rightarrow 1$) line. A CO component at the Y-axis $\sim 5\prime$–$8\prime$ and velocity of $-18$–$-10$ km s$^{-1}$ can be seen on the northwest side of the DHN in Figure 11 of Appendix A. There is no morphological indication that it is related to the DHN. Diffuse CO emission around the Y-axis $\sim 8\prime$–$11\prime$ (Galactic latitude $\sim 0^\circ:9$) and velocity of $-30$–$-22$ km s$^{-1}$ can be seen in Figure 5(a); it might be spatially connected with the $-35$ km s$^{-1}$ feature as seen in Figure 11 of Appendix A. The broad velocity emission evident at the Y-axis $\sim -10^\circ$–$-8^\circ$ lies at the northern edge of “the
distributions of the \(^{12}\text{CO}\) possibly links the in Figure 15 shows lower ratios of less than 0.4. Figure 7 shows ratios for each of these features are presented in Figures 14–16 features. The individual velocity channel distributions of the line connecting feature" identified by Enokiya et al. (2014), which

3.2. Excitation Conditions of the Molecular Gas

Next, we discuss the excitation condition of the molecular gas in the \(-35 \text{ km s}^{-1}\) and 0 km s\(^{-1}\) features. Figure 6 shows the distributions of the \(^{12}\text{CO}\) \(J = 2\rightarrow 1/J = 1\rightarrow 0\) velocity-integrated intensity ratios for the \(-30 \text{ km s}^{-1}, 0 \text{ km s}^{-1}\) and 10 km s\(^{-1}\) features. The individual velocity channel distributions of the line ratios for each of these features are presented in Figures 14–16 in Appendix A. The \(-35, 0,\) and 10 km s\(^{-1}\) features all show typical ratios of \(\sim 0.8\) and up to 1.1, whereas the foreground emission which is seen at velocities between \(-7\) and \(-4 \text{ km s}^{-1}\) in Figure 15 shows lower ratios of less than 0.4. Figure 7 shows curves of the ratio as a function of temperature \(T_k\) and density \(n(H_2)\) derived using LVG calculations (see the next subsection for details). The ratio 0.8 indicates the excited condition of molecular gas with high temperature >20 K and/or high density >10\(^3\) cm\(^{-3}\), while the ratio 0.4 indicates only low temperature (~10 K) at low density 10\(^2\) cm\(^{-3}\). A high excitation condition of the molecular gas is one of the major characteristics of the CMZ. The high observed CO ratios therefore lend support to the placement of the candidate molecular counterparts of the DHN—the 0 and \(-35 \text{ km s}^{-1}\) features—near the GC, as also discussed in Enokiya et al. (2014). The 10 km s\(^{-1}\) feature in Figure 6(c) also shows high excitation conditions and thus is perhaps located in the GC, although, as discussed above, the gas distribution of the 10 km s\(^{-1}\) feature does not spatially coincide with the infrared emission of the DHN, suggesting that it is an independent, unrelated feature. We also note here that the less excited foreground emission can reduce the CO intensities and thus can alter the intensity ratios in the DHN feature by absorption. We present model calculations of the absorption in Appendix B using the LVG assumption, indicating that, although absorption can alter the ratios, ratios larger than 0.9 still indicate high excitation gas in the DHN.

3.3. Physical Conditions of the Molecular Gas

Here, we estimate the total molecular masses of the \(-35 \text{ km s}^{-1}\) feature and the 0 km s\(^{-1}\) feature. We adopt the X-factor—the conversion factor from the integrated intensity of \(^{12}\text{CO}(J = 1\rightarrow 0)\) to \(\text{H}_2\) column density—of \(0.7 \times 10^{20} (\text{K km s}^{-1})^{-1} \text{ cm}^{-2}\) (Torii et al. 2010b), and derive the masses of the \(-35 \text{ km s}^{-1}\) and 0 km s\(^{-1}\) features as \(0.8 \times 10^4 M_\odot\) and \(3.3 \times 10^4 M_\odot\), respectively, consistent with previous estimates using NANTEN2 (Enokiya et al. 2014). As mentioned in the previous subsection, absorption by foreground gas can differentially reduce the CO intensities. Our model calculations shown in Appendix B suggest that these total molecular masses can be underestimated by 30%–80%.

Next, we discuss \(T_k\) and \(n(H_2)\) of the \(-35 \text{ km s}^{-1}\) and 0 km s\(^{-1}\) features. We utilize an LVG analysis (e.g., Goldreich & Kwan 1974) to estimate these parameters. For this analysis we take intensity ratios of different \(J\) levels of the CO emission. We use the \(^{12}\text{CO}(J = 2\rightarrow 1),^{13}\text{CO}(J = 1\rightarrow 0),\) and \(^{13}\text{CO}(J = 2\rightarrow 1)\) emission for the analysis and do not include the \(^{12}\text{CO}(J = 1\rightarrow 0)\) emission, since subthermally excited \(^{12}\text{CO}(J = 1\rightarrow 0)\) could selectively trace the diffuse envelopes of molecular features differently and more predominantly than the other three lines. We apply the LVG analysis to the five regions A–E in the \(-35 \text{ km s}^{-1}\) and 0 km s\(^{-1}\) features identified in Figure 8. Here, we use the intensity ratios integrated over the velocity ranges indicated in the spectra in Figure 8 shown by dotted lines.

We adopt the abundance ratios of \([^{12}\text{CO}] / [^{13}\text{CO}] = 24\) (Langer & Penzias 1990; Riquelme et al. 2010) and the fractional CO abundance to be \(X(\text{CO}) = [^{12}\text{CO}] / [\text{H}_2] = 10^{-4}\) (e.g., Frerking et al. 1982; Leung et al. 1984). We estimate velocity gradients of 0.4 km s\(^{-1}\) pc\(^{-1}\) by assuming the observed velocity variations of \(\sim 2 \text{ km s}^{-1}\) and the width of the DHN of \(\sim 5 \text{ pc}\), therefore giving \(X(\text{CO})/(dv/dr) = 2.5 \times 10^{-4} (\text{km s}^{-1} \text{ pc}^{-1})^{-1}\). Figure 9 shows the results of the calculations, where the distributions of the two line ratios, \(^{13}\text{CO}(J = 2\rightarrow 1)/^{13}\text{CO}(J = 1\rightarrow 0)\) and \(^{13}\text{CO}(J = 2\rightarrow 1)/^{12}\text{CO}(J = 2\rightarrow 1)\), are presented, and details of the results are summarized in Table 1. Here, the errors are estimated with (1) 1σ baseline fluctuations of the spectra, (2) 10% relative calibration error between the Mopra observations and the CSO observations (which is only applied when comparing between \(J = 2\rightarrow 1\) and \(J = 1\rightarrow 0\), and is applied only to \(^{13}\text{CO}(J = 2\rightarrow 1)/^{13}\text{CO}(J = 1\rightarrow 0)\) in the present analysis), and (3) absorption rate of up to 50% for the \(^{12}\text{CO}(J = 2\rightarrow 1)\) intensity due to the foreground cool gas (applied only to
Figure 5. $^{12}$CO($J=1–0$) (a) and $^{12}$CO($J=2–1$) (b) velocity-position ($Y$-axis) distributions of the $−35$ km s$^{-1}$ and 0 km s$^{-1}$ features. Horizontal dotted lines show the positions of the intersections of the DHN strands.

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Figure 6. Distributions of the $^{12}$CO($J=2–1)/^{12}$CO($J=1–0$) intensity ratio around $−31$ km s$^{-1}$, 0 km s$^{-1}$, and 14 km s$^{-1}$. Here, only a part of the whole velocity range of each of the $−35$ km s$^{-1}$, 0 km s$^{-1}$, and 10 km s$^{-1}$ features is shown. Contours show the integrated intensity of $^{12}$CO($J=2–1$) emission and are plotted at every 0.9 K km s$^{-1}$ from 0.7 K km s$^{-1}$. Maps of the individual velocity channel distributions within these three features are shown in Figures 14–16 of the Appendix.

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$^{13}$CO($J=2–1)/^{12}$CO($J=2–1$). Absorption of $^{13}$CO is ignored. The $n$(H$_2$) and $T_k$ ranges covered by the present analysis are $10^2–10^4$ cm$^{-3}$ and 7–200 K, respectively. As a result, we deduced that all five regions have $T_k$ of 20–40 K at $n$(H$_2$) $\sim 10^3$ cm$^{-3}$, which is significantly higher than the typical $T_k$ of molecular gas in the Galactic disk, $\sim 10$ K. Temperatures of $\sim 100$ K are allowed for regions B and D. These two regions are located around the top of the DHN.

4. DISCUSSION

Our detailed observations of the DHN with Mopra and the CSO indicate that both the $−35$ km s$^{-1}$ and 0 km s$^{-1}$ features are associated with the DHN. The spatial distribution of the 0 km s$^{-1}$ feature shows remarkably good correspondence with the infrared emission of the DHN. The association of the $−35$ km s$^{-1}$ feature is less clear compared with the
0 km s\(^{-1}\) feature, but the complementary distribution between the molecular gas and the DHN and velocity variation along the DHN support the association. The high excitation condition shown by the \(^{12}\text{CO}\) J = 2–1/1–0 ratio (Figure 6) and estimated high temperature of about 30 K (Figure 9) also support the placement of the two molecular features within the CMZ.

The two competing scenarios for the DHN are currently (1) a torsional Alfvén wave launched from the CND (Morris et al. 2006) and (2) an extension of the polarized northern lobe of the magnetic radio arc (Law et al. 2008; Tsuboi & Handa 2010). Enokiya et al. (2014) find that the −35 and 0 km s\(^{-1}\) features are continuations to higher latitude of molecular ridges that extend down to the Galactic plane; they also find that they are located in the GC. The ridge at 0 km s\(^{-1}\) appears to be pointing toward the CND rather than to the radio arc, although this does not provide an incontrovertible clue supporting the CND hypothesis. The results presented here for the detailed distribution of molecular emission toward the DHN indicate that the both the −35 and 0 km s\(^{-1}\) features are associated with the DHN; this was not conclusive in Enokiya et al. (2014). These two molecular features cannot be easily understood with either of the two present scenarios, therefore further investigations, including theoretical studies, are required.

The warm temperature of the molecular counterparts of the DHN is a characteristic that helps associate these features with the clouds of the CMZ. The energy injection rate required to keep the high temperature is estimated to be \(1 \times 10^{36}\) erg s\(^{-1}\) (Goldsmith & Langer 1978). Here, we assume a cylinder with a length of 30 pc for each feature to roughly estimate its volume, the diameters of which are estimated to be 10 pc and 5 pc for each feature to roughly estimate its volume, and we also assume a uniform density of \(10^3\) cm\(^{-3}\) and uniform temperature of the molecular gas, 30 K. It is reasonable to expect that the heating mechanism for the molecular gas is similar to that operating throughout the CMZ since 30 K is within a range of the typical temperatures of molecular gas in the CMZ.

### Table 1: LVG Results

| Region | l   | b   | \(n(H_2)\) (cm\(^{-3}\)) | \(T_k\) (K) |
|--------|-----|-----|---------------------------|-------------|
| A      | −0:02| 0:74| \(3\times10^3\) ± 0.5 \times 10^3 | 1\times10^3 ± 0.5 |
| B      | 0:04 | 0:81| \(1.9\pm 1.3 \times 10^3\) | 43\times10^3 ± 0.5 |
| C      | 0:03 | 0:72| \(6.9\pm 1.2 \times 10^2\) | 20\times10^3 ± 0.5 |
| D      | 0:04 | 0:77| \(9.3\pm 1.7 \times 10^2\) | 34\times10^3 ± 0.5 |
| E      | 0:04 | 0:63| \(2.1\pm 0.3 \times 10^2\) | 33\times10^3 ± 0.5 |

**Notes.** Column 4: number density of \(H_2\). Column 5: kinetic temperature.

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**Figure 7.** Curves of the \(^{12}\text{CO}\) J = 2–1/1–0 ratio as a function of \(T_k\) and \(n(H_2)\), estimated using the LVG calculations.

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

**Figure 8.** Left: the five regions A–E used in the LVG analysis are depicted by arrows on the integrated intensity images of \(^{12}\text{CO}\) J = 2–1) emission. Contours are plotted at the same level as Figures 4(a) and 4(c). Right: spectra toward the five peaks A–E. Black, red, blue, and green show profiles of \(^{12}\text{CO}\) J = 1–0), \(^{12}\text{CO}\) J = 2–1), \(^{13}\text{CO}\) J = 1–0), and \(^{13}\text{CO}\) J = 2–1) emission, respectively.

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though the heating mechanisms in the CMZ are still under active
discussion.

One possibility is heating by UV radiation from the large
population of massive stars in the CMZ. We estimate
the total infrared luminosity toward the DHN ($l = 0^{h}00^{-0}08$, $b = 0^{d}60^{-0}85$) as $8.5 \times 10^{5} \, L_{\odot} = 3.3 \times 10^{39} \, \text{erg s}^{-1}$ using the
integrated fluxes of the four IRAS bands and the equation given
in Table 1 of Sanders & Mirabel (1996), 3.5 orders of magnitude
larger than the cooling energy of the gas estimated above. In
the 24 $\mu$m image in Figure 1, the diffuse emission distributed
around the DHN accounts for roughly about 50% of the flux
density of the DHN. Thus, if we consider the contribution of the
diffuse emission, the total infrared luminosity is still much larger
than the cooling energy. Stellar heating is therefore a possible
explanation of the observed warm gas.

Cosmic rays are also a possible heating source for the
molecular gas in the DHN. The non-thermal radio emission,
which is used to probe the distribution of the cosmic-ray
electrons, shows a distribution extending to high latitude (Yusef-
Zadeh et al. 2013), including the northern part of the polarized
lobe (Tsuboi & Handa 2010).

Another way to heat molecular gas is dissipative heating of
the kinetic energy of the turbulent gas via ion-neutral friction
and/or magnetic reconnection. In the low latitude region of the
CMZ close to the Galactic plane, highly turbulent molecular gas
with a strong magnetic field possesses plenty of energy, but the
velocity widths of the molecular features in the DHN are only
about a few km s$^{-1}$, much smaller than the typical figures in the
CMZ, making it less likely as the origin of the warm molecular
gas in the DHN.

5. SUMMARY

The present study is summarized as follows;

1. We have carried out new observations of $^{12}\text{CO}(J = 1-0)$, $^{13}\text{CO}(J = 1-0)$, $^{12}\text{CO}(J = 2-1)$, and $^{13}\text{CO}(J = 2-1)$ emission using
   the CSO and Mopra telescopes toward the DHN with angular resolutions of $\sim 33''$, corresponding to
   $\sim 1.3$ pc at the distance of the GC, 8 kpc.

2. Both molecular features, at $-35$ km s$^{-1}$ and 0 km s$^{-1}$,
   are physically associated with the DHN. The 0 km s$^{-1}$
   feature traces the infrared distribution of the DHN very
   well, indicating a clear association. The association of the
   $-35$ km s$^{-1}$ feature is less clear compared with the 0 km s$^{-1}$
   feature, but the complementary spatial distribution between
   the molecular gas and the DHN and the velocity variation
   along the DHN suggests a physical association with the
   DHN.

3. The molecular masses of the $-35$ km s$^{-1}$ and 0 km s$^{-1}$
   features are estimated at $0.8 \times 10^4 \, M_{\odot}$ and $3.3 \times 10^4 \, M_{\odot}$,
   respectively. The two molecular features also have high
   temperatures ($\sim 30$ K), typical of GC clouds. The same
   heating mechanism that operates throughout the CMZ may
   therefore also be playing a dominant role in the DHN.

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Figure 10. Distributions of the two CO features in the CO($J = 2–1$) emission. The $-35$ km s$^{-1}$ feature is shown in panels (a) and (b), and the $0$ km s$^{-1}$ feature is in panels (c) and (d). Panels (a) and (c) show the $^{12}$CO($J = 2–1$), and panels (b) and (d) are $^{13}$CO($J = 2–1$). The contour levels of each panel are as follows. (a) minimum: 2 K km s$^{-1}$, step: 1.5 K km s$^{-1}$, (b) minimum: 0.8 K km s$^{-1}$, step: 0.6 K km s$^{-1}$. (c) minimum: 2 K km s$^{-1}$, step: 2 K km s$^{-1}$. (d) minimum: 0.8 K km s$^{-1}$, step: 0.6 K km s$^{-1}$.

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

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**APPENDIX A**

**DETAILED DISTRIBUTIONS AND CONDITIONS OF THE MOLECULAR FEATURES**

Here, we present the detailed velocity structure of the molecular gas toward the DHN. Figure 10 shows the spatial distributions of the $-35$ and $0$ km s$^{-1}$ features in CO($J = 2–1$) emission. The CO($J = 2–1$) emission traces clumpy structures in the DHN compared with the CO($J = 1–0$) emission in Figure 2. The $^{13}$CO emission traces only the dense components in the DHN and has a negligible contribution from unrelated foreground emission.

Figure 11 shows the velocity channel distributions of the $^{12}$CO($J = 1–0$) emission with a velocity interval of $5.5$ km s$^{-1}$. The $-35$ and $0$ km s$^{-1}$ features are seen around $-36$ to $-30$ km s$^{-1}$ and $-2.7$ to $+2.8$ km s$^{-1}$, respectively. The $10$ km s$^{-1}$ feature, which seems to be unrelated to the DHN, is distributed around $8–14$ km s$^{-1}$. The inter-velocity features seen in Figure 5 occur in the velocity intervals at $-30$ to $-19$ km s$^{-1}$ and $-19$ to $-8$ km s$^{-1}$.

Figures 12 and 13 show the detailed velocity channel distributions of the $-35$ km s$^{-1}$ feature and the $0$ km s$^{-1}$ feature in the $^{12}$CO($J = 1–0$ and $J = 2–1$) transitions with a velocity separation of $1.6$ km s$^{-1}$. In Figure 12, the $^{12}$CO($J = 2–1$) emission clearly shows that the two filaments at $\sim-34$ km s$^{-1}$ show a complementary distribution with the DHN, and that the filament at $\sim-31$ km s$^{-1}$ coincides well with the DHN. These velocity structures are clearly seen in Figure 3(a).

Figures 14–16 show the velocity channel distributions of the $^{12}$CO $J = 2–1$/$J = 1–0$ intensity ratio in the $-35$ km s$^{-1}$, $0$ km s$^{-1}$ and $10$ km s$^{-1}$ features. All of these features have highly excited components that show ratios around 1.0.

**APPENDIX B**

**ABSORPTION BY FOREGROUND GAS**

We make a model of a molecular cloud uniformly veiled by a layer of cool absorber in order to quantify the effect of the foreground gas on the intensities of CO lines of the DHN. Here, two sets of parameters are chosen for a hot molecular cloud and a cool molecular cloud; ($T_k$, $n(H_2)$) = (30 K, 1000 cm$^{-3}$) and (10 K, 1000 cm$^{-3}$), respectively. ($T_k$, $n(H_2)$) of the foreground absorber is assumed to be (10 K, 500 cm$^{-3}$). Here, we also assume that the foreground emission covers the velocity range of the DHN uniformly, having no frequency dependence, because no clear absorption feature is seen on the CO profiles (see Figure 8). The velocity coverage of the foreground absorber is thus assumed to be the same or larger than that of the DHN features. Distributions of the resulting brightness...
temperature, $T_{\text{obs}}$, as a function of $X$(CO)/$(d\nu/dr)$ are shown in Figure 17, where $T_{\text{obs}}$ is calculated with the following equation,

$$T_{\text{obs}} = J_{\nu}(T_{\text{cloud}})(1 - e^{-\tau_{\text{cloud}}})e^{-\tau_{fg}} + J_{\nu}(T_{fg})(1 - e^{-\tau_{fg}}) - J_{\nu}(T_{bg})(1 - e^{-\tau_{\text{cloud}}+\tau_{fg}}),$$

where $\tau_{\text{cloud}}$ and $\tau_{fg}$ are the optical depths of the molecular cloud and foreground absorber, and $T_{\text{cloud}}$, $T_{fg}$, and $T_{bg} = 2.7$ K are the excitation temperatures of the molecular cloud, the foreground absorber and the cosmic microwave background, respectively. ($T_{\text{cloud}}$, $\tau_{\text{cloud}}$), and ($T_{fg}$, $\tau_{fg}$) are given with the LVG calculations. Here, we use $X$(CO)/$(d\nu/dr)$ of $2.5 \times 10^{-3}$ (km s$^{-1}$ pc$^{-1}$)$^{-1}$, same as in Section 3.3. $J_{\nu}(T) = (h\nu/k_{B})(e^{h\nu/k_{B}T} - 1)$, where $h$, $k_{B}$, and $\nu$ are the Planck constant, the Boltzmann constant, and the rest frequency of the observed line, respectively.

In the case of the hot cloud in Figure 17(a), the $^{12}$CO $J = 2–1$/$J = 1–0$ ratio increases to over 0.9 at $X$(CO)/$(d\nu/dr) < 2 \times 10^{-6}$ (km s$^{-1}$ pc$^{-1}$)$^{-1}$. The molecular features in the DHN show intensity ratios up to 1.1, as seen in Figure 6, consistent with the results of Figure 17(a). In this $X$(CO)/$(d\nu/dr)$ range, which is depicted by the filled area in Figure 17, $T_{\text{obs}}$ of $^{12}$CO($J = 1–0$) is reduced by 30%–80%, and $^{12}$CO($J = 2–1$) by 35%–85%. On the other hand, in the cool cloud case in Figure 17(b), the ratio varies over a range of 0.65–0.85 and never beyond 0.9 at the $X$(CO)/$(d\nu/dr)$ range where the ratio is >0.9 in the hot cloud case in Figure 17(a). This indicates that although the intensity ratio is strongly affected by the foreground gas, the CO spectra of the DHN with high ratios larger than 0.9 still indicate high excitation gas.

Figure 11. Velocity channel distributions of $^{12}$CO($J = 1–0$) toward the DHN. (A color version of this figure is available in the online journal.)
Figure 12. Detailed velocity channel distributions of $^{12}$CO($J=1–0$) and $^{12}$CO($J=2–1$) toward the $−35$ km s$^{-1}$ feature. Upper eight panels show $^{12}$CO($J=1–0$) and lower eight panels show $^{12}$CO($J=2–1$).

(A color version of this figure is available in the online journal.)
Figure 13. Detailed velocity channel distributions of $^{12}$CO($J = 1–0$) and $^{12}$CO($J = 2–1$) toward the 0 km s$^{-1}$ feature. Upper eight panels show $^{12}$CO($J = 1–0$) and lower eight panels show $^{12}$CO($J = 2–1$).

(A color version of this figure is available in the online journal.)
Figure 14. Velocity channel distributions of $^{12}$CO($J = 2–1$)/$^{12}$CO($J = 1–0$) ratios toward the $-35$ km s$^{-1}$ feature. Contours show the $^{12}$CO($J = 2–1$) emission and are plotted at every 0.9 K km s$^{-1}$ from 0.7 K km s$^{-1}$.

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

Figure 15. Velocity channel distributions of $^{12}$CO($J = 2–1$)/$^{12}$CO($J = 1–0$) ratios toward the 0 km s$^{-1}$ feature. Contours show the $^{12}$CO($J = 2–1$) emission and are plotted at every 0.9 K km s$^{-1}$ from 0.7 K km s$^{-1}$.

(A color version of this figure is available in the online journal.)
Figure 16. Velocity channel distributions of $^{12}$CO($J=2–1$)/$^{12}$CO($J=1–0$) ratios toward the 10 km s$^{-1}$ feature. Contours show the $^{12}$CO($J=2–1$) emission and are plotted at every 0.9 K km s$^{-1}$ from 0.7 K km s$^{-1}$. (A color version of this figure is available in the online journal.)

Figure 17. Curves of the $^{12}$CO($J=1–0$) and $^{12}$CO($J=2–1$) brightness temperatures derived with the LVG analysis as a function of $X$(CO)/(dv/dr). Here, two sets of the parameters of molecular cloud are shown: (a) $T_k = 50$ K and $n$(H$_2$) = $10^3$ cm$^{-3}$, and (b) $T_k = 10$ K and $n$(H$_2$) = $10^3$ cm$^{-3}$. Solid lines show the temperatures absorbed by the foreground cool absorber and the dashed line shows the ratios between the two transitions. Dotted lines show the original temperatures not affected by the foreground gas. The filled areas show the region with ratios larger than 1.0. (A color version of this figure is available in the online journal.)
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