A HIGH-VELOCITY MOLECULAR CLOUD NEAR THE CENTER OF THE GALAXY

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Received 1998 March 2; accepted 1998 November 18

ABSTRACT

We report the detection of a peculiar molecular cloud, CO 0.02–0.02, lying about 5' Galactic east from the center of the Galaxy. 12CO images taken with Nobeyama Radio Observatory (NRO) 45 m telescope showed that it is relatively compact (~3 × 4 pc2) as well as having a very large velocity width (ΔV ≥ 100 km s⁻¹). The cloud has a virial mass about 1 order of magnitude larger than the LTE mass, 9 × 10⁴ M☉, indicating the cloud is apparently gravitationally unbound.

New observations with the James Clerk Maxwell Telescope 15 m and the NRO 45 m telescopes show that CO 0.02–0.02 is very bright in the CO (J = 3–2) and in the HCN and HCO⁺ (J = 1–0) lines. It appears that the environment may have an unusually high density and temperature, which may be related to the very broad CO line width.

We propose that CO 0.02–0.02 may have been accelerated, heated, and compressed in a series of supernovae shocks that have occurred within the last (3–5) × 10⁴ yr. Subject headings: Galaxy: center — ISM: clouds — ISM: molecules

1. INTRODUCTION

Molecular gas in the Galactic center region has a highly complex spatial distribution and kinematic structure, which has led to the identification of remarkable variety of peculiar features (Bania 1977, 1980, 1986; Bally et al. 1987, 1988; Uchida et al. 1992, 1996; Burton & Liszt 1978, 1983, 1992; Oka et al. 1998b). It has long been known that giant molecular clouds in the region show large velocity widths, typically up to 5 times greater than those of the disk cloud population (Oka et al. 1998a). These results have led to the conclusion that the local environment has a higher pressure than typical of disc population material (Spitzer & Blitz 1992; Oka et al. 1998a).

We recently made large-scale 12CO and 13CO images of the Galactic center region, mapping on a 34" grid with the 2 × 2 focal plane array receiver on the Nobeyama Radio Observatory (NRO) 45 m telescope (Oka et al. 1998b). In these data sets, those giant molecular clouds with large velocity widths do not always appear to be superpositions of clouds with "normal" velocity widths, but rather seem to consist of individual compact (d ≤ 10 pc) clouds having relatively large velocity widths (ΔV ≥ 30 km s⁻¹). These compact clouds with large velocity widths are neither gravitationally bound nor confined by the higher external pressure in the Galactic bulge, and thus they may be transient features with lifetimes of ~10⁵ yr. If they are of a transient nature, their frequency among the molecular cloud ensemble requires that they are being formed continuously.

CO 0.02–0.02 is one such compact cloud having a large velocity width, and it is centered at (l, b) ≈ (+0°:02, −0°:02), about 5° Galactic east (we adopt this form of nomenclature to express relative direction in a galactic coordinate reference frame) from Sgr A* (see Fig. 1a). This cloud stands out because of its broad line width (ΔV ≥ 100 km s⁻¹) and its compact size (~3 × 4 pc²). The 12CO (J = 1–0) images show that this cloud is well isolated at velocities between VLSR = 80 km s⁻¹ and 150 km s⁻¹. The velocity of the peak intensity toward CO 0.02–0.02, VLSR = 90 km s⁻¹, is shifted by ~50 km s⁻¹ from the main ridge of intense CO emission from the Galactic center (Fig. 1b). Even in our high-resolution images, the cloud appears as a single entity, which distinctly differs from Clump 1 (Bania, Stark, & Heilman, 1986) or Clump 2 (Stark & Bania 1986). In addition, severely suffering the contamination of foreground gas, CO 0.02–0.02 seems to have a faint negative velocity extension to VLSR = −80 km s⁻¹ elongated toward the negative longitude.

Here we report fully sampled CO (J = 3–2) observations, which are complemented with HCN J = 1–0 and HCO⁺ (J = 1–0) observations, to clarify the spatial and velocity structure. Combined with the CO (J = 1–0) data, these data are then used to estimate the physical conditions in this unusual object. We adopt D = 8.5 kpc as the distance to the Galactic center.

2. OBSERVATIONS

CO (J = 3–2) (345.795989 GHz) observations were obtained with the James Clerk Maxwell Telescope (JCMT) at Mauna Kea, Hawaii. An area covering 10′ × 6′ was mapped in the 12CO (J = 3–2) line on a 3′3 grid that included CO 0.02–0.02 and the Galactic center circumnuclear ring. A smaller region around CO 0.02–0.02 was also mapped in the 13CO (J = 3–2) line on the same grid spacing. The JCMT beamwidth was 14.3 FWHM and the efficiency ηLSR = 0.70 at 345 GHz (using facility receiver B3i). Pointing errors were corrected by observing 345 GHz continuum emission from NGC 6334 I (nomenclature of McBreen et al. 1979). A digital autocorrelation spectrometer was used in its 920 MHz bandwidth mode, achieving an 800 km s⁻¹ wide velocity coverage with 0.66 km s⁻¹ resolution.

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The $J = 1 \rightarrow 0$ lines of HCN (88.631 GHz) and HCO$^+$ (89.188523 GHz) were measured with the NRO 45 m telescope using receivers S80 and S100. An area that included CO 0.02−0.02 and CO 0.13−0.13 (see Oka et al. 1998b for the nomenclature) was mapped on a grid with 17” sampling. The telescope has a FWHM beamwidth of 18” ± 1” at 86 GHz and an $\eta_{fss}$ of $\approx 0.58$ at 115 GHz (Oka et al. 1998b). Pointing errors were corrected every two hours by observing the SiO maser emission (43 GHz) from VX Sgr. The pointing accuracy was better than 3” (rms) in both azimuth and elevation. Typical system noise temperatures of the receivers ranged from 400 to 600 K, including atmospheric losses during the observations. We used wide-band acousto-optical spectrometers with an instantaneous band-width of 250 MHz and a frequency resolution of 250 kHz, which correspond to an 840 km s$^{-1}$ wide velocity coverage with 0.84 km s$^{-1}$ resolution. The observations were made by position switching to a clean reference position located at $(l, b) = (0^\circ, -2^\circ)$. Typical 60 s on-source integrations resulted in spectra having a noise level of $\approx 0.15$ K rms. Spectra were also obtained of the H$^{13}$CN and H$^{13}$CO$^+$ ($J = 1 \rightarrow 0$) isotopomers toward the center of CO 0.02−0.02, integrating for 22 minutes on-source.

3. SPATIAL AND VELOCITY STRUCTURES

Figure 2a shows the distribution of the CO ($J = 3 \rightarrow 2$) emission integrated over the velocity range $-100$ to $+200$ km s$^{-1}$. This map delineates the cloud structure more clearly than does the $J = 1 \rightarrow 0$ data because of the better sampling; however, its distribution does confirm the general structure observed in CO ($J = 1 \rightarrow 0$), CO 0.02−0.02 appears as a well-defined, bright object in the integrated map, with an intense peak at $(l, b) = (+0.013, -0.019)$. CO 0.02−0.02, its finger-like extension, and a chain of small clumps lie at the edge of an emission cavity ($\approx 3 \times 2$ pc$^2$) that can be seen to the Galactic southwest. Figures 2b and 2c show the distribution of HCN and HCO$^+$ ($J = 1 \rightarrow 0$) emission integrated over the velocity range $-100$ to $+200$ km s$^{-1}$. CO 0.02−0.02 is also the brightest object in these integrated maps, and the southwestern emission cavity is still clearly seen. The other large cloud at lower latitude is the $\approx +50$ km s$^{-1}$ cloud, which dominates the HCN and HCO$^+$ maps in the velocity range between $+20$ and $+80$ km s$^{-1}$.

Figure 3 shows the longitude-velocity map of CO ($J = 1 \rightarrow 0$) and HCN ($J = 1 \rightarrow 0$) emissions around CO 0.02−0.02. In HCN ($J = 1 \rightarrow 0$) emission, CO 0.02−0.02 appears with a well-defined entity over a wide velocity range from $V_{LSR} \approx 40$ to $160$ km s$^{-1}$. Its velocity width is larger than the other Galactic center clouds by at least a factor of 2. In addition, the clumps at $V_{LSR} \approx 10$ km s$^{-1}$ and $-40$ km s$^{-1}$ in the same longitude are likely negative velocity extensions of CO 0.02−0.02, since they occupy nearly the same positions as the main body in the plane of the sky with small spatial extensions (see also Fig. 4). However, the association of the clump at $(l, V_{LSR}) \approx (-0.03, -70$ km s$^{-1}$) with CO 0.02−0.02 is controversial. Velocity channel maps showing the CO ($J = 3 \rightarrow 2$) emission around CO 0.02−0.02 are reproduced in Figure 4. This emission has a strong peak at $V_{LSR} \approx +90$ km s$^{-1}$. Despite the severe contamination of foreground gas at velocities close to $V_{LSR} \approx -50, -30$, and

| Line                | CO 0.02−0.02 | Galactic Center Clouds | Disk Clouds |
|---------------------|--------------|------------------------|-------------|

| CO$^{13}$CO ($J = 1 \rightarrow 0$) | 8            | 5.2$^a$                | 5−8$^b$     |
| CO$^{13}$CO ($J = 3 \rightarrow 2$) | 11           | ...                    | ...         |
| CO ($J = 3 \rightarrow 2/J = 1 \rightarrow 0$) | 1.3          | 0.4$^c$                | 0.3$^c$     |
| HCN/CO ($J = 1 \rightarrow 0$)       | 0.2          | 0.08$^{6*}$            | 0.01−0.05$^e$ |
| HCN/H$^{13}$CN ($J = 1 \rightarrow 0$) | 8            | ...                    | ...         |
| HCO$^+/H^{13}$CO$^+$ ($J = 1 \rightarrow 0$) | $>25$      | ...                    | 1−6$^f$     |

$^a$ From large-scale surveys (Oka et al. 1998b).
$^b$ From Galactic plane surveys (Liszt 1993).
$^c$ From the CIA survey (Dame et al. 1987) and the COBE data (Bennett et al. 1994).
$^d$ From large-scale surveys (Jackson et al. 1996).
$^e$ From Galactic plane surveys (Heller & Blitz 1997).
$^f$ For nearby clouds (Guélin, Langer, & Wilson 1982).
0 km s\(^{-1}\), small emission clumps with negative velocity are associated with the spatial position of the intensity peak at \(V_{\text{LSR}} = 80\) to 100 km s\(^{-1}\). Thus, the gas belonging to CO 0.02–0.02 spans the velocity range \(V_{\text{LSR}} = -80\) to +180 km s\(^{-1}\).

Emission cavities associated with CO 0.02–0.02 also appear in velocity channel maps at \((l, b, V_{\text{LSR}}) \approx (0^\circ, -0^\circ 02, -50\) km s\(^{-1}\)), \((0^\circ 01, -0^\circ 03, 10\) km s\(^{-1}\)), \((0^\circ 025, -0^\circ 01, 30\) km s\(^{-1}\)), \((0^\circ, -0^\circ 025, 80\) km s\(^{-1}\)), and \((0^\circ 02, 0^\circ, 110\) km s\(^{-1}\)). The cavity at \((l, b, V_{\text{LSR}}) \approx (0^\circ 02, 0^\circ, 110\) km s\(^{-1}\)) forms a shell-like structure with a diameter of 1 pc in the Galactic northeastern portion of CO 0.02–0.02. The rounded head of CO 0.02–0.02 in the lower adjacent velocity channel \((V_{\text{LSR}} = +80\) to +100 km s\(^{-1}\)) may be related to this small shell. Because of contamination by ambient emission, the lower velocity extent of the small shell remains uncertain, while its higher velocity emission merges with noise at \(V_{\text{LSR}} \approx +140\) km s\(^{-1}\). The cavity at \((l, b, V_{\text{LSR}}) \approx (0^\circ, -0^\circ 025, 80\) km s\(^{-1}\)) also forms a shell-like structure with a diameter of 2 pc. The southwestern emission cavity seen in the integrated intensity maps seems not to be a coherent expanding shell but the superpositions of several small cavities. All the molecular emission from CO 0.02–0.02 peaks at the position between the small shell-like
are thermalized at a temperature $T_\text{ex}$. For the $^{12}$CO ($J = 3 - 2$) line, the general equation for estimating the column density is given by

$$N_{12\, \text{CO}} = 4.65 \times 10^{12} T_{\text{ex}} \frac{33.2}{T_{\text{ex}}} \times \int T^*_R(3 - 2) dV \frac{\tau}{1 - e^{-\tau}}, \quad (1)$$

where $\tau$ is the $^{12}$CO ($J = 3 - 2$) line optical depth, and $\tau/(1 - e^{-\tau})$ is a correction factor that takes account of the optical depths. From this relationship, the optical depth toward the cloud center is estimated to be 2.7, based on the observed $^{12}$CO/$^{13}$CO ratio. The excitation temperature between the $J = 3$ and $J = 2$ levels is estimated from the $^{12}$CO ($J = 3 - 2$) peak antenna temperature and the optical depth, taking the relationship

$$T^*_R = \frac{h \nu/k}{\exp (h \nu/k T_{\text{ex}}) - 1} (1 - e^{-\tau}), \quad (2)$$

to be $T_{\text{ex}} = 56 \, \text{K}$. Taking the $^{12}$CO ($J = 3 - 2$) emission integrated over the velocity range $V_{\text{LSR}} = -100$ to $+200 \, \text{km s}^{-1}$, adopting $T_{\text{ex}} = 56 \, \text{K}$ and $[^{12}$CO]/[^{13}$CO] = $24 \times 10^{-6}$ (Lis & Goldsmith 1989, 1990), and including the helium correction 1.36, the total mass of CO 0.02–0.02 is then found to be $9.1 \times 10^4 \, \text{M}_\odot$.

An independent estimate of the mass can be obtained from the $^{13}$CO ($J = 1 - 0$) intensity, using the relationship

$$N_{13\, \text{CO}} = 4.58 \times 10^{13} T_{\text{ex}} \frac{5.29}{T_{\text{ex}}} \times \int T^*_R(1 - 0) dV \frac{\tau}{1 - e^{-\tau}}, \quad (3)$$

where $\tau$ is the $^{13}$CO ($J = 1 - 0$) line optical depth. Here the excitation temperature between the $J = 1$ and $J = 0$ levels is estimated from the CO ($J = 1 - 0$) peak antenna temperature, as 42 K. From the $^{13}$CO ($J = 1 - 0$) emission integrated over the velocity range $V_{\text{LSR}} = +50$ to $+150 \, \text{km s}^{-1}$, and adopting $T_{\text{ex}} = 42 \, \text{K}$ and $[^{13}$CO]/[^{12}$CO] = $10^{-6}$ (Lis & Goldsmith 1989, 1990), the mass $M = 2.6 \times 10^3 \, \text{M}_\odot$, which is similar to the $^{12}$CO ($J = 1 - 0$) value, $M = 3.1 \times 10^3 \, \text{M}_\odot$, but is larger than that derived from the CO ($J = 3 - 2$) intensity by a factor of 3.

The discrepancies in the estimated masses and excitation temperatures may be due to the inapplicability of one-zone LTE analysis. The different transitions trace material in different degrees of excitation; for instance, the $J = 3 - 2$ line of CO mainly traces highly excited gas, while the $J = 1 - 0$ line traces moderately excited gas. We take $9 \times 10^4 \, \text{M}_\odot$ as the LTE mass of CO 0.02–0.02, which is derived by the CO ($J = 3 - 2$) line intensity, since the CO ($J = 1 - 0$) intensities may suffer contaminations of foreground and background gas with low excitation. From the LTE mass and the size of the cloud, $3 \times 4 \times 3 \, \text{pc}$, the average gas density is as high as $n(\text{H}_2) \approx 5.6 \times 10^4 \, \text{cm}^{-3}$, which is slightly higher than that estimated by the LVG analysis (§ 4.1). The LVG density and temperature may have suffered downward shifts by the contamination of gas with low excitation in the CO ($J = 1 - 0$) intensity.

### 3. Energetics

The size parameter and the velocity dispersion of CO 0.02–0.02 are measured from the $^{12}$CO ($J = 3 - 2$) data.
Fig. 4.—Velocity channel maps of CO ($J = 3-2$) emission, each covering a velocity interval of 20 km s$^{-1}$, starting with $V_{\text{LSR}} = -100$ km s$^{-1}$ and ending at $V_{\text{LSR}} = 200$ km s$^{-1}$. Contour intervals are 40 K km s$^{-1}$. White contours begin at 520 K km s$^{-1}$. Crosses denote the position of the intensity peak at $V_{\text{LSR}} = 800$ to 100 km s$^{-1}$.  

cube over the ranges $l = -36^\circ$ to $+108^\circ$, $b = -108^\circ$ to $+36^\circ$, and $V_{\text{LSR}} = -100$ to $+200$ km s$^{-1}$, to be $S = D \tan (\sigma_l \sigma_b)^{1/2} = 1.6$ pc, and $\sigma_V = 54$ km s$^{-1}$. If we take the velocity range $V_{\text{LSR}} = 40$ to 200 km s$^{-1}$ (taking only the positive velocity component), the velocity dispersion becomes $32$ km s$^{-1}$, while the size parameter does not change. A virial theorem mass is determined by

$$M_{\text{VT}} = 3f_p \frac{S \sigma_V^2}{G},$$

(4)
Thus, \( CO_{0.02} \) is larger than the LTE mass obtained in the preceding section. The size and velocity dispersions of \( CO_{0.02} \) given above, the kinetic energy of \( CO_{0.02} \) \( \approx 10^{48} \) ergs. We consider two mechanisms for acceleration: supernova explosions (type II, Ib), or Wolf-Rayet stellar winds.

Since a supernova loses a large amount of its initial energy (\( \sim 10^{51} \) ergs) through radiation, especially in high-density medium (e.g., Chevalier 1974), the kinetic energy estimated above requires an energy supply that might be available from several to several tens of supernovae. Multiple emission cavities in and around \( CO_{0.02} \) indeed suggest that acceleration could have been driven by a series of supernova explosions. The absence of a radio continuum source (\( S_{20\ cm} \leq 15 \) mJy/beam; Yusef-Zadeh, Morris, & Chance 1984) has been explained in terms of a deficiency of relativistic electrons caused by synchrotron loss. In fact, given fields of 1 mG (e.g., Morris 1996), the synchrotron lifetime of a 0.55 GeV electron that is able to contribute to radio emission at 20 cm is \( \sim 1.5 \times 10^6 \) yr. This is compatible with the notion that energy from the relativistic electrons produced in the supernova blast wave has already been radiated away by synchrotron emission.

A W-R star (\( M \geq 20 M_\odot \)) injects kinetic energy into interstellar space as a stellar wind at a rate typically \( \sim 6 \times 10^{44} \) ergs yr\(^{-1}\). If the energy source of \( CO_{0.02} \) is W-R stellar wind(s), its kinetic energy and expansion time would require the presence of more than (110–450) W-R stars within the cloud. These massive stars would, however, also ionize the ambient gas, which would in turn emit a thermal radio continuum. As an example, O9 stars (\( M = 20 M_\odot \)) on the zero-age main sequence emit \( 10^{48.08} \) s\(^{-1}\) Lyman continuum photons (Panagia 1979). The number of Lyman continuum photons \( Q_{L\gamma} \) and the thermal radio flux \( S_{\nu} \) are related by the equation

\[
Q_{L\gamma} = \frac{4.8 \times 10^{48}}{\eta} T_e^{-0.45} v^{0.1} S_{\nu} D^2
\]

(Mezger et al. 1979), where \( \eta \) is the dilution factor, \( T_e \) is the electron temperature, \( v \) is the observed frequency in GHz, and \( D \) is the distance to the source in kpc. If half of the Lyman continuum photons are taken up in ionizing the ambient gas and if we adopt \( T_e = 10^4 \) K, this implies a radio flux of \( S_{10\ GHz} = 10^{-40} \) Jy.

The observed flux of \( S_{10\ GHz} \sim 8 \) Jy (Handa et al. 1987),
with no enhancement exceeding 1 Jy toward CO 0.02−0.02, is incompatible with the above value. Thus, radio continuum data do not favor acceleration of the material by the winds from a W-R star cluster.

It seems most likely that CO 0.02−0.02 has been accelerated, heated, and compressed by several tens of supernovae within the last $(3−5) \times 10^4$ yr. Why is this unusual object in the vicinity of the Galactic nucleus? What causes such a high supernova rate in this limited area? Although these queries remain mysteries, the answers may be related to higher star formation activity in the recent past (Krabbe et al. 1995). A series of supernova explosions or a superposition of W-R stellar winds might produce a localized region of high pressure, especially in the region close to the center where many evolved stars have been found. The prevalence of such compact clouds with large velocity widths, as well as the boisterous molecular gas kinematics, may also indicate that active star formation has occurred in the Galactic center cloud ensemble as recently ago as several times $10^7$ yr ago.

We thank the JCMT and the NRO staffs for excellent support. We are also grateful to the anonymous referee for his or her comments and suggestions to improve the manuscript. T. O. is financially supported by the Special Postdoctoral Researchers Program of RIKEN.

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