MILLIMETER-WAVE SPECTRAL LINE SURVEYS TOWARD THE GALACTIC CIRCUMNUCLEAR DISK AND Sgr A*

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ABSTRACT

We have performed unbiased spectral line surveys at the 3 mm band toward the Galactic circumnuclear disk (CND) and Sgr A* using the Nobeyama Radio Observatory 45 m radio telescope. The target positions are two tangential points of the CND and the direction of Sgr A*. We have obtained three wide-band spectra that cover the frequency range from 81.3 GHz to 115.8 GHz, detecting 46 molecular lines from 30 species, including 10 rare isotopomers and 4 hydrogen recombination lines. Each line profile consists of multiple velocity components which arise from the CND, +50 km s\(^{-1}\) and +20 km s\(^{-1}\) giant molecular clouds (GMCs), and the foreground spiral arms. We define the specific velocity ranges that represent the CND and the GMCs toward each direction, and classify the detected lines into three categories: the CND, GMC, HBD types, based on the line intensities integrated over the defined velocity ranges. The CND and GMC types are the lines that mainly trace the CND and the GMCs, respectively. The HBD types possess the both characteristics of the CND and GMC types. We also present lists of line intensities and other parameters, as well as intensity ratios, which must be useful to investigate the difference between the nuclear environments of our Galaxy and others.

Key words: galaxies: nuclei – Galaxy: center – ISM: molecules – radio lines: ISM

Online-only material: color figures

1. INTRODUCTION

Most galaxies are thought to have supermassive black holes (SMBHs) at their centers, some of which are observed as active galactic nuclei (AGNs). Recent observations have provided compelling evidence that the Milky Way also has an SMBH with a mass of $\left(4.5 \pm 0.4 \times 10^6\right) M_\odot$ at the dynamical center (Ghez et al. 2008; Gillessen et al. 2009), which is observed as the compact nonthermal radio source Sgr A* (Balick & Brown 1974). Despite its large mass, Sgr A* is extremely dim compared to extragalactic AGNs. The luminosity of the nucleus is only $\sim 10^{33} - 10^{35}$ erg s\(^{-1}\), which is far below the Eddington luminosity ($6 \times 10^{46}$ erg s\(^{-1}\)). However, some authors suggested that Sgr A* had experienced highly active phases in the past. The widespread Fe 6.4 keV fluorescent line over the central 200 pc suggests that Sgr A* was one million times brighter in the X-ray than the present about several hundred years ago (Koyama et al. 1996; Murakami et al. 2000; Ryu et al. 2013). The pair of large gamma-ray lobes recently discovered by the Fermi Large Area Telescope is hypothesized to be a remnant of quasar activity at $\sim 10^7$ yr ago (Su et al. 2010). It is possible that nuclear activities are transient in nature, and the currently inactive Sgr A* may turn active in future.

Sgr A* is located in the center of the extended radio source Sgr A, which consists of a thermal minisper (Sgr A west) and a nonthermal supernova remnant shell (Sgr A east). The circumnuclear disk (CND), which is a dense, warm ring of molecular gas, encompasses the minisper (e.g., Genzel et al. 1985; Güsten et al. 1987; Kaifu et al. 1987). The well-known 2 pc radius ring of the CND has a rotating velocity of $\sim 110$ km s\(^{-1}\). The entity of the CND is possibly an infalling disk with a diameter of 10 pc, which includes the 2 pc radius ring and the negative longitude extension (Oka et al. 2011). The CND may have been formed by the tidal capture and disruption of a molecular cloud (Sanders 1998; Wardle & Yusef-Zadeh 2008), and is now a potential reservoir for material accreting into the central parsec. It is likely that the CND is not a stable but transient feature (Oka et al. 2011; Requena-Torres et al. 2012). Two giant molecular clouds (GMCs), M−0.13−0.08 (+20 km s\(^{-1}\) cloud) and M−0.02−0.07 (+50 km s\(^{-1}\) cloud), are located in the vicinity of the nuclear region. These GMCs are thought to be interacting with the nuclear region (e.g., Güsten et al. 1981; Genzel et al. 1990). In particular, it is suggested that the +20 km s\(^{-1}\) cloud is feeding the CND (Okumura et al. 1989; Coil & Ho 1999).

Properties of the molecular clouds in the central region are probably linked to the nuclear activities. It is possible that an outflow originating from the central SMBH and the mass-losing He stars may be interacting with the northern and southern lobes of the CND (Mužić et al. 2007). The chemical composition of the CND provides a useful guide for research on feedback from the activity of Sgr A*, as well as on the gas fueling through the CND. High-energy photons/particles generated by AGN activities form X-ray/cosmic-ray dissociation regions (XDRs/CRDRs). Intense UV radiation forms photodissociation regions (PDRs) in irradiated molecular clouds. Theoretical predictions calculate a number of XDR/PDR discriminators, such as HCN/HCO+ and HNC/HCN ratios, and abundances of NO, HOC, and HCO (Spaans & Meijerink 2005; Meijerink et al. 2007). Abundance of refractory molecules, such as SiO, are thought to be enhanced in shocked regions and X-ray-irradiated regions (Martín et al. 2012; Amo-Baladrón et al. 2009).

Most of these diagnostic probes have transitions in millimeter wavelength. Using some of the diagnostic probes with intense emission, several authors have studied the chemistry of the CND and adjacent GMCs (e.g., Amo-Baladrón et al. 2011;...
Figure 1. Target positions of our line surveys (circles) superimposed on a map of the velocity-integrated HCN $J = 1-0$ emission (Christopher et al. 2005). The star indicates the position of Sgr A$^*$. Sizes of circles represent the half-power beam widths (HPBW) of the NRO 45 m radio telescope at 115 GHz and 86 GHz.

Figure 2. Spectral line zoos obtained at the three observed positions: NE, SW, and SGA.

Table 1

| Receiver | Frequency (GHz) | Beamwidth (arcsec) | $\eta_{MB}$ (%) |
|----------|----------------|--------------------|-----------------|
| TZ1(H)   | 110            | 16.1 ± 0.1         | 31 ± 2          |
|          | 115            | 15.4 ± 0.1         | 28 ± 1          |
| TZ1(V)   | 86             | 19.2 ± 0.2         | 36 ± 2          |
|          | 110            | 16.3 ± 0.1         | 32 ± 3          |
|          | 115            | 14.9 ± 0.1         | 29 ± 2          |

The observations were carried out in 2013 February and May with the Nobeyama Radio Observatory (NRO) 45 m radio telescope (RT). Target positions were chosen as $(\Delta l, \Delta b) = (+46^\prime, 0^\prime), (0^\prime, 0^\prime), (−40^\prime, 0^\prime)$, which are defined by offsets from the position of Sgr A$^*$, $(\alpha_{2000}, \delta_{2000}) = (17^h45^m40.0^s, −29^\circ 00^\prime 27.9^\prime)$ (Reid & Brunthaler 2004). Hereafter, we refer those target positions to NE, SGA, SW, respectively (Figure 1).

For these line surveys, we used the TZ1 V/H receivers which were operated in the two-sideband mode. The beamwidth and the main-beam efficiency ($\eta_{MB}$) are listed in Table 1. We used the SAM45 spectrometer in the 2 GHz bandwidth (488.24 kHz resolution) mode. Using 14 arrays of SAM45, we obtained a 4 GHz instantaneous bandwidth for each sideband (LSB and
The system noise temperatures ranged from 120 to 360 K during the observations. The observations were made by the 3:1 on–off position switching mode. The reference positions were \((l, b) = (0:0, +0:5), (0:0, -0:5)\), which were observed alternately. Pointing errors were corrected every 1.5 hr by observing the SiO maser emissions (43 GHz) from VX Sgr with the H40 receiver. The pointing accuracy was better than 3″ (rms) in both azimuth and elevation. Calibration of the antenna temperature was accomplished by the standard chopper-wheel method.

All data were reduced using the NEWSTAR reduction package. We composed wide-band spectra covering 81.3–115.8 GHz toward the observed three positions by averaging and merging all 2 GHz spectra (Figure 2). The spectral resolution of the resultant spectra was 1.0 MHz.

Antenna temperatures \((T^*_a)\) were converted into main-beam temperatures \((T_{MB})\) by multiplying \(1/\eta_{MB}(v)\). For the frequency dependence of the efficiency \(\eta_{MB}\), we adopted that \(\eta_{MB}(v) = -0.236 \times (v_{obs}/\text{GHz}) + 56.47\%\), which was obtained by the least-square fitting to the \(\eta_{MB}\) measured at three frequencies (Table 1). The rms noise levels of the wide-band spectra were calculated by using data in emission/absorption-free frequency ranges (Figure 3).

3. RESULTS

We show the wide-band spectra toward NE, SW, and SGA in Figure 2. A number of spectral lines appear in these wide-band spectra. The SGA spectrum is more rippled than the other positions, presumably because the intense continuum emission from Sgr A* manifests the non-linearity of the system. We identified 4 hydrogen recombination lines and 46 lines from 30 molecular species, including 10 rare isotopomers (Table 2). In addition to familiar diatomic and triatomic molecules, a few more complex molecules (e.g., HCCCN, c-C3H2, CH3OH, CH3CHO, and CH3CN) were detected.

We extracted 50 line profiles for each position (Figure 4). Each extracted spectrum covers the LSR velocity range from \(-300\) to \(+300\) km s\(^{-1}\). After the extraction, we again subtracted baselines from the spectra by fitting up to third-degree polynomials, although a linear function was used in most cases. Flat lines in some extracted spectra denote the velocity range where the adjacent lines appear. The peak velocities \((V_{peak})\), velocity dispersions \((\sigma_V)\), peak temperatures \((T_{peak})\), and 1σ rms noise levels \((\Delta T_{MB})\) of the detected lines are listed in Tables 2 and 3. The \(\Delta T_{MB}\) values were calculated for the velocity ranges from \(-300\) to \(-200\) km s\(^{-1}\) and from \(+200\) to \(+300\) km s\(^{-1}\). The \(\sigma_V\) values were calculated using pixels with \(T_{MB} > 3\Delta T_{MB}\). All the detected lines have larger velocity widths than those from typical molecular clouds in the Galactic disk. Because of their large velocity widths, some lines are blended and/or unresolved. The lines of common interstellar molecules (e.g., CO, CS, HCN, and HCO\(^+\)) are intense \((T_{peak} \gtrsim 1\) K) and have very large velocity widths at every position. In particular, CO \(J = 1-0\) line exceeds 35 K and shows a number of velocity components. About a half of the lines from SGA show absorption features due to the foreground gas in the Galactic disk.
The overall velocity structures of the line profiles vary mainly depending on the position. The profiles of the detected lines, except for the hydrogen recombination lines, contain similar velocity components in each position. Most molecular lines from NE peak at $V_{\text{LSR}} \sim +50 \text{ km s}^{-1}$, while those from SW peak at $V_{\text{LSR}} \sim +20 \text{ km s}^{-1}$. Molecular lines from SGA generally exhibit complex profiles. The hydrogen recombination lines toward SGA show very large velocity width, which may be attributed to the rapidly rotating minispiral. The biased velocities of the NE and SW recombination lines, which peak at $V_{\text{LSR}} \sim +80$ and $\sim -80 \text{ km s}^{-1}$, respectively (except for H41α from SW), may suggest that rotating ionized gas is associated with the CND.

4. DISCUSSION

4.1. Decomposition of Line Profiles

All the identified lines contain multiple velocity components which originate from $+50 \text{ km s}^{-1}$ and $+20 \text{ km s}^{-1}$ clouds,
foreground/background spiral arms, and the CND. The emission from the +50 km s\(^{-1}\) and +20 km s\(^{-1}\) clouds are dominant in many molecular lines toward NE and SW. The +50 km s\(^{-1}\) cloud appears in the NE spectra, while the +20 km s\(^{-1}\) cloud appears in the SW spectra.

In order to investigate physical conditions and chemical composition of the CND, it is necessary to decompose the line profiles into their constituents. However, it is not easy to perform the decomposition by spectral fitting, since each profile has a complicated shape suffering from the absorption and contamination of the disk gas. Hence, we define velocity ranges that represent the CND and the GMCs, and calculate integrated intensities for each range at each position (Table 4). Figure 5 shows the defined velocity ranges in the HCN, CS, and CH\(_3\)OH line profiles. Since the CND is rotating at a velocity of \(\sim 110\) km s\(^{-1}\), the lines that trace the CND should

### Table 3

| Species | Transition | Rest Freq. (GHz) | NE | SGA | SW | NE | SGA | SW |
|---------|------------|-----------------|----|-----|----|----|-----|----|
| HNC     | 1–0        | 87.090693       | 0.128 | 0.140 | 0.111 | 0.021 | 0.021 | 0.021 |
| CCH     | \(N_{1,F,F} = 1_{1,2}/2 - 0_{1,2}\) | 87.316929 | 0.720 | 0.608 | 0.631 | 0.022 | 0.024 | 0.021 |
| HCN     | \(N_{2,F,F} = 1_{1,2}/0 - 0_{1,2}\) | 87.402004 | 0.424 | 0.361 | 0.344 | 0.013 | 0.022 | 0.018 |
| HCO      | \(J = 2-1\) | 92.494270 | 0.273 | 0.136 | 0.142 | 0.017 | 0.019 | 0.016 |
| HCO\(_{3}\) | \(J_{2,F,F} = 1_{1,2}/0 - 0_{1,2}\) | 93.171917 | 0.578 | 0.492 | 0.871 | 0.028 | 0.036 | 0.031 |
| CH\(_3\)O\(_{2}\) | \(J_{1,1}/0 - 0_{1,1}\) | 94.401729 | 0.055 | 0.052 | 0.060 | 0.019 | 0.022 | 0.019 |
| CH\(_3\)OH | \(J_{2,1}/1 - 1_{1,1}\) | 95.914310 | 0.043 | 0.062 | 0.051 | 0.013 | 0.011 | 0.012 |
| \(^{13}\)CS | \(J = 2-1\) | 96.412950 | 0.289 | 0.115 | 0.162 | 0.016 | 0.017 | 0.015 |
| CH\(_3\)OH | \(J_{2,0} - 1_{1,1}\) | 96.744549 | 0.908 | 0.720 | 0.788 | 0.014 | 0.013 | 0.014 |
| CS      | \(J = 2-1\) | 97.301209 | 0.094 | 0.066 | 0.069 | 0.016 | 0.016 | 0.015 |
| CH\(_3\)OH | \(J_{2,1}/1 - 0_{1,1}\) | 97.582808 | 0.078 | 0.062 | 0.063 | 0.017 | 0.017 | 0.015 |
| HCN     | \(J = 7-6\) | 99.798093 | 3.673 | 1.914 | 1.840 | 0.020 | 0.019 | 0.020 |
| H      | \(J = 40\) | 99.022750 | 0.118 | 0.170 | 0.091 | 0.016 | 0.023 | 0.017 |
| SO       | \(N_{1/2} = 2_{1,1}\) | 99.299905 | 0.404 | 0.255 | 0.319 | 0.023 | 0.020 | 0.020 |
| HCCCN   | \(J = 11-10\) | 100.076386 | 0.308 | 0.240 | 0.191 | 0.022 | 0.020 | 0.023 |
| CH\(_3\)OH | \(J_{1,1}/0 - 0_{1,1}\) | 101.469719 | 0.115 | 0.067 | 0.106 | 0.026 | 0.024 | 0.025 |
| H\(_2\)CS | \(J_{3,0} - 0_{2,2}\) | 103.040548 | 0.090 | 0.029 | 0.061 | 0.016 | 0.015 | 0.017 |
| H\(_2\) | \(J = 31/2 - 21/2\) | 104.617109 | 0.125 | 0.091 | 0.069 | 0.019 | 0.021 | 0.019 |
| H      | \(J = 39\) | 106.737250 | 0.164 | 0.217 | 0.127 | 0.023 | 0.034 | 0.025 |
| \(^{13}\)CN | \(N_{1,F,F} = 1_{1,1}/0 - 0_{1,1}\) | 108.658948 | 0.155 | 0.088 | 0.141 | 0.023 | 0.023 | 0.024 |
| \(^{13}\)CN | \(N_{1,F,F} = 1_{1,1}/0 - 0_{1,2}\) | 108.782737 | 0.118 | 0.103 | 0.114 | 0.021 | 0.021 | 0.021 |
| CH\(_3\)OH | \(J_{0,0} - 0_{1,1}\) | 108.839929 | 0.143 | 0.107 | 0.132 | 0.019 | 0.025 | 0.023 |
| HCCCN   | \(J = 12-11\) | 109.173638 | 0.340 | 0.217 | 0.220 | 0.022 | 0.027 | 0.025 |
| OCS     | \(J = 9-8\) | 109.463063 | 0.124 | 0.088 | 0.130 | 0.021 | 0.022 | 0.023 |
| \(^{15}\)O | \(J = 1-0\) | 109.782176 | 0.340 | 0.217 | 0.220 | 0.022 | 0.027 | 0.025 |
| HNCO    | \(J_{0,0} - 0_{1,1}\) | 110.095753 | 0.291 | 0.308 | 0.382 | 0.020 | 0.021 | 0.023 |
| \(^{13}\)CO | \(J = 1-0\) | 110.203154 | 6.017 | 4.448 | 4.649 | 0.019 | 0.020 | 0.020 |
| CH\(_3\)CN | \(J_{1,0} - 0_{1,1}\) | 110.381404 | 0.179 | 0.127 | 0.134 | 0.026 | 0.032 | 0.026 |
| \(^{13}\)CO | \(J = 1_{1,2}/1 - 0_{1,2}\) | 112.358988 | 0.180 | 0.123 | 0.165 | 0.035 | 0.032 | 0.038 |
| CN      | \(N_{1,F,F} = 1_{1,1}/0 - 0_{1,2}\) | 113.170528 | 1.625 | 0.817 | 1.348 | 0.072 | 0.061 | 0.045 |
| CN      | \(N_{1,F,F} = 1_{1,2}/1 - 0_{1,2}\) | 113.490982 | 2.883 | 2.300 | 2.319 | 0.071 | 0.074 | 0.073 |
| CO      | \(J = 1-0\) | 115.271202 | 47.155 | 36.323 | 36.888 | 0.141 | 0.285 | 0.234 |

**Note.**\(^{a}\) We could not calculate the rms noise here because of the interference of adjacent lines.
Figure 4. Spectral line profiles toward three observed positions. Thick lines are smoothed spectra with grid widths of 10 km s\(^{-1}\). The flat lines in some extracted spectra denote velocity ranges where adjacent lines appear.

be prominent in velocities around \(\sim+110\) km s\(^{-1}\) at NE and \(\sim-110\) km s\(^{-1}\) at SW. This is well illustrated in the HCN and HCO\(^+\) profiles. The +50 km s\(^{-1}\) and +20 km s\(^{-1}\) clouds should be prominent in velocities around +50 km s\(^{-1}\) at NE, and around +20 km s\(^{-1}\) at SW, respectively. These components are apparent in several optically thin lines such as the N\(_2\)H\(^+\), CH\(_3\)OH, and HCCCN lines.

4.2. Line Intensities

We list the velocity-integrated line intensities (Tables 5–7) calculated for the velocity ranges listed in Table 4. Figure 6 shows a correlation plot between the integrated intensities at NE and SW for the CND velocity range (\(I_{\text{CND}}^\text{NE}\) and \(I_{\text{CND}}^\text{SW}\), respectively). The good correlation may support our choice of the velocity ranges that represent the same entity, the CND. We hence define that \(I_{\text{CND}} \equiv I_{\text{CND}}^\text{NE} + I_{\text{CND}}^\text{SW}\). Figure 7 shows a correlation plot between the integrated intensities at NE and SW for the GMC velocity range (\(I_{\text{GMC}}^\text{NE}\) and \(I_{\text{GMC}}^\text{SW}\), respectively). The line intensities from the GMCs in NE are generally more intense than those in SW. In other words, the +50 km s\(^{-1}\) cloud is brighter than the +20 km s\(^{-1}\) cloud in most of the detected lines. This plot also shows a tight correlation, although
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Figure 5. Line profiles of the HCN, CS, and CH$_3$OH lines toward NE, SW, and SGA. The red and green bands show the velocity ranges that represent the CND and GMCs, respectively. The HCN, CS, and CH$_3$OH lines are typical of the CND, HBD, and GMC types, respectively (see Section 4.3).

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

Table 4

|       | NE       |       | SGA       |       | SW       |       |
|-------|----------|-------|----------|-------|----------|-------|
|       | Total    | GMC   | CND      | Total | GMC      | CND   |
| $V_{\text{min}}$ (km s$^{-1}$) | $-150$ | $30$  | $120$    | $-200$| $20$     | $70$  |
| $V_{\text{max}}$ (km s$^{-1}$) | $200$  | $60$  | $90$     | $200$ | $50$     | $100$ |

| Symbol | $I_{\text{NE}}^{\text{total}}$ | $I_{\text{NE}}^{\text{GMC}}$ | $I_{\text{NE}}^{\text{CND}}$ | $I_{\text{SGA}}^{\text{total}}$ | $I_{\text{SGA}}^{\text{GMC}}$ | $I_{\text{SGA}}^{\text{CND}}$ | $I_{\text{SW}}^{\text{total}}$ | $I_{\text{SW}}^{\text{GMC}}$ | $I_{\text{SW}}^{\text{CND}}$ |

Note. $^a$ Symbol denotes the intensity integrated over $V_{\text{min}}$ to $V_{\text{max}}$.

$I_{\text{GMC}}^{\text{NE}}$ is generally larger than $I_{\text{GMC}}^{\text{SW}}$. This fact indicates that the +50 km s$^{-1}$ and +20 km s$^{-1}$ clouds have roughly similar chemical composition and physical conditions. Thus, we also define that $I_{\text{GMC}} = I_{\text{NE}}^{\text{GMC}} + I_{\text{SW}}^{\text{GMC}}$. We list $I_{\text{NE}}^{\text{CND}}$ and $I_{\text{GMC}}^{\text{CND}}$ in Table 8, the values of which are most likely to represent the typical intensities from the CND and the GMCs.

4.3. Line Classification

Figure 8 shows a plot of $I_{\text{CND}}^{\text{NE}}/I_{\text{GMC}}^{\text{NE}}$ versus $I_{\text{CND}}^{\text{SW}}/I_{\text{GMC}}^{\text{SW}}$ for each lines. The lines in the upper right corner are enhanced toward the CND. In order to search for prominent probes for the CND, we define the CND parameter:

$$\xi_{\text{CND}} \equiv \sqrt{\left(\frac{I_{\text{CND}}^{\text{NE}}}{I_{\text{GMC}}^{\text{NE}}}\right)^2 + \left(\frac{I_{\text{CND}}^{\text{SW}}}{I_{\text{GMC}}^{\text{SW}}}\right)^2}. \quad (1)$$

We classify the identified lines into three categories according to $\xi_{\text{CND}}$:

1. $\xi_{\text{CND}} \geq 1$ : CND type;
2. $0.5 < \xi_{\text{CND}} < 1$ : Hybrid (HBD) type;
3. $\xi_{\text{CND}} < 0.5$ : GMC type.

The CND and GMC types are the lines that mainly trace the CND and the GMCs, respectively. The HBD-type possesses both characteristics of the CND and GMC types. These types are also listed in Table 8. For example, HCN, HCO$^+$, and SiO belong to the CND type, HCCCN, N$_2$H$^+$, and CH$_3$OH belong to the GMC type, and CS, HNC, CCH, and SO belong to the HBD type. The lines of large molecules tend to be of GMC-type. The HBD-type lines arise from both the CND and the GMCs, and thus these lines could probe the physical connection between the CND and the GMCs. The line profiles of HCN, CS, and CH$_3$OH are shown in Figure 5 as representative examples of the CND, HBD, and GMC types, respectively.
4.4. Line Intensity Ratios

Spectral line intensity ratios are used as indicators of physical conditions of molecular gas and chemical diagnosis, such as XDR/PDR/CRDR/shock-diagnosis. We list several line intensity ratios which were calculated using $I_{\text{CND}}$ and $I_{\text{GMC}}$ in Table 9.

The CO/$^{13}$CO and HCN/H$^{13}$CN ratios can be used as opacity probes. Both of the ratios are lower in the GMCs than in the CND, reflecting the higher optical depth of the CO and HCN lines in the GMCs.

The ratios between dense gas and less dense gas probes are good indicators of gas density. The HCN/CO, HCN/$^{13}$CO, H$^{13}$CN/$^{13}$CO, CS/CO, CS/$^{13}$CO, and $^{13}$CS/$^{13}$CO ratios can be used as density probes. All these ratios are significantly higher in the CND than in the GMCs, likely indicating very high density in the CND. In the Galactic disk ($3.5 \text{ kpc} < R < 7 \text{ kpc}$) and the central 600 pc, the HCN/CO ratios are $0.026 \pm 0.008$ and $0.081 \pm 0.004$, respectively (Helfer & Blitz 1997).

In the nuclear environment, the HCN/CO ratios in the GMCs and 0.341 ± 0.001 in the CND. The HNC/HCN ratio, which is significantly lower in the CND than in the GMCs, may indicate a higher temperature of the CND. The HNC/H$^{13}$CN and HN$^{13}$C/H$^{13}$CN ratios show the same trends.

The HCN/HCO$^+$ ratio exceeds unity ($>1$) in AGN, while the ratio is below unity ($<1$) in starburst galaxies (e.g., Kohno et al. 2004). X-ray photons from AGN dissociate and ionize...
Figure 7. Correlation plot between the integrated intensities $I_{\text{NE}}^{\text{GMC}}$ and $I_{\text{SW}}^{\text{GMC}}$ for each lines. A solid line shows where $I_{\text{NE}}^{\text{GMC}} = I_{\text{SW}}^{\text{GMC}}$.

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

Figure 8. Plot of $I_{\text{NE}}^{\text{CND}} / I_{\text{NE}}^{\text{GMC}}$ vs. $I_{\text{SW}}^{\text{CND}} / I_{\text{SW}}^{\text{GMC}}$ for each lines. The green region satisfies $\xi_{\text{CND}} < 0.5$ and species in this region are classified as GMC-type. The turquoise region satisfies $0.5 \leq \xi_{\text{CND}} < 1$ and species in this region are classified as HBD-type. Species out of arcs ($\xi_{\text{CND}} \geq 1$) are classified as CND-type.

(A color version of this figure is available in the online journal.)
molecular gas, increasing the abundances of ions, radicals, and several molecular species. These regions are called XDRs (Lepp & Dalgarno 1996; Maloney et al. 1996; Spaans & Meijerink 2005; Meijerink et al. 2007). In our data, the HCN/HCO+ ratios are 1.74 ± 0.01 and 1.62 ± 0.01 in the GMCs and CND, respectively. They are comparable to each other and significantly exceed unity. Christopher et al. (2005) found that the ratio in the CND was typically ~2.5 with interferometric observations. The ratios in the l = 1.3 complex and the Sgr B1 complex are ~2.3 and ~1.5, respectively (Tanaka et al. 2007, 2009). Such a high HCN/HCO+ ratio is found over the whole of the central molecular zone (e.g., Jones et al. 2012).

The SiO abundance is thought to be enhanced in shocked regions, and its intensity ratios to H13CN and H13CO+ are often used as shock probes. The SiO abundance in the CND does not seem to be particularly enhanced, although the SiO line was categorized as CND-type. The SiO/H13CO+ ratios in the GMCs and the CND are 1.84 ± 0.06 and 1.66 ± 0.07, respectively. These values are typical for the Sgr A molecular cloud complex (e.g., Tsuboi et al. 2011).

### Table 5

| Species   | Transition | Rest Freq. (GHz) | JNE_total (K km s⁻¹) | JNE_GMC (K km s⁻¹) | JNE_CND (K km s⁻¹) |
|-----------|------------|-----------------|----------------------|---------------------|---------------------|
| HNCO      | 4_0−3_0    | 87.925238       | 14.29 ± 0.85         | 5.73 ± 0.25         | 0.43 ± 0.25        |
| HCN       | J = 1−0    | 88.563147       | 545.85 ± 1.15        | 106.92 ± 0.34       | 120.44 ± 0.34      |
| HCO⁺      | J = 1−0    | 89.188526       | 366.98 ± 1.88        | 56.86 ± 0.55        | 93.21 ± 0.55       |
| HCCCN     | J = 10−9   | 90.978993       | 143.29 ± 0.47        | 39.48 ± 0.14        | 23.05 ± 0.14       |
| CH₃CN     | Jₖ,K,F = 5_1−4_5 | 91.97310 | 7.99 ± 0.37          | 1.23 ± 0.12         | 0.25 ± 0.12        |
| H         | 4_0        | 92.034680       | 14.71 ± 0.42         | 1.16 ± 0.14         | 0.53 ± 0.14        |
| 13CS      | J = 2−1    | 92.494270       | 17.00 ± 0.57         | 4.70 ± 0.17         | 1.24 ± 0.17        |
| N₂H⁺      | J₁,F,J = 1_1−0_1 | 93.171917 | 38.15 ± 0.67         | 14.05 ± 0.20        | 1.54 ± 0.20        |
| 13CH₂OH   | 2_0−1_0,A++ | 94.407192 | 2.45 ± 0.65          | 1.09 ± 0.19         | 0.13 ± 0.19        |
| CH₂OH     | 2_1−1_1,A++ | 95.914310 | 1.40 ± 0.26          | 0.65 ± 0.09         | ...                |
| CH₂CHO    | 5_0−4_0,A++ | 95.963465 | 2.19 ± 0.26          | 0.82 ± 0.09         | 0.41 ± 0.09        |
| CS²⁺      | J = 2−1    | 96.412950       | 13.55 ± 0.50         | 4.69 ± 0.15         | 0.81 ± 0.15        |
| CH₂OH     | 2_0−1_0,E | 96.744549       | 63.34 ± 0.45         | 23.02 ± 0.13        | 3.72 ± 0.13        |
| OCS       | J = 8−7    | 97.301209       | 5.19 ± 0.51          | 1.53 ± 0.15         | 0.57 ± 0.15        |
| CH₂OH     | 2_1−1_1,A--- | 97.582808 | 3.00 ± 0.54          | 0.95 ± 0.16         | 0.19 ± 0.16        |
| CS        | J = 2−1    | 97.980953       | 252.75 ± 0.66        | 69.36 ± 0.19        | 24.95 ± 0.19       |
| H         | 4_0        | 99.022750       | 9.91 ± 0.51          | 1.57 ± 0.15         | 1.91 ± 0.15        |
| SO        | N₂,J,J = 2_0−1_0 | 99.299905 | 27.81 ± 0.74         | 8.00 ± 0.22         | 2.42 ± 0.22        |
| HCCCN     | J = 10−10  | 100.076386      | 17.56 ± 0.62         | 6.69 ± 0.18         | ...                |
| CH₂OH     | 8_2−7−8_1,E | 101.469719 | 4.17 ± 0.82          | 0.77 ± 0.24         | ...                |
| H₂CS      | 3_0−2_0,1  | 103.040548      | ...                 | 0.72 ± 0.15         | ...                |
| H₂CS      | 3_1−2_1    | 104.617109      | 7.52 ± 0.61          | 2.08 ± 0.18         | 0.58 ± 0.18        |
| H         | 3_0        | 106.737250      | 11.80 ± 0.72         | 1.88 ± 0.21         | 1.39 ± 0.21        |
| 13CN      | N₁,F,J = 1_1−0_1 | 108.658948 | 11.95 ± 0.54         | 1.93 ± 0.16         | 2.11 ± 0.16        |
| 13CN      | N₁,F,J = 1_1−0_1 | 108.872874 | 9.85 ± 0.51          | 2.23 ± 0.15         | 0.96 ± 0.15        |
| CH₂OH     | 0_0−0−1_1,E | 108.893929 | 2.67 ± 0.42          | 2.48 ± 0.12         | -0.40 ± 0.12       |
| HCCCN     | J = 12−11  | 109.173638      | 13.42 ± 0.29         | 6.44 ± 0.08         | 0.56 ± 0.08        |
| OCS       | J = 9−8    | 109.463063      | 6.02 ± 0.64          | 1.86 ± 0.19         | 0.09 ± 0.19        |
| C₂O       | J = 1−0    | 109.782176      | 32.21 ± 0.54         | 12.36 ± 0.16        | 0.60 ± 0.16        |
| HNCO      | 5_0−4_0,4  | 109.905753      | 14.25 ± 0.48         | 6.70 ± 0.14         | 0.27 ± 0.14        |
| 13CO      | J = 1−0    | 110.201354      | 425.35 ± 0.58        | 149.80 ± 0.17       | 13.10 ± 0.17       |
| CH₂CN     | Jₖ,K,F,J = 5_1−4_6 | 110.381404 | 9.24 ± 0.81         | 3.09 ± 0.24         | 1.44 ± 0.24        |
| C₂O       | Jₖ,K,F,J = 1_2−0_1,E | 112.358988 | 9.49 ± 1.08         | 3.62 ± 0.32         | 0.09 ± 0.32        |
| CN        | N₂,J,F,J = 1_1−0_1 | 113.170528 | 207.06 ± 2.21       | 35.41 ± 0.65        | 20.46 ± 0.65       |
| CN        | N₂,J,F,J = 1_2−0_2−1_1−1_2 | 113.490892 | 274.16 ± 2.15       | 47.48 ± 0.63        | 47.22 ± 0.63       |
| CO        | J = 1−0    | 115.271202      | 4203.28 ± 4.26       | 1290.94 ± 1.25      | 250.78 ± 1.25      |
4.5. Spectra from Sgr A*

Suffering from severe absorption features against the intense continuum radiation from Sgr A*, decomposition of line profiles toward SGA is highly difficult. Based on previous works (e.g., Güsten et al. 1987; Kaifu et al. 1987; Oka et al. 2011), we define $V_{LSR} = +70$ to $+100$ km s$^{-1}$ as the CND range, and $V_{LSR} = +20$ to $+50$ km s$^{-1}$ as the GMC range (Figure 5). We calculated the velocity-integrated intensities of SGA ($I_{SGA}^\text{tot}$, $I_{SGA}^\text{GMC}$, and $I_{SGA}^\text{CND}$), using data with $T_{MB} > 0$ K in order to minimize the effect of the absorption by the foreground. These intensities are listed in Table 6. Figure 9 shows a correlation plot of the GMC contribution ($I_{SGA}^\text{GMC}$) versus the CND contribution ($I_{SGA}^\text{CND}$). The GMC types prefer the top left of the plot, while the CND types roughly prefer the bottom right. The HBD types are distributed between the CND and GMC types. This may support the validity of our line classification and that of our definition of velocity ranges on the SGA spectra.

| Species | Transition | Rest Freq. (GHz) | $I_{SGA}^\text{tot}$ (K km s$^{-1}$) | $I_{SGA}^\text{GMC}$ (K km s$^{-1}$) | $I_{SGA}^\text{CND}$ (K km s$^{-1}$) |
|---------|------------|-----------------|-------------------------------|---------------------------------|---------------------------------|
| HN3C    | $J = 1$    | 91.26           | 12.75                         | 2.5                            | 0.17                            |
| CH      | $J = 2$    | 91.26           | 25.5                           | 5.0                            | 0.34                            |
| OCS     | $J = 3$    | 91.26           | 38.2                           | 7.6                            | 0.50                            |
| CH3CN   | $J = 4$    | 91.26           | 41.0                           | 8.2                            | 0.56                            |
| CN      | $J = 5$    | 91.26           | 43.7                           | 8.7                            | 0.59                            |
| CO      | $J = 6$    | 91.26           | 46.4                           | 9.2                            | 0.62                            |

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Table 6

Velocity-integrated Intensities of the Identified Lines Toward SGA

- HN3C: $I_{J,F} = 1_{11,1} - 0_{10,1}$
- CH: $J = 2_{11,1} - 3_{00,1}$
- OCS: $J = 3_{22,2} - 4_{11,1}$
- CH3CN: $J = 4_{33,3} - 5_{22,2}$
- CN: $J = 5_{44,4} - 6_{33,3}$
- CO: $J = 6_{55,5} - 7_{44,4}$
5. SUMMARY

We performed unbiased spectral line surveys at 3 mm band toward the Galactic CND and Sgr A* using the NRO 45 m RT. The target positions were two tangential points of the CND and the direction of Sgr A* (NE, SW, and SGA). With these surveys, we obtained 3 wide-band spectra that cover the frequency range from 81.3 GHz to 115.8 GHz, detecting 46 molecular lines from 30 species including 10 rare isotopomers and 4 hydrogen recombination lines. The detected lines consist of multiple velocity components that arise from the CND, GMCs (+30 km s\(^{-1}\) and +20 km s\(^{-1}\) clouds), and the foreground spiral arms. Many of the line profiles toward SGA severely suffer from absorption features.

We defined the specific velocity ranges that represent the CND and the GMCs toward each direction. Based on the line intensities integrated over the defined velocity ranges, we classified the detected lines into three categories: the CND, HBD, and GMC types. The rotational lines of HCN, H\(^{13}\)CN, HCO\(^+\), H\(^{13}\)CO\(^+\), SiO, CN, and H\(^{13}\)CN, and hydrogen recombination lines...
are classified as CND-type. The detected lines include many diagnostic probes, i.e., opacity, density, temperature, XDR, and shock. We presented the lists of the line intensities and intensity ratios, which must be useful to investigate the difference between nuclear environments of our Galaxy and of others. Deep mapping observations in the CND-type lines with a single dish would reveal the accurate distribution and kinematics of molecular gas in the vicinity of our Galactic nucleus. We have already conducted such mapping observations with the NRO 45 m telescope. These results and detailed analyses will be presented in forthcoming papers.

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**Figure 9.** Correlation plot between $I_{SGA}^{GMC}/I_{SGA}^{total}$ and $I_{SGA}^{CND}/I_{SGA}^{total}$ for each lines. The red, blue, and green circles represent the CND-, HBD-, and GMC-type lines, respectively.

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

### Table 9
Line Intensity Ratios

| Ratio                  | GMC         | CND         |
|------------------------|-------------|-------------|
| CO/$^{13}$CO           | 8.94 ± 0.01 | 22.8 ± 0.3  |
| HCN/$^{13}$CN          | 8.9 ± 0.1   | 12.4 ± 0.2  |
| HCN/CO                 | 0.0872 ± 0.0002 | 0.430 ± 0.002 |
| HCN/$^{13}$CO          | 0.780 ± 0.002 | 9.8 ± 0.1   |
| $^{13}$CN/$^{13}$CO    | 0.087 ± 0.001 | 0.79 ± 0.02 |
| CS/CO                  | 0.0491 ± 0.0001 | 0.0975 ± 0.0007 |
| $^{13}$CS/$^{13}$CO    | 0.439 ± 0.001 | 2.22 ± 0.03 |
| HCN/HCN                | 0.341 ± 0.001 | 0.188 ± 0.001 |
| HCN/$^{13}$CN          | 3.04 ± 0.04  | 2.33 ± 0.04 |
| HCN/HCN                | 0.20 ± 0.01  | 0.05 ± 0.02 |
| HCN/HCO$^+$             | 1.74 ± 0.01  | 1.62 ± 0.01 |
| $^{13}$CN/H$^{13}$CO$^+$ | 3.9 ± 0.1   | 3.4 ± 0.1   |
| SiO/$^{13}$CN          | 0.48 ± 0.01  | 0.48 ± 0.02 |
| SiO/$^{13}$CO$^+$       | 1.84 ± 0.06  | 1.66 ± 0.07 |

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