A Large-scale CO $J=3–2$ Survey of the Galactic Center

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Abstract. We have surveyed the central molecular zone (CMZ) of our Galaxy in the CO $J=3–2$ line with the Atacama Submillimeter-wave Telescope Experiment (ASTE). Molecular gas in the Galactic center shows high $J=3–2/J=1–0$ intensity ratio ($\sim 0.9$) while gas in the Galactic disk shows the lower ratio ($\sim 0.5$). The high-velocity compact cloud CO 0.02–0.02 and the hyperenergetic shell CO 1.27+0.01, as well as gas in the Sgr A region exhibit high $J=3–2/J=1–0$ intensity ratio exceeding 1.5. We also found a number of small spots of high ratio gas. Some of these high ratio spots have large velocity widths and some seem to associate with nonthermal ‘threads’ or filaments. These could be spots of hot molecular gas shocked by unidentified supernovae which may be abundant in the CMZ.

1. Introduction
The ‘Central Molecular Zone’ (CMZ) of the Galaxy, a region of radius $\sim 200$ pc, contains large amount of dense molecular gas ($n \geq 10^4$ cm$^{-3}$; e.g., [1]) and exhibits uniformly high gas temperature ($T_k = 30–60$ K; [2]). Molecular gas in the CMZ shows highly complex distribution and kinematics which are characterized by expanding arcs/shells and filaments [3]. A population of high-velocity compact clouds (HVCCs) is also unique in the CMZ [3,4,5].

Large amount of hot plasma [6] and widespread distribution of radioactive nuclei there [7] may suggest that a number of supernova explosion have occurred in the CMZ in the recent past. The widespread SiO emission could be understood as a result of shocks such as fossil superbubbles [8,9]. These suggest that the boisterous molecular gas kinematics in the CMZ may be a result of violent release of kinetic energy by a number of supernova explosions.

To assess the effect of supernova explosions on the kinematics and physical conditions of the CMZ, it is crucial to pick up supernova/molecular cloud interacting zone completely. For this objective, we are performing a large-scale, high resolution CO $J=3–2$ survey of the CMZ. Here we report results of the survey in 2005 and their implications.

2. Observations
The CO $J=3–2$ (345.79599 GHz) mapping observations were carried out with the Japanese 10 m submillimeter-wave telescope at Pampa la Bola, Chile (ASTE; [10]). The telescope has a FWHM beam size of $22''$ at 345 GHz. The observations were done 2005 July 19–25 in good, stable...
Figure 1. (a) The velocity-integrated intensity map of CO J=3–2 emission. (b) The same map as (a) for data with $R_{3–2/1–0} \geq 1.5$. Data severely contaminated by the foreground disk gas have been excluded. (c) Longitude-velocity map of CO J=3–2 emission integrated over the observed latitudes (contours), superposed on the same map for data with $R_{3–2/1–0} \geq 1.5$ (grays).

weather conditions. All spectra were obtained with an XF-type autocorrelation spectrometer in the 512 MHz bandwidth (1024 channel) mode. We mapped a $\Delta l \times \Delta b = 2^\circ \times 0.5^\circ$ area with a 34$''$ grid spacing, collecting 6990 spectra in total. The on-source integration time was 10 seconds for each position and rms noise was 0.3 K in $T_A^*$. The complete description of the data acquisition
and reduction procedure will be presented in the forthcoming paper [11].

3. Results
A map of CO $J=3–2$ emission integrated over velocities between $V_{LSR} = -200$ km s$^{-1}$ and +200 km s$^{-1}$ is presented in Fig.1a. CO $J=3–2$ emission extends over the current spatial coverage of the ASTE survey. Its distribution closely follows characteristics of the CMZ delineated by the CO $J=1–0$ surveys (e.g., [3]). Four major cloud complexes are seen also in the CO $J=3–2$ map, from left to right, the $l = 1.3^\circ$ complex, the Sgr B complex near $l = 0.7^\circ$, the Sgr A complex near $l = 0.0^\circ$, and the Sgr C complex near $l = 0.5^\circ$. At the center of the $l = 1.3^\circ$ complex, we see a clear hole of emission, which is the hyperenergetic shell CO 1.27+0.01 [5]

4. CO $J=3–2/J=1–0$ Intensity Ratio
We took the CO $J=3–2/J=1–0$ intensity ratio to extract highly excited gas from the CMZ, since the ratio is sensitive to the temperature and density of molecular gas. Fig.2 shows a frequency distribution of CO $J=3–2/J=1–0$ intensity ratio ($R_{3–2/1–0}$) weighted by CO $J=1–0$ intensity. The $R_{3–2/1–0}$ distribution has a prominent peak at 0.85 which is the typical value in the CMZ, and a shoulder at $\sim 0.5$ which is mostly attributable to the foreground spiral arms. The ratio close to unity indicates that the bulk of molecular gas in the CMZ is thermalized and moderately opaque.

Generally, $R_{3–2/1–0}$ can be a measure of temperature and density. High ratios are found in UV-irradiated cloud surfaces near early-type stars and shocked molecular gas adjacent to supernova remnants. We tried to extract highly excited gas from the CO data sets by $R_{3–2/1–0} \geq 1.5$. One-zone LVG calculations say that $R_{3–2/1–0} \geq 1.5$ corresponds to $n(H_2) \geq 10^{3.6}$ cm$^{-3}$ and $T_K \geq 48$ K when $N_{CO}/dV = 10^{17}$ cm$^{-2}$ (km s$^{-1}$)$^{-1}$. The spatial distribution of high ratio gas in the CMZ (Fig.2b,c) is characterized by a number of clumps or spots as well as some diffuse components described as follows.

4.1. Sgr A Region
The most prominent one is a high ratio clump at Sgr A, which consists of several high-velocity features. The high ratio clump has a size of $6' \times 4'$. We see a pair of high-velocity

![Figure 2. Frequency distribution of $R_{3–2/1–0}$ weighted by CO $J=1–0$ intensity. Gray area shows the contribution of four spiral arms in the Galactic disk.](image)

![Figure 3. Curves of CO antenna temperatures as a function of $N_{CO}/dV$ of the cool absorber. Shaded area indicates the $N_{CO}/dV$ range where $R_{3–2/1–0}$ exceeds 1.5.](image)
emission, which is much larger than the circumnuclear disk (CND; $d \sim 100''$; [13]). We suggest this high ratio clump include the CND itself and its extension. A small red-shifted clump at $(l, b) \simeq (0.01, -0.02)$ is a well-known HVCC, CO 0.02-0.02 [4]. High ratio clumps which may be generated by the interaction with Sgr A East [12] appear at $l \simeq -0.03^\circ$, as three velocity components at $V_{\text{LSR}} \simeq -70, +30, +70$ km s$^{-1}$. Another component at $(l, V_{\text{LSR}}) \simeq (-0.1^\circ, +40$ km s$^{-1}$) with a relatively narrow velocity width may be a cloud surface irradiated by UV photons from the central cluster.

4.2. $l=1.3^\circ$ Complex

The $l = 1.3^\circ$ complex is the large molecular feature having a prominent elongation toward positive latitude [3]. Two expanding shells have been identified at the center of $l = 1.3^\circ$ complex (CO 1.27+0.01; [5]). High ratio gas is associated with both of the expanding shells, and it is abundant especially in the Galactic northwestern rim of the ‘minor’ shell. The association of high $R_{3–2/1–0}$ gas with these expanding shells ensures that they are generated by a series of supernova explosions, suggesting that a microburst of star formation has occurred there in the recent past.

4.3. $l=0.9^\circ$ Anomaly

An anomalous gathering of high ratio gas in the $\Delta l \times \Delta b \sim 0.2^\circ \times 0.2^\circ$ area centered at $(l, b) \simeq (+0.9^\circ, -0.1^\circ)$. This region corresponds to the edge of the Sgr B complex and a tangent of the star forming ring (Arm I; [14]). The spatial distribution and kinematics of high ratio gas is highly complex. Although the origin of this anomaly is unknown, some compact components in the anomaly can be attributable to the previously identified features. A spot at $(l, b) \simeq (+0.87^\circ, -0.23^\circ)$ has a large velocity width, lying in the rim of an expanding shell-like feature with a diameter of $\sim 0.7^\circ$. This expanding shell touches with the SiO rich core M 0.83–0.18 [9]. Blue-shifted wing emission at $(l, V_{\text{LSR}}) \simeq (0.85^\circ, -120$ km s$^{-1}$) seems to be associated with the radio shell of SNR 0.9+0.1, which is bright in TeV $\gamma$-ray [15].

4.4. Absorption by Foreground Gas

We see several narrow velocity-width features in $|l| \leq 0.6$, $-60 \leq V_{\text{LSR}} \leq 15$ km s$^{-1}$. They avoid the $l-V$ loci of the foreground spiral arms. These features can be explained by the existence of cool absorber in interarm regions. We made a model with a warm opaque cloud veiled by a layer of cool absorber (Fig.3). Since the $J=2$ level is subthermally excited in the cool absorber, the $J=3–2$ line is hardly absorbed unless $N_{\text{CO}}/dV \geq 10^{16}$ cm$^{-2}$ (km s$^{-1}$)$^{-1}$ where radiative excitation dominates. This effect raises $R_{3–2/1–0}$ without participation of highly excited, less opaque gas. Thus we must see the data in velocities of interarm gas with great care.

4.5. High $R_{3–2/1–0}$ Spots

We found a number of high ratio spots (Fig.4). Most of these spots have compact appearances and prefer high-velocity ends of giant molecular clouds within the CMZ. Many high ratio spots have compact entities with large velocity width, exhibiting signs of shocked gas. Some of those associate with nonthermal threads or filaments. Four high ratio spots seem to be relevant to the bundle of nonthermal filaments of the Galactic Center Radio Arc.

These facts strongly suggest that supernova/molecular cloud interaction plays an important role in accelerating electrons and forming nonthermal threads or filaments, which are unique and abundant in the CMZ. It has been reported that shocked molecular gas is associated with the nonthermal filament ‘Snake’ at the intersection with the SNR G359.1–0.5 [16]. The association of shocked gas with nonthermal filaments prefers the hypothesis that localized magnetic tubes with a milligauss field are illuminated by relativistic electrons at these filaments.
Figure 4. Spatial distribution of high ratio ($R_{3-2/1-0} \geq 1.5$) spots superposed on the VLA 90 cm image [17]. Circles indicate high-velocity compact clouds (HVCCs) or high-velocity wings with high ratio. Triangles are high ratio spots in velocity ends of clouds. Crosses are those in cloud edges. The ‘x’ denotes a high ratio cloud in the 20 km s$^{-1}$ arm.

5. Summary
We have surveyed a $\Delta l \times \Delta b = 2^\circ \times 0.5^\circ$ area of the CMZ in CO $J=3-2$ line. The CO $J=3-2$ distribution closely follows characteristics of the CMZ delineated by the CO $J=1-0$ surveys. The analysis of the $J=3-2/J=1-0$ intensity ratio shows that the bulk of molecular gas in the CMZ is thermalized and moderately opaque. We found clumps and small spots of high ratio gas as well as diffuse high ratio features in the CMZ. Most of them are likely shocked gas generated by the interaction with unidentified supernovae, while some could be UV-irradiated surfaces of molecular clouds. Continuation of the CO $J=3-2$ survey, as well as follow-up studies of high ratio features detected, will reveal the ubiquity and origin of shocked molecular gas in the CMZ.

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