A Complete Survey of the Central Molecular Zone in NH$_3$

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Abstract

We present a map of the major part of the central molecular zone (CMZ) of simultaneous observations in the NH$_3$ ($J, K$) = (1,1) and (2,2) lines using the Kagoshima 6-m telescope. The mapped area is $-1.000 \leq l \leq 1.625$, $-0.375 \leq b \leq +0.250$. The kinetic temperatures derived from the (2,2) to (1,1) intensity ratios are 20–80 K or exceed 80 K. The gases corresponding to temperature of 20–80 K and $\geq 80$ K contain 75% and 25% of the total NH$_3$ flux, respectively. These temperatures indicate that the dense molecular gas in the CMZ is dominated by gas that is warmer than the majority of the dust present there. A comparison with the CO survey by Sawada et al. (2001) shows that the NH$_3$ emitting region is surrounded by a high pressure region on the $l$–$v$ plane. Although NH$_3$ emission traces dense gas, it is not extended into a high pressure region. Therefore, the high pressure region is less dense and has to be hotter. This indicates that the molecular cloud complex in the Galactic center region has a “core” of dense and warm clouds which are traced by the NH$_3$ emission, and an “envelope” of less dense and hotter gas clouds. Besides heating by ambipolar diffusion, the hot plasma gas emitting the X-ray emission may heat the hot “envelope”.

Key words: Galaxy: center - Interstellar: molecules - Interstellar: ammonia

1. Introduction

Gas temperature is one of the basic parameters that control star formation activity. In the same volume, the interstellar medium is believed to be isothermal and the gas and dust temperatures should be the same. However, several surveys of the interstellar medium in the Galactic center region reveal different temperatures of gas and dust.

The dust temperature is measured in the submillimeter/infrared continuum. It is found to be as cold as 20 K in the 450 µm and 850 µm continuum by the Submillimetre Common-User Bolometer Array (Pierce-Price et al. 2000) or 15–22 K in the 45–175 µm continuum by the Infrared Space Observatory (Lis et al. 2001).

However, the molecular gas is warmer than the dust. In the millimeter line observations made using the IRAM 30-m telescope, the gas temperature is found to be as high as 60–70 K by multi-line analysis (Lis et al. 2001). A more direct estimation of the gas temperature is derived from NH$_3$ line observations. Morris et al. (1983) observed the NH$_3$ ($J, K$) = (1,1), (2,2), and (3,3) lines of the Galactic center region at $b = -2 \degree$ using the NRAO 11-m telescope. They concluded that the kinetic temperature is uniformly between 30 and 60 K. Hüttemeister et al. (1993a) observed the NH$_3$ ($J, K$) = (1,1), (2,2) and (4,4), (5,5) lines of selected clouds using the NRAO 43-m telescope and a few small maps using the Bonn 100-m telescope. They reported two temperature components of the gas; the first, derived from the intensity ratio of (2,2) to (1,1), was as low as 25 K, while the second, derived from the intensity ratio of (5,5) to (4,4), was as high as 200 K.

These NH$_3$ surveys suggest that the gas in the Galactic center would be a mixture of hot and cold gases. However, the previous surveys cover only limited regions, such as a single strip along the Galactic plane or only selected clouds. Therefore, a large-scale survey is required to comprehensively study the conditions of the entire molecular gas in the central molecular zone (CMZ).

We have observed the CMZ in the NH$_3$ lines to investigate the dense gas. We present the large-scale data of the Galactic center in the NH$_3$ ($J, K$) = (1,1) and (2,2) lines.
for the first time. In section 2, we describe the observations. The data are presented in section 3. In section 4, we discuss the physical conditions of the molecular gas in the CMZ through comparisons with previous observations. In this paper, we assume that the distance to the Galactic center is 8.5 kpc. For the direction and position in the sky, we use Galactic east as the positive Galactic longitude, and Galactic north as the positive Galactic latitude.

2. Observations

2.1. Data from the Kagoshima 6-m Telescope

We conducted a large-scale survey using the Kagoshima 6-m telescope of the National Astronomical Observatory of Japan (NAOJ) from September 2000 to April 2002. We made simultaneous observations in two inversion transitions of the NH$_3$ (J,K) = (1,1) and (2,2) lines at 23.694495 and 23.722633 GHz, respectively. At a wavelength of 1.3 cm, the telescope beamwidth is 9.5 and the main beam efficiency ($\eta_{mb}$) is 0.59. We used a K-band HEMT amplifier whose system noise temperature is 200–300 K and a 2048-channel TeO$_2$ crystal acoustic-optical spectrometer with a bandwidth of 250 MHz and frequency resolution of 250 kHz. At the NH$_3$ (1,1) and (2,2) frequencies, these correspond to 3200 km s$^{-1}$ velocity coverage and 3.2 km s$^{-1}$ velocity resolution. We obtained approximately 250 NH$_3$ (1,1) and (2,2) spectra at $-1^\circ \leq l \leq 1^\circ$, and $-0^\circ.375 \leq b \leq 0^\circ.250$ with a spacing of $0^\circ.125$. The surveyed area corresponds to 390 x 90 pc based on the distance to the Galactic center, 8.5 kpc. All data were obtained by position switching between the target positions and reference positions. The reference positions were obtained at the Galactic latitude $b \leq -1^\circ$, where neither NH$_3$ (1,1) nor (2,2) emission was detected. We integrated at least 30 min at each point. The relative pointing error is better than 1', which was verified by the observations of several H$_2$O (frequency 22.235080 GHz) maser sources.

Data reduction was performed using the UltraSTAR package developed by the radio astronomy group at the University of Tokyo (Nakajima et al. 2006, in preparation). To improve the signal to noise ratio, the obtained spectra are smoothed to a velocity resolution of 5 or 10 km s$^{-1}$. The rms noise level after 5 km s$^{-1}$ smoothing is typically 0.080 K in the unit of the main beam brightness temperature defined by $T_{mb} = T_A^* / \eta_{mb}$, where $T_A^*$ is the antenna temperature calibrated by the chopper wheel method (Kutner & Ulich 1981). In this paper, the intensities are presented in the main beam temperature.

2.2. Data from the Kashima 34-m Telescope

In order to confirm the “0'9 wing feature” (see section 3.6), we carried out a single point observation at $(l, b) = (0^\circ.7880, 0^\circ.000)$. This observation was made using the 1'6 beam of the Kashima 34-m telescope of the National Institute of Information and Communications Technology (NICT) on April 18, 2006. The single point spectra in the NH$_3$ (1,1) and (2,2) lines were obtained by the same method using the Kagoshima 6-m telescope survey.

3. Results

3.1. Profiles

Figure 1 shows the line profiles of NH$_3$ (1,1) and (2,2) at $(l, b) = (0^\circ.750, -0^\circ.125)$ near the giant molecular cloud Sgr B shown with a velocity resolution of 5 km s$^{-1}$. The line shapes of the two NH$_3$ transitions are very similar over a 150 km s$^{-1}$ range.

In quiescent clouds, the NH$_3$ line profile comprises five quadruple hyperfine components consisting of a main line and two symmetric pairs of satellite lines. The intensity ratio of the main line and the satellite lines provides the optical depth of each rotational level, and a unique rotational temperature is derived from the ratio of the optical depth at different rotational levels.

In the Galactic center region, molecular emission is extended in the sky and shows violent motion even in the comparatively small area covered by a single telescope beam. In fact, none of our data profiles show satellite lines above the noise level. Therefore, it is difficult to separate the five quadruple hyperfine components from the observed spectra with a large beam. However, we can derive the rotational and kinetic temperatures without the opacity estimation (see section 4.1).

3.2. Integrated Intensity Distribution

Figure 2 shows the integrated intensity maps of NH$_3$ (1,1) and (2,2). Our entire observed area almost covers the CMZ. The overall distribution is well traced in other molecular emission lines such as the CO (Sawada et al. 2001) and CS (Tsuboi et al. 1999) lines. The total integrated intensity in the entire observed area of NH$_3$ (1,1) and (2,2) is $\int T_{mb}(1,1)dv = 1580$ K km s$^{-1}$ and $\int T_{mb}(2,2)dv = 1330$ K km s$^{-1}$, respectively. These values correspond to $2.26 \times 10^5$ Jy km s$^{-1}$ and $1.90 \times 10^5$ Jy km s$^{-1}$ in flux units. The NH$_3$ emission is concentrated at $-0.500 \leq l \leq 1.625$ and its distribution is asymmetrical with respect to Sgr A* at $l = -0^\circ.06$. The intensity of the NH$_3$ line located at the Galactic eastern side of Sgr A* is 81% in the entire observed area, although it is 73% in the CS line derived from a map by Tsuboi et al. (1999). The NH$_3$ emissions are also extended along Galactic latitude. The total intensity at the observed positions on $b = 0^\circ$, effectively covering a strip of one beamwidth, is only 27% in the entire observed area. The overall distribution along Galactic latitude appears to be symmetric about $b = -0^\circ.05$, where Sgr A* is located. The full width at half maximum (FWHM) along Galactic latitude is $\Delta b = 0^\circ.2 - 0^\circ.3$, which is almost the same as CO; however, it is more confined at the 1'3 region and at $l = -0^\circ.125$.

The strongest NH$_3$ emission in our observations originates from the Sgr B cloud, which has a large number of H$\alpha$ regions. The second prominent feature is seen near Sgr A corresponding to the Sgr A clouds. Another NH$_3$ cloud at $l = 1^\circ.2$ is often called the 1'3 region. We summarize the integrated intensities for major regions in Table 1.
3.3. Prominent Clouds

We identify four NH$_3$ clouds which both (1,1) and (2,2) intensities exceed the 3 $\sigma$ level. All of them are identified to be the known molecular clouds seen in other molecular lines.

The two clouds that appear at ($l$, $b$, $v_{LSR}$) $\simeq$ ($-0.125$, $-0.125$, 10 km s$^{-1}$) and ($l$, $b$, $v_{LSR}$) $\simeq$ ($0.125$, $-0.125$, 55 km s$^{-1}$) are the “Sgr A 20 km s$^{-1}$ cloud” and “Sgr A 40 km s$^{-1}$ cloud”, respectively, which were identified by Güsten et al. (1981). A cloud appearing at ($l$, $b$, $v_{LSR}$) $\simeq$ ($0.750$, $-0.125$, 40 km s$^{-1}$) is associated with the Sgr B1 and Sgr B2 HII regions. Sgr B2 is one of the most massive star forming regions in our Galaxy. A cloud appeared at ($l$, $b$, $v_{LSR}$) $\simeq$ ($1.25$, $-0.125$, 80 km s$^{-1}$) is the 1.3 region cloud. It is the weakest among the four identified clouds. Although the 1.3 region has a large latitudinal scale height ($\Delta b \gtrsim 0.3\degree$) in the CO emission (Oka et al. 1996), the NH$_3$ emitting area is as small as $\Delta b = 0.2\degree$. The NH$_3$ emission is more confined than the CO emission in the 1.3 region. These four identified clouds in the $l$-$v$ space are shown in Figure 3.

3.4. “0.9 Wing Feature”: A High Velocity Wing at $l = 0.9\degree$

In the $l$-$v$ diagrams at $b = -0.125$ and $0.000$, a prominent blueshifted wing is seen near $l = 0.9\degree$. This is shown in Figure 3 and 4. This wing is extended even with the 9.5 beam. We detected this wing feature at $0.750 \leq l \leq 0.875$ and $-0.125 \leq b \leq 0.000$. The wing at $l = 0.750$ extends from $v_{LSR} = 0$ km s$^{-1}$ to $-30$ km s$^{-1}$. It is blueshifted from the main spectral feature by 80 km s$^{-1}$. This blueshifted wing is also seen in previous observations of both the NH$_3$ (Morris et al. 1983) and CS (Tsuboi et al. 1999) emission, although no one mentioned about this feature. The wing is associated with the double peak profiles ($v_{LSR} = 20$ and 80 km s$^{-1}$) at ($l$, $b$) = ($0.875$, $0.000$), ($0.875$, $-0.125$). Although the 80 km s$^{-1}$ component is the main ridge through the entire Galactic center region linked with $l > 1\degree$, the 20 km s$^{-1}$ component is seen only at these four positions. The FWHM of the 20 km s$^{-1}$ component is larger than 50 km s$^{-1}$. The blueshifted wing of the 20 km s$^{-1}$ component is conspicuous in the $l$-$v$ diagram at $b = 0.000$, whereas that in the $l$-$v$ diagram at $b = -0.125$ is blended with the intense emission from Sgr B cloud. However, the 20 km s$^{-1}$ component of ($l$, $b$) = ($0.875$, $-0.125$) is stronger than that of ($l$, $b$) = ($0.875$, $0.000$).

We made higher resolution observations at ($l$, $b$) = ($0.880$, $0.000$) using the Kashima 34-m telescope. Figure 5 shows the spectra obtained in the (1,1) and (2,2) lines. From these observations, the blueshifted wing and the 20 km s$^{-1}$ component are confirmed in both the (1,1) and (2,2) lines.

4. Discussion

4.1. Gas Temperature of the CMZ

The intensity ratio of the (2,2) line to (1,1) line, $R_{(2,2)/(1,1)}$, is controlled by the kinetic temperature and optical depth of NH$_3$ gas. Previous estimations of the optical depth of NH$_3$ are $\tau \sim 3$–10 for the Sgr A 20 km s$^{-1}$ cloud (Güsten et al. 1981), $\tau \sim 4$ in the stronger NH$_3$ emitting sources, and $\tau \sim 2.3 \pm 1.0$ in the weaker sources (Hüttemeister et al. 1993a). Because the flux of our observations originates from weaker and more extended sources than the previous observations, the optical depth may be significantly smaller than these results.

The CS line can also trace dense gas. In the Galactic center region, the CS line emission has moderate optical depth, $\tau \leq 2$–3. The total molecular mass in the CMZ is $M$(H$_2$) = (3–8) $\times$ 10$^7$$M_\odot$ (Tsuboi et al. 1999). Dahmen et al. (1998) estimate that the large scale $^{12}$CO ($J = 2–1$) emission in the CMZ is of moderate ($\tau \gtrsim 1$) or low optical depth ($\tau < 1$) and the total molecular mass in the CMZ is $M$(H$_2$) = (2–5) $\times$ 10$^7$$M_\odot$. The total fluxes in the NH$_3$ ($1,1$) and (2,2) lines are $\int Sdv = 2.26 \times 10^5$ and 1.90 $\times$ 10$^5$ Jy km s$^{-1}$, respectively. In the case where the NH$_3$ emission is optically thin, the total mass of the molecular gas in the whole region is $M_{\text{mol}} = 1 \times 10^8$$M_\odot$ based on $X$(NH$_3$) = 10$^{-9}$ (Hüttemeister et al. 1993a). The total masses derived from NH$_3$, CS, and CO are consistent. This suggests that the NH$_3$ line should have moderate optical depth or low optical depth.

Therefore, we estimate the rotational temperature $T_{\text{rot}}$ from $R_{(2,2)/(1,1)}$ in the optically thin ($\tau \ll 1$) and optically thick ($\tau \sim 10$) cases using the method of Morris et al. (1983). The conversion from $T_{\text{rot}}$ to $T_k$ is performed according to Hüttemeister et al. (1993a). It shows that $T_k$ is always higher than $T_{\text{rot}}$. When $T_{\text{rot}}$ is less than 20 K, it is very close to $T_k$, and when $T_{\text{rot}}$ is 40 K, $T_k$ is 80 K, which is almost two times higher than $T_{\text{rot}}$ (see Table 2).

Before we calculate the temperature, we examine the $R_{(2,2)/(1,1)}$ statistics. Figure 6 shows a histogram of $R_{(2,2)/(1,1)}$ for pixels in the entire observed area at which an NH$_3$ (1,1) line was detected over a 1.5 $\sigma$ level after smoothing to 10 km s$^{-1}$. The $R_{(2,2)/(1,1)}$ is within a range from 0.5 to 1.8 in our data.

Previous observations indicate the discrepancies in the gas and dust temperatures in the Galactic center. The gas temperature is always higher than the dust temperature. The hot gas temperature is approximately 100 K and the cold dust temperature is approximately 20 K. For the obtained value of $R_{(2,2)/(1,1)}$, we divide the ratios into three regimes ($R_{(2,2)/(1,1)} = 0.5$–0.6, $R_{(2,2)/(1,1)} = 0.7$–0.8, and $R_{(2,2)/(1,1)} > 0.9$) which correspond to gas temperatures ranging from that of cold dust (20 K) to hot gas (exceeding 100 K).

$R_{(2,2)/(1,1)} = 0.5$–0.6 corresponds to $T_{\text{rot}} \approx 20$–30 K and $T_k \approx 20$–40 K. The NH$_3$ flux with $R_{(2,2)/(1,1)} = 0.5$–0.6 is approximately 25% of the total NH$_3$ flux. The low value of $T_{\text{rot}}$ and $T_k$ is close to the dust temperatures given by Pierce-Price et al. (2000) and Lis et al. (2001). This low $R_{(2,2)/(1,1)}$ gas is as cool as the cold dust.
The gas with \( R_{(2,2)/(1,1)} = 0.7 \sim 0.8 \), which corresponds to \( T_{\text{rot}} \sim 30 \sim 40 \) K and \( T_k \sim 40 \sim 80 \) K, is warmer than the cold dust. The NH\(_3\) flux of this warm gas is approximately 50% of the total NH\(_3\) flux. \( R_{(2,2)/(1,1)} \) of this dominant gas component is consistent with the ratios found by Morris et al. (1983).

The histogram also shows a small number of high ratio \( (R_{(2,2)/(1,1)} > 0.9) \) pixels. The NH\(_3\) flux with this high \( R_{(2,2)/(1,1)} \) is approximately 25% of the total NH\(_3\) flux. These high \( R_{(2,2)/(1,1)} \) pixels appear at the edge of the NH\(_3\) emitting region on the \( l-v \) plane (see Figure 7). In fact, when we compare the obtained (1,1) and (2,2) profiles, \( R_{(2,2)/(1,1)} \) sometimes appears to increase in both the line edges. Figure 8 shows the spectra of NH\(_3\) (1,1) and (2,2) at \((l, b) = (0.125, -0.125)\) and \((l, b) = (0.625, 0.000)\) with a velocity resolution of 5 \( \text{km s}^{-1} \). These spectra show the higher (2,2)/(1,1) ratio at the edges of the profiles, because the line width of (2,2) has extended more than that of (1,1).

Before considering this ratio enhancement due to gas property, we should check effects of the satellite lines. The satellite lines of (2,2) that have a wider frequency spacing than those of (1,1). The separations of satellite lines in the (2,2) transition are \( +26.02, +16.38, -16.38, \) and \(-26.03 \) \( \text{km s}^{-1} \). Those in the (1,1) transition are \( +19.85, +7.46, -7.38, \) and \(-19.56 \) \( \text{km s}^{-1} \). This means that the broadening due to the satellites in the (2,2) transition might be more sufficient than that in the (1,1) transition. To evaluate this effect, we examine it with the cases of some optical depths. A typical NH\(_3\) line exhibits a Gaussian shape profile with a 60 \( \text{km s}^{-1} \) width and the typical ratio of the NH\(_3\) (2,2) line to the (1,1) line is 0.75. In the case of moderate and low optical depth \( (\tau < 1) \), the satellite lines of (2,2) are much weaker than the main line and could not affect the observed line width of (2,2). In the case of the high optical depth \( (\tau > 30) \), the satellite lines affect the observed line width. The wider separation in the (2,2) line results in greater broadening than that in the case of the (1,1) line, which gives ratio enhancement at the line edge. Thus, in this case, the higher ratio at the line edges were not real. However, the NH\(_3\) emission in the CMZ is not high optically thick \( (\tau \ll 30) \). Therefore, the higher ratio at the line edges means that the gas near the velocity edge is hotter than bulk of the cloud.

The cold gas, which is as cool as the cold dust, constitutes approximately 25% of the dense molecular gas based on the NH\(_3\) emission. Our complete survey of the CMZ shows that the dense molecular gas in the CMZ is dominated by gas that is warmer than the majority of dust present there.

### 4.2. Comparison with Pressure Distribution

Although we cannot estimate the molecular gas temperature in regions where no NH\(_3\) emission is detected, we can make rough evaluations using other spectral lines. Using the intensity ratios of \( ^{12}\text{CO} \) \((J = 2 \sim 1)\) over \( ^{12}\text{CO} \) \((J = 1 \sim 0)\), \( R_{^{12}\text{CO}(2 \sim 1)/(1 \sim 0)} \), and of \( ^{13}\text{CO} \) \((J = 2 \sim 1)\) over \( ^{12}\text{CO} \) \((J = 2 \sim 1)\), Sawada et al. (2001) derived the gas pressure of molecular clouds in the Galactic center region.

Our NH\(_3\) observations are made with the same beam-size and the same sampling grid as that in the observations in \( ^{12}\text{CO} \) \((J = 1 \sim 0)\) using the CfA 1.2-m telescope (Bitran et al. 1997) and \( ^{12}\text{CO} \) \((J = 2 \sim 1)\) using the Tokyo-Usukara-ESO-Calán 60-cm telescope (Sawada et al. 2001). Therefore, we can make direct comparisons with the \( R_{^{12}\text{CO}(2 \sim 1)/(1 \sim 0)} \) distribution.

Figure 9 shows an NH\(_3\) (1,1) \( l-v \) diagram superimposed on the \( R_{^{12}\text{CO}(2 \sim 1)/(1 \sim 0)} \) \( l-v \) diagram by Sawada et al. (2001). In the CO lines, the absorption caused by the foreground arms has an effect at \( v_{\text{LSR}} \sim -50, -30, 0 \) \( \text{km s}^{-1} \). This absorption effect is not seen in NH\(_3\) line. When comparing the distributions of the NH\(_3\) emission and \( R_{^{12}\text{CO}(2 \sim 1)/(1 \sim 0)} \) on the \( l-v \) plane at \( b = -0.125 \) and \( 0.000 \), the NH\(_3\) emitting region is surrounded by the high \( R_{^{12}\text{CO}(2 \sim 1)/(1 \sim 0)} \) region. In the Sgr B molecular cloud complex with its intense NH\(_3\) emission, \( R_{^{12}\text{CO}(2 \sim 1)/(1 \sim 0)} \) is not very high.

For \( b = 0.000 \), Sawada et al. (2001) provide the gas pressure distribution using the large velocity gradient (LVG) approximation (Goldreich & Kwan 1974). For \( n(\text{H}_2) = 10^4 \text{ cm}^{-3} \), which is the NH\(_3\) critical density (Morris et al. 1983; Ho & Townes 1983), we can also obtain the distribution of kinetic temperature from their LVG approximation (see Figure 9 (c)). This provides an upper limit for the temperature in the region emitting NH\(_3\), and a lower limit for the region without NH\(_3\) emission.

For \( b = -0.125 \), we cannot obtain the \( T_k \) limit because Sawada et al. (2001) derive \( n(\text{H}_2) T_k \) only for \( b = 0.000 \). However, using the \( b = 0.000 \) data, we find a correlation between \( n(\text{H}_2) T_k \) and \( R_{^{12}\text{CO}(2 \sim 1)/(1 \sim 0)} \), as shown in Figure 10. The correlation is summarized as follows: \( n(\text{H}_2) T_k \) increases with \( R_{^{12}\text{CO}(2 \sim 1)/(1 \sim 0)} \) and \( n(\text{H}_2) T_k = 4 \times 10^4 \) K \( \text{cm}^{-3} \) when \( R_{^{12}\text{CO}(2 \sim 1)/(1 \sim 0)} = 1.0 \). This implies that the high \( R_{^{12}\text{CO}(2 \sim 1)/(1 \sim 0)} \) value indicates a high pressure region that can in principle be dense or hot.

Although NH\(_3\) emission can trace dense gas, it does not extend into the high pressure region, at least at high intensities. Therefore, the high pressure region is less dense and hotter. In the Galactic center, the molecular cloud complex has “cores” of dense and warm clouds which are traced in the NH\(_3\) emission, and an “envelope” of less dense and hotter gas clouds. For the cores, the pressure is found to be \( n(\text{H}_2) T_k \sim 5 \sim 10 \times 10^4 \) K \( \text{cm}^{-3} \) from the LVG approximation and the kinetic temperature is \( T_k \sim 20 \sim 100 \) K based on our NH\(_3\) ratio. In the case where the molecular gas in a beam is in pressure equilibrium, the density is \( n(\text{H}_2) \gtrsim 10^3 \text{ cm}^{-3} \). For the envelope, the pressure is found to be \( n(\text{H}_2) T_k \gtrsim 10^5 \text{ K cm}^{-3} \) from the LVG approximation. The density \( n(\text{H}_2) \) should be less than \( 10^3 \text{ cm}^{-3} \) in the envelope because of the absence of NH\(_3\) emission there. This reveals that the kinetic temperature of the envelope is at least 100 K.

### 4.3. Origin of the High Pressure Region

In the previous section, we showed that the large scale structure of the molecular cloud complex in the CMZ exhibits a dense core surrounded by a hot envelope. What is the heating source of the envelope? There are four possibilities.
The first is radiation from massive stars. For $l < 0\degree.35$, the H II regions traced by the H109α line (Pauls & Mezger 1975) appear in the high pressure region (see Figure 11 (a)). This suggests that the high pressure region is heated by intense radiation from the massive OB stars.

This model appears to be invalid for $l > 0\degree.35$, because the H II regions appear in the core of the Sgr B cloud that exhibits intense NH$_3$ emission. Therefore, a hot gas heated by intense radiation should be present there. However, we believe this feature is due to a dilution effect.

The hot gas must be compact and surrounded by a large amount of cold gas. In this case, the derived gas temperature with our 9′ beam should be low. In fact, hot and compact gas regions in Sgr B are detected by high resolution observations. Hüttemeister et al. (1993b) obtained two emission cores of 4″ at $v_{\text{LSR}} = 65$ km s$^{-1}$ with $T_k = 150–300$ K in Sgr B2. They also found the 85 km s$^{-1}$ component with $T_k = 160$ K in Sgr B2(N). Actually, the 85 km s$^{-1}$ component, which is as large as 120″, is detected in the high pressure region.

There is further evidence of star formation during a short period in the high pressure region. In the high pressure region, 134 OH/IR stars observed using VLA (Lindqvist et al. 1991) are located (see Figure 11 (b)). This suggests that star formation was active during a short period in the high pressure region. These stars should heat the gas by radiation during this period. Although intense radiation from the OB stars heats the molecular gas, late OH/IR stars are also sufficient to heat the dust and gas. However, the dust is known to be cool. Photons with energy below 13.6 eV, which cannot ionize the hydrogen, can heat warm gas, thereby transforming it to hot gas. Using the blackbody spectra and the 13.6 eV cutoff, we can estimate the equivalent number of OH/IR stars required for an OB star to heat up the molecular gas. The typical temperatures of an OH/IR star and an OB star are 3000 K and 30000 K, respectively. The typical absolute magnitude of an OB star is $M_V = -6$. For an OH/IR star, the typical absolute magnitude is $M_V = -4$ and $M_V = -6$ in the case of a supergiant. Using these values, we find that approximately 10 OH/IR stars or 1 OH/IR supergiant is equivalent to an OB star. This implies that OH/IR and OB stars are comparable heating sources. The distribution of OH/IR stars on the $l$–$v$ plane suggests that they heat the molecular gas in the high pressure region.

However, stellar radiation may not be a major heating mechanism for the CMZ gas. The stellar radiation heats the molecular gas through dust heating. In that case, the dust temperature should be higher than the gas temperature. However, our observations indicate that the major portion of the molecular gas is warmer than the dust. Heating by extremely hot plasma gas emitting X-ray is the second possibility. X-ray emission and radio continuum are intense for $l < 0\degree.35$ (Wang et al. 2002; Handa et al. 1987). This is consistent with the high pressure region, which is conspicuous for $l < 0\degree.35$.

The cooling luminosity of clouds in the CMZ exceeds the X-ray luminosity by a factor of 40–400 (Morris et al. 1983). Therefore, it seems that the gas cannot be heated by X-ray emission itself. However, the distribution of the hot plasma gas emitting X-ray is well coincident with the high pressure region. The total mass of the hot molecular gas in the high pressure region is $2 \times 10^6 M_\odot$ from the CO line intensity with the conversion factor $X = 2 \times 10^{19}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$ (Dahmen et al. 1998). The total thermal energy required to heat the warm gas (30 K) to the hot gas (100 K) is $3 \times 10^{49}$ erg. Conversely, in X-rays, the total thermal energy radiated from the hot plasma gas with a temperature of $10^8$ K is $(4–8) \times 10^{53}$ erg (Yamauchi et al. 1990). This value is $10^4$ times larger than the energy required to heat the warm gas to hot gas. Therefore, the hot plasma gas emitting X-ray can heat the hot gas in the high pressure region with any insufficient processes.

The third is the shock heating through cloud-cloud collisions. This mechanism is suggested by Güsten et al. (1985) and Hüttemeister et al. (1993a). In the case of the cloud-cloud collisions, the gas temperature increases with the density and the line width (Güsten et al. 1985). However, our result shows the high pressure region is less dense than the NH$_3$ emitting region. Hüttemeister et al. (1993a) reported that there is no good correlation between the temperature and the line width. These results suggest that the cloud-cloud collisions heating is not strongly supported. However, the energy of the turbulent motions in the clouds within 300 pc of the center is larger than the thermal energy required to heat to the hot gas, $10^{49}$ erg. The energy of the turbulent motions is $10^{53}$ erg (Güsten et al. 1985). The heating through cloud-cloud collisions cannot be ruled out by our data.

The last is the heating of the ambipolar diffusion. Hüttemeister et al. (1993a) suggests that the gas can bring to $\sim 200$ K, if the ionization fraction is of order $10^{-8}$ and the magnetic field strength is 500 $\mu$G.

4.4. Star Formation in the Galactic Center

In the CMZ, the distribution of H II regions extends more toward the Galactic eastern side than the OH/IR stars. This distribution difference suggests that star formation activity moves from the Galactic west to Galactic east. Stars become OH/IR stars 10$^8$ years after their formation (Oka et al. 1996). The distribution shows that in the high pressure region, star formation was active 10$^8$ years ago. The lifetime of an H II region is 10$^5$ years and OB stars are younger than 10$^6$ years. Therefore, the timescale of the transition of star formation is 10$^8$ years.

4.5. Physical Conditions of the Molecular Clouds

For the four major clouds, we estimate the average intensity ratio of the NH$_3$ (2,2) to (1,1) lines using a correlation plot between these two lines. The estimated ratio and the derived rotational and kinetic temperatures are shown in Figure 12 and Table 3. In order to reduce the noise fluctuation, we only use those pixels where the (1,1) and (2,2) intensities exceed the 3 $\sigma$ level. All the four clouds show almost the same ratio of approximately 0.75. The rotational temperature corresponding to the observed ratio of 0.7–0.8 is 36–42 K in the optically thin case and 24–34 K in the optically thick case. This implies that the
kinetic temperatures of these Galactic center clouds are higher than those of the Galactic disk clouds. The temperature of 40 massive protostar candidates is 15–20 K (Sridharan et al. 2002) and that of quiescent cores near the Ori GMC is 14–19 K (Li et al. 2003). Table 4 lists the physical parameters of each of the four clouds estimated under the optically thin ($\tau \ll 1$) assumption. The sizes of four clouds are determined from the FWHM of the contour in the $l$-$v$ diagram (see Figure 3). The estimated column densities for the two metastable levels from the integrated line intensities are $N(1,1)=(2.5–11) \times 10^{14}$ cm$^{-2}$ and $N(2,2)=(1.2–5.5) \times 10^{14}$ cm$^{-2}$. Using the abundance ratio of X (NH$_3$) = 10$^{-9}$ (Hüttemeister et al. 1993a) and spherically symmetric geometry, the H$_2$ number density is $n$(H$_2$) $\sim 10^3–10^4$ cm$^{-3}$. The luminosity mass, which is estimated from the integration of the column densities, is $M_{\text{lum}}=(2.7–23) \times 10^6 M_\odot$. Using the method of McGary & Ho (2002), the estimated intrinsic line width is approximately 5–10 km s$^{-1}$ smaller than the observed line width in the observed line width range. Using the derived intrinsic line width, the virial mass is estimated to be $M_{\text{vir}}=(2.8–30) \times 10^6 M_\odot$. Among these four clouds, the Sgr B molecular cloud complex is the densest and most massive.

The luminosity mass and the virial mass are consistent in the order of magnitude. This suggests that the optically thin assumption is appropriate for these clouds.

4.6. Origin of the 0$^9$9 Wing Feature

At $l = 0^99$ we find a unique feature (see section 3.6). A blueshifted wing as wide as 50 km s$^{-1}$ is observed. The estimated ratio $R_{(2,2)/(1,1)}$ of the 20 km s$^{-1}$ component, which comprises the 0$^9$9 wing feature, is 0.89±0.12 (see Table 5). To derive $R_{(2,2)/(1,1)}$, the components near $l = 0^99$ are integrated. The integrated velocity ranges of the 20 km s$^{-1}$ and 80 km s$^{-1}$ components are $-30 < v_{\text{LSR}} < 50$ km s$^{-1}$ and $50 < v_{\text{LSR}} < 120$ km s$^{-1}$, respectively. The estimated ratio is higher than the ratios of other components: 0.69±0.08 for the 80 km s$^{-1}$ component and 0.7–0.8 for the four identified clouds shown in section 4.5. The rotational temperature corresponding to $R_{(2,2)/(1,1)} = 0.89\pm0.12$ is 45±6 K in the optically thin case and 42$^{+17}_{-13}$ K in the optically thick case.

This high ratio is also seen in previous observations. This ratio is consistent with the value shown in Fig. 4 of Morris et al. (1983), who, however did not mention this high ratio feature. A part of the 0$^99$ wing feature is identified as M+0.83−0.10 by Hüttemeister et al. (1993a). The $R_{(2,2)/(1,1)}$ for M+0.83−0.10 has a higher value, $R_{(2,2)/(1,1)} = 1.1$. The size of this feature is estimated to be approximately one beamsize 9.5′ $= 24$ pc because evidence of the feature is seen in two profiles spaced 0′′.125 = 18 pc apart. The mass $M_{\text{lum}} = 1.8 \times 10^6 M_\odot$ is derived from the column density, $N(\text{NH}_3) = 4.2 \times 10^{14}$ cm$^{-2}$, by assuming the abundance ratio, X (NH$_3$) = 10$^{-9}$, and optically thin emission. The velocity offset from the 20 km s$^{-1}$ component is $\Delta v = 50$ km s$^{-1}$. The kinetic energy is $10^{52}$ erg in the case where the 20 km s$^{-1}$ component is ejected from the 80 km s$^{-1}$ component.

What is the origin of this feature? There are two possibilities.

The morphology in the $l$-$v$ diagram and profiles suggest that the 0$^99$ wing feature may be ejected from the Sgr B cloud. It should have been ejected by star formation activity and/or supernova (SN) explosions. The higher gas temperature supports this idea. However, the kinetic energy of the component requires $10^3$ SN explosions. Therefore, we do not favor the explosion approach to explain the origin. In the case of an explosive origin, a tracer of lower density gas should exhibit a wider wing there. However, we cannot confirm this feature, because the wing is overlapped by foreground gas in the spiral arms.

The other possibility is gas infall from the off-plane. There are several models that suggest the exchange of gas between the disk and halo. Some of them show that infalling gas is accumulated by the Galactic magnetic field (Matsumoto & Shibata 1992). The 0$^99$ wing feature may be a compact and in-plane version of the molecular spur found in NGC 891 (Handa et al. 1992).

In the NRO CS survey, several high velocity wing features like the 0$^99$ wing feature at other positions were observed (Tsuboi et al. 1999). None of them, except the 0$^99$ wing feature, exhibit any wings in our survey. However, most of them may exhibit a similar wing feature in high resolution observations of NH$_3$.

5. Conclusions

We have presented a map of the major part of the CMZ by simultaneous observations in NH$_3$ (J, K) = (1, 1) and (2, 2) lines with the Kagoshima 6-m telescope. Given below are our observations and conclusions:

1. From the $l$-$b$-$v$ data cube, we identified and investigated four clouds, which correspond to Sgr A 20 km s$^{-1}$ cloud, Sgr A 40 km s$^{-1}$ cloud, Sgr B molecular cloud complex, and the 13 region.

2. We found a unique “0$^99$ wing feature” which is a prominent high velocity wing. $R_{(2,2)/(1,1)}$ has a slightly higher value of 0.89±0.12. In an ejection scenario, the kinetic energy is estimated to be $10^{52}$ erg, which requires $10^3$ SN explosions. The other possibility of its origin is infall from off-plane.

3. The kinetic temperatures derived from the (2,2) to (1,1) intensity ratios are 20–80 K or exceed 80 K. The gases corresponding to temperature of 20–80 K and $\geq 80$ K contain 75% and 25% of the total NH$_3$ flux, respectively. Our complete survey of the CMZ showed that the dense molecular gas in the CMZ is dominated by gas that is warmer than the majority of dust present in that region.

4. A comparison with the CO survey by Sawada et al. (2001) showed the molecular cloud complex in the Galactic center has a core of dense and warm clouds, and an envelope of less dense and hotter gas clouds. The heating mechanisms of the hot envelope
are still in mystery, we propose heating by the thermal energy of the hot plasma gas observed in X-ray emission, besides by ambipolar diffusion.

5. H II regions are distributed over the Galactic east side to a greater extent than OH/IR stars. This distribution difference shows the transition of star formation from the Galactic west to Galactic east.

6. We present the physical conditions of the four clouds estimated under the optically thin assumption. All the clouds have an almost similar $R(2,2)/(1,1)$ value of approximately 0.75. The kinetic temperatures of these Galactic center clouds are higher than those of the Galactic disk clouds.

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References

Bitran, M., Alvarez, H., Bronfman, L., May, J., & Thaddeus, P. 1997, A&AS, 125, 99
Dahmen, G., Huttemeister, S., Wilson, T. L., & Mauersberger, R. 1998, A&A, 331, 959
Goldreich, P., & Kwan, J. 1974, ApJ, 189, 441
Güsten, R., Walmsley, C. M., & Pauls, T. 1981, A&A, 103, 197
Güsten, R., Walmsley, C. M., Ungerechts, H., & Churchwell, E. 1985, A&A, 142, 381
Handa, T., Sofue, Y., Nakai, N., Hirabayashi, H., & Inoue, M. 1987, PASJ, 39, 709
Handa, T., Sofue, Y., Ikeuchi, S., Kawabe, R., & Ishizuki, S. 1992, PASJ, 44, 227
Ho, P. T. P., & Townes, C. H. 1983, AR&A, 21, 239
Hunter, S. D., et al. 1997, ApJ, 481, 205
Hüttemeister, S., Wilson, T. L., Bania, T. M., & Martin-Pintado, J. 1993, A&A, 280, 255
Hüttemeister, S., Wilson, T. L., Henkel, C., & Mauersberger, R. 1993, A&A, 276, 445
Kutner, M. L., & Ulich, B. L. 1981, ApJ, 250, 341
Li, D., Goldsmith, P. F., & Menten, K. 2003, ApJ, 587, 262
Lindqvist, M., Winnew, A., Habing, H. J., & Matthews, H. E. 1992, A&AS, 92, 43
Lis, D. C., Scabry, E., Zylka, R., & Li, Y. 2001, ApJ, 550, 761
Matsumoto, R., & Shibata, K. 1992, PASJ, 44, 167
McGary, R. S., & Ho, P. T. P. 2002, ApJ, 577, 757
Morris, M., Polish, N., Zuckerman, B., & Kaifu, N. 1983, AJ, 88, 1228
Nakajima et al., 2006, in preparation

Oka, T., Hasegawa, T., Hayashi, M., Handa, T., & Sakamoto, S. 1996, ApJ, 460, 334
Oka, T., Hasegawa, T., Hayashi, M., Handa, T., & Sakamoto, S. 1998, ApJ, 493, 730
Pauls, T., & Mezger, P. G. 1975, A&A, 44, 259
Pierce-Price, D., et al. 2000, ApJ, 545, 121
Rodríguez-Fernández, N. J., et al. 2001, A&A, 365, 174
Rodríguez-Fernández, N. J., Martin-Pintado, J., Fuente, A., & Wilson, T. L. 2004, A&A, 427, 217
Sawada, T., et al. 2001, ApJS, 136, 189
Strong, A. W., et al. 1988, A&A, 207, 1
Sridharan, T. K., Beuther, H., Schilke, P., Menten, K. M., & Wyrowski, F. 2002, ApJ, 566, 931
Tsujii, M., Handa, T., & Ukita, N. 1999, ApJS, 120, 1
Wang, Q. D., Gotthelf, E. V., & Lang, C. C. 2002, Nature, 415, 148
Yamauchi, S., Kawada, M., Koyama, K., Kumieda, H., & Tawara, Y. 1990, ApJ, 365, 532