HIGH ATOMIC CARBON ABUNDANCE IN MOLECULAR CLOUDS IN THE GALACTIC CENTER REGION

KUNIHKO TANAKA1, TOMOHARU OKA1, SHINJI MATSUMURA1, MAKOTO NAGA2, AND KAZUHISA KAMEGI3

1 Department of Physics, Faculty of Science and Technology, Keio University, 3-14-1 Hiyoshi, Yokohama, Kanagawa 223-8522, Japan; ktanaka@phys.keio.ac.jp
2 High Energy Accelerator Research Organization, 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan
3 Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 3-1-1 Yoshinodani, Chuo-ku, Sagamihara, Kanagawa 252-5210, Japan

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ABSTRACT

This Letter presents a Nyquist-sampled, high-resolution [C I] $^3P_1-^3P_0$ map of the $-0:2 < l < 1:2 \times -0:1 < b < 0:0$ region in the Central Molecular Zone (CMZ) taken with the Atacama Submillimeter Telescope Experiment 10 m telescope. We have found that molecular clouds in the CMZ can be classified into two groups according to their [C I]$/^{13}$CO intensity ratios: a bulk component consisting of clouds with a low, uniform [C I]$/^{13}$CO ratio (0.45) and another component consisting of clouds with high [C I]$/^{13}$CO ratios (>0.8). The [C I]-enhanced regions appear in M$-0.02-0.07$, the circumnuclear disk, the 180 pc ring, and the high-velocity compact cloud CO+0.02-0.02. We have carried out a large velocity gradient analysis and have derived the C$^0$/CO column density ratio for M$-0.02-0.07$ as 0.47, which is approximately twice that of the bulk component of the CMZ (0.26). We propose several hypotheses on the origin of high C$^0$ abundance in M$-0.02-0.07$, including cosmic-ray/X-ray dissociation and mechanical dissociation of CO in the pre-existing molecular clouds. We also suggest the possibility that M$-0.02-0.07$ is a cloud at an early stage of chemical evolution from diffuse gas, which was possibly formed by the bar-induced mass inflow in the Galactic center region.

Key words: cosmic rays – evolution – Galaxy: center – ISM: kinematics and dynamics

1. INTRODUCTION

The Central Molecular Zone (CMZ) in the inner ≃200 pc around the Galactic center is the Milky Way’s most active site of massive star formation; the CMZ contains three well-known supermassive clusters and a burst-like star formation region, Sgr B2 (Morris & Serabyn 1996). Recent observations have revealed energetic molecular bubbles and high-velocity compact clouds (HVCs) that are also considered to be probes of massive stellar clusters (Oka et al. 2007; Tanaka et al. 2007, 2009). Many theoretical and observational studies have been conducted to understand how gas is supplied to these cluster formation activities, and hence for the formation of giant molecular clouds (GMCs) wherein massive stars are formed. Birnley et al. (1991) theorized a model of gas kinematics in the bar potential in the inner Galaxy, in which the gas inflows from the innermost cusped $x_1$ orbit to the $x_2$ orbits. The bar-induced gas flow can trigger large-scale mass condensation in the $x_1-x_2$ orbit-crowding regions and subsequent burst-like cluster formation in Sgr B2 (Hasegawa et al. 1994). The gas in the $x_2$ orbits is assumed to be transported to the central ∼10 pc region possibly by the inner bar of the Galaxy or by other processes (Morris & Serabyn 1996; Namekata et al. 2009). This secondary gas flow could facilitate the formation of GMCs in the Sgr A complex, the circumnuclear disk (CND), and the massive stellar clusters in the Sgr A and Radio Arc regions (Namekata et al. 2009; Oka et al. 2011).

Atomic carbon (C$^0$) can be used as an indicator of GMC formation process in the CMZ. The origin of abundant interstellar C$^0$ has been a controversial issue and several explanations have been proposed. In terms of chemical evolution, C$^0$ is thought to be abundant in the early stage of molecular cloud formation (Suzuki et al. 1992; Lee et al. 1996; Maezawa et al. 1999); C$^0$ is mainly present in the interface layer between the atomic and molecular phases in the photodissociation regions (PDRs; Hollenbach & Tielens 1999), but it is also abundant in the inner regions of young molecular clouds because C$^0$ → CO conversion requires a timescale of the order of Myr (Suzuki et al. 1992; Lee et al. 1996). This timescale is comparable to the dynamical timescales of molecular clouds, and hence one can expect molecular cloud formation regions to be clearly visible owing to their high C$^0$ abundances.

Jaffe et al. (1996), Ohja et al. (2001), and Martin et al. (2004) conducted surveys of the submillimeter [C I] emission toward the CMZ. Ohja et al. (2001) found that the [C I] $^3P_1-^3P_0$ map of the CMZ was not investigated in detail. In this Letter, we present a new high-resolution [C I] $^3P_1-^3P_0$ map of the CMZ and report the discovery of molecular clouds with high C$^0$ abundance.

2. OBSERVATIONS

We carried out mapping observations of the CMZ in the [C I] $^3P_1-^3P_0$ (492.1607 GHz) line by using the Atacama Submillimeter Telescope Experiment (ASTE; Ezawa et al. 2004) 10 m telescope in 2010 October and November. As a front end we used the ALMA band 8 QM receiver (Satou et al. 2008). The telescope beam size was 17″ at 500 GHz. The digital back end was operated in the wide-band mode with a channel width of 512 kHz. The typical system noise temperature during the observations was 2000–3000 K.

We performed on-the-fly scans covering the $-0:2 < l < 1:25 \times -0:1 < b < 0:0$ region. The reference position was taken at ($l$, $b$) = (1°, −1°). The antenna pointing was checked by CO $J = 4-3$ observations toward V1427 Aql, and the pointing accuracy was maintained within 5″. The data were formed into an $l-b-v_{LSR}$ data cube with a 17″ × 17″ × 2 km s$^{-1}$ grid and a 34″ angular resolution. The antenna temperatures were calibrated using a standard chopper-wheel method, and were then corrected for the main-beam efficiency of 0.50. The
estimated rms intensity calibration error was 8%. The total on-
source integration time was 8 hr, thus giving an rms noise level of
0.3 K in the $T_{\text{MB}}$ scale. The intensity scale was checked by
comparing our data with the data obtained using the Caltech
Submillimeter Observatory (CSO) telescope (Serabyn et al.
1994). The peak intensity at ($l, b$) = (−0.056, −0.045) was
7.0 ± 0.3 K in our data, which was in good agreement with the
intensity of 7 K in the CSO data.

3. RESULTS

3.1. [C i]-enhanced Regions

Figure 1 shows the velocity-channel maps of the [C i] line in a
velocity range from −60 to 120 km s$^{-1}$. By comparing the maps
with the $^{13}$CO $J = 1$−0 map (Oka et al. 1998), we observe several
regions with high [C i]/$^{13}$CO intensity ratio. M−0.02−0.07 (the
50 km s$^{-1}$ cloud) has a [C i] peak intensity that is approximately
twice that of M−0.13−0.08 (the 20 km s$^{-1}$ cloud) and Sgr B2,
whereas these three GMCs have similar peak $^{13}$CO intensities
(Oka et al. 1998). Another notable observation is the strong [C i]
emission from CO+0.02−0.02 in high velocity channels ($v_{\text{LSR}} \geq 100$ km s$^{-1}$). CO+0.02−0.02 is one of the most
energetic HVCCs in the CMZ (Oka et al. 2008). Despite its
weak detection in the $^{13}$CO map, the peak [C i] intensity of this
cloud is very high (5.5 K) and is comparable to the [C i] intensity
in Sgr B2.

We made a scatter plot of the $^{13}$CO intensity versus the [C i]
intensity ($T_{^{13}\text{CO}}$ and $T_{\text{[C i]}}$, respectively). The [C i] data were
convolved with a 60$^\prime$ beam and regridded to match the resolution
of the $^{13}$CO data. The velocity resolution of the [C i] and $^{13}$CO
data was also reduced to 4 km s$^{-1}$ in order to improve the
signal-to-noise ratio. The scatter plot shown in Figure 2 clearly
indicates the presence of [C i]-enhanced region in the CMZ. The
data points are divided into two components according to their
$T_{\text{[C i]}}/T_{^{13}\text{CO}}$ ratios: a bulk component with a uniform $T_{\text{[C i]}}/T_{^{13}\text{CO}}$
of 0.45 and another component with a ratio approximately
twice that of the bulk component.

We extracted clouds that belong to the latter, [C i]-enhanced
component according to the following criteria: (1) $T_{\text{[C i]}} > 0.45 \times T_{^{13}\text{CO}} + \sigma_T$, where $\sigma_T$ is the noise level of $T_{\text{[C i]}}$,
and (2) the size of the high-$T_{\text{[C i]}}$ region is greater than one resolution
element in each of the $l$, $b$, and $v_{\text{LSR}}$ directions. Figure 3
shows the distribution of the [C i]-enhanced regions in the
velocity-integrated intensity map and the $l$-$v_{\text{LSR}}$ diagram. The
[C i]-enhanced regions correspond to three clouds in Sgr A: M−0.02−0.07, CO+0.02−0.02, and the CND. An increase in the
$T_{\text{[C i]}}/T_{^{13}\text{CO}}$ ratio for the Sgr A complex has been observed in the
low-resolution data of Ohja et al. (2001), and our results show
that the increase is mainly due to the contribution from
M−0.02−0.07. The Sgr A complex has another massive GMC
M−0.13−0.08, but this cloud has a typical, low $T_{\text{[C i]}}/T_{^{13}\text{CO}}$
ratio.

Figure 2(b) shows that the 180 pc ring also has a high
$T_{\text{[C i]}}/T_{^{13}\text{CO}}$ ratio, although most part of the ring was not
identified as a [C i]-enhanced region according to the above
criteria owing to its low [C i] intensity. The best-fit value for the
$T_{\text{[C i]}}/T_{^{13}\text{CO}}$ ratio was 0.88.

3.2. C$^0$/CO Abundance Ratio

We carried out a large velocity gradient analysis to estimate the
$N_{\text{C$^0$}}/N_{\text{CO}}$ column density ratio on the basis of the $T_{\text{[C i]}}/T_{^{13}\text{CO}}$
ratio. For the bulk component, the $N_{\text{C$^0$}}/N_{\text{CO}}$ ratio was calculated as 0.26, assuming both the [C i] and $^{13}$CO lines to be optically
thin, $T_{\text{mb}} = 50$ K, and $n_{\text{H}} = 10^3.5$ cm$^{-3}$ (Martin et al. 2004;
Nagai et al. 2007). The C$^13$/C$^0$ isotopic ratio was assumed to be 24 according to Langer & Penzias (1990). In a typical
CMZ environment, $T_{\text{[C i]}}$ decreases with increasing excitation
temperature of the $^{13}$CO line, whereas $T_{\text{[C i]}}$ is insensitive to the
physical conditions. Hence, the enhanced $T_{\text{[C i]}}/T_{^{13}\text{CO}}$ ratios of
M−0.02−0.07, CO+0.02−0.02, the CND, and the 180 pc
ring can be attributed either to high C$^0$ abundance or to high
excitation temperature of $^{13}$CO.

The $T_{\text{[C i]}}/T_{^{13}\text{CO}}$ ratio averaged over M−0.02−0.07 was
0.87, which is likely to be caused by the enhanced $N_{\text{C$^0$}}/N_{\text{CO}}$
ratio. Otherwise, the $T_{\text{[C i]}}/T_{^{13}\text{CO}}$ ratio of 0.87 would require
$T_{\text{mb}} = 370$ K when $n_{\text{H}} = 10^3.5$ cm$^{-3}$ or $n_{\text{H}} = 10^6.6$ cm$^{-3}$
when $T_{\text{mb}} = 50$ K; however, it is unlikely that the entire cloud
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The temperature and density of the 180 pc ring were estimated as
$\sim 30$ K and $\sim 10^{14}$ cm$^{-3}$, respectively (Nagai et al. 2007).

The $N_{\text{C$^0$}}/N_{\text{CO}}$ ratio was then estimated to be 0.61−0.77 by
assuming C/C$^{13}$ = 24. However, this $N_{\text{C$^0$}}/N_{\text{CO}}$ ratio may be
overestimated because a higher C$^{13}$/C$^0$ isotopic ratio of $\geq 40$
has been suggested for the ring (Riquelme et al. 2010). The
$N_{\text{C$^0$}}/N_{\text{CO}}$ ratio decreases to 0.37−0.47 if we adopt 40 instead of
24 as the C$^{13}$/C$^0$ ratio.

4. DISCUSSIONS

4.1. M−0.02−0.07

M−0.02−0.07 is the largest [C i]-enhanced region in our
data sets. The $N_{\text{C$^0$}}/N_{\text{CO}}$ ratio for the cloud is 0.47, which is
approximately five times the typical value for the Milky Way
(0.1; Oka et al. 2005), and roughly corresponds to the ratio for the
central regions in nearby galaxies (0.3−5; Israel & Baas 2002; Hartschuh et al. 2008).

The $N_{\text{C$^0$}}/N_{\text{CO}}$ abundance ratio is a sensitive indicator of
molecular cloud formation. Maezawa et al. (1999) found a
"[C i]-rich" molecular cloud in the Taurus region and concluded
that the cloud was at an early stage of evolution from the atomic
gas. However, unlike the quiescent dark clouds in the Galactic
disk, the GMCs in the CMZ are exposed to dissociative
processes besides photodissociation by the interstellar radiation
field; they are irradiated by strong ultraviolet (UV) radiation
from OB stars ($G_0 \sim 10^4$; Rodríguez-Fernández et al. 2004)
and are possibly exposed to enhanced cosmic-ray/X-ray
ionization and dissociative shocks. Therefore, in addition to the time-dependent chemical model, we discuss these possible explanations for C\textsuperscript{0} overabundance in the following sections.

4.1.1. Photodissociation

In terms of the stationary PDR model (Hollenbach et al. 1991), high \textit{N}_\text{C}/\textit{N}_{\text{CO}} ratio can be attributed to an intense UV field; \textit{N}_{\text{CO}} decreases with increasing UV field strength (\textit{G}_0) whereas \textit{N}_\text{C} is insensitive to \textit{G}_0. However, \textit{G}_0 for M−0.02−0.07 is not remarkably higher than that for other GMCs adjacent to H\textsc{ii} regions. The [C\textsc{i}] \textsuperscript{2} \textsubscript{P}_{3/2}−\textsubscript{2} \textsubscript{P}_{1/2} intensity of M−0.02−0.07, which is a good measure of \textit{G}_0, is $8 \times 10^{-4}$ erg s\textsuperscript{-1} cm\textsuperscript{-2} str\textsuperscript{-1} (Poglitsch et al. 1991). This value is within the range of typical values for regions outside Sgr A, $(0.6−1) \times 10^{-3}$ erg s\textsuperscript{-1} cm\textsuperscript{-2} str\textsuperscript{-1} (Mizutani et al. 1994). A similar [C\textsc{i}] intensity is also observed for the Radio Arc and Sgr B1 regions (Mizutani et al. 1994), where no [C\textsc{i}] enhancement is observed in our data sets.
Figure 3. (a) Velocity-integrated [C I] intensity of [C I]-enhanced region (contours) overlying total velocity-integrated intensity of [C I] (gray scale). The contours are drawn at 50 K km s\(^{-1}\) intervals. (b) Same as (a), but in longitude–velocity diagram. The contour levels are 0.1, 1, 2, 3, 4, and 5 K.

Figure 4. (a) Velocity-integrated [C I] intensity in v\(_{LSR}\) range of 30–70 km s\(^{-1}\) (gray scale) in Sgr A, smoothed to 60\('\) resolution. Contours of 13CO \(J=1-0\) are drawn at 50 K km s\(^{-1}\) intervals beginning from 150 K km s\(^{-1}\). (b) [C I]-integrated intensity of [C I]-enhanced regions, with overlaid contours of 6 cm continuum extracted from Very Large Array (VLA) archival data.

In addition, the spatial distribution of the [C I] emission deviates from the stationary PDR model. The [C I] peak of a photodissociative origin is expected to appear at the cloud surface (Hollenbach et al. 1991; Kamegai et al. 2003) rather than at the cloud center. However, this does not correspond to the observed distribution of the [C I] emission shown in Figure 4. The strong [C I] emission originates from a ridge from \((l, b) = (0^\circ, -0^\circ.03)\) to \((-0^\circ.05, -0^\circ.1)\), coinciding with the \(^{13}\)CO ridge. The [C I] ridge does not show a significant positional offset from the \(^{13}\)CO ridge toward either of the two dominant UV sources, the Central cluster and the G\(\sim\)0.02–0.07 \(\text{H II}\) region.

4.1.2. Cosmic-Ray/X-Ray Ionization

Chemical models show that a high ionization rate due to cosmic rays or X-rays increases C\(^0\) abundance (Flower et al. 1994; Meijerink et al. 2006). In fact, very high \(N_{\text{C}^0}/N_{\text{CO}}\) ratios \((\gtrsim 1)\) are found for the central regions of starburst galaxies and
active nuclei (Israel & Baas 2002; Hitcshfeld et al. 2008) and for GMCs interacting with supernova remnants (SNRs; White 1994; Ariyaka et al. 1999), where high cosmic-ray/X-ray flux is expected.

M−0.02−0.07 is located near Sgr A*, which is considered as a possible source of cosmic rays in the CMZ (Chernyakova et al. 2011). It is also argued that Sgr A* underwent a strong X-ray outburst in the recent past (Koyama et al. 1996). In addition, M−0.02−0.07 interacts with the Sgr A-East SNR (Yusef-Zadeh et al. 2001), which is another possible cosmic-ray source in the Sgr A region. The cosmic-ray/X-ray dissociation by these sources may explain the high C0 abundance in M−0.02−0.07. An advantage of the cosmic-ray/X-ray dissociation model over the standard PDR model is that it can explain the spatial coexistence of the 13CO and [C I] emissions more easily, because the X-rays and cosmic rays can penetrate deeper into a cloud than UV photons.

### 4.1.3. Mechanical Dissociation

Propagation of a fast shock thorough dense molecular gas can dissociate CO in the post shock gas (Hollenbach & McKee 1980). White (1994) suggested that the very high C0/CO ratio (1.3−2.9) for the IC443 C-shocked region can be attributed to the blast wave from the SNR, or to the enhanced cosmic-ray flux in the SN-shocked region.

The dissociative shock from Sgr A-East may provide an alternative explanation for the high C0/CO ratio, especially at the Galactic northern and western edge of the SNR shell where the shape of the [C I]-enhanced region spatially correlates well with that of the SNR (Figure 4(b)). Another possible source of the dissociative shock is cloud−cloud collision. It is suggested that cloud−cloud collision is rather frequent in the CMZ because of the high volume filling factor of molecular clouds and the presence of a bar potential (Hasegawa et al. 1994; Hüttemeister et al. 1998).

### 4.1.4. Time-dependent Chemistry

The high C0 abundance of M−0.02−0.07 can be also explained by time-dependent chemical models. The models of Suzuki et al. (1992), Lee et al. (1996), and Bergin et al. (1997) showed that molecular clouds are C0 abundant for ~1 Myr after their formation. Hence, the M−0.02−0.07 region can be understood as a young molecular cloud similar to the [C I]-rich cloud in the Taurus region (Maezawa et al. 1999).

In fact, the [C I]-enhanced region in M−0.02−0.07 appears spatially separated from the evolved, star-forming dense core region of the cloud. In Figure 5, the distribution of the [C I] emission is compared to that of the N2H+ J = 1−0 line (T. Oka et al. 2011, private communication), which is a tracer of evolved dense cores. M−0.02−0.07 is remarkably weak in N2H+ as compared to the neighboring GMC, M−0.13−0.08, the N2H+ J = 1−0/H13CN J = 1−0 ratio for M−0.02−0.07 is 0.59, which is two times lower than that in M−0.13−0.08, 1.1 (T. Oka et al. 2011, private communication). Further, we note a negative spatial correlation between [C I] and N2H+ in the internal structure of M−0.02−0.07. The [C I] peak velocity of M−0.02−0.07 is 50−65 km s−1, whereas the N2H+ peak velocity is 45−50 km s−1. The T[C I]/T[13CO] ratio at the N2H+ peak is 0.54, which is significantly lower than that averaged over the entire cloud. Since N2H+ becomes abundant in the later phase (>1 Myr) of chemical evolution (Hirahara et al. 1995; Bergin et al. 1997), the observed negative spatial correlation between N2H+ and [C I] is consistent with the chemical evolution scenario.

### 4.2. Mass Inflow in the CMZ

If the [C I]-enhanced region in M−0.02−0.07 is a young molecular cloud with an age not much greater than the chemical timescale of C0 → CO conversion, supply of a large amount of diffuse gas in the past ~1 Myr would be required for its formation. From the mass of M−0.02−0.07 (~105 M⊙; Zylka et al. 1990), the supply rate is estimated as ~0.1 M⊙ yr−1, which is within a reasonable range that could be explained by the mass inflow rates specified in the literature. Morris & Serabyn (1996) estimated the inflow rate to be 0.1−1 M⊙ yr−1 at ~200 pc from the Galactic center. Namekata et al. (2009) argued that M−0.02−0.07 is a part of a gas disk formed by the mass inflow to the central ~15 pc region driven by the inner bar potential. The mass inflow rate estimated by their model is ~0.1 M⊙ yr−1, which is also in good agreement with our estimate.
The high $T_{IC_0}/T_{ICO}$ ratio for the 180 pc ring can also be explained in the framework of the bar-driven inflow model. Binney et al. (1991) showed that the 180 pc molecular ring is formed by shock compression of the atomic gas at the inner edge of the innermost $x_1$ orbit and that the molecular gas rapidly flows into the inner $x_2$ orbits. The residence time of the molecular gas in the ring is shorter than the orbital period of the ring, $\sim \pi R_{ring}/V_{ring} \sim 6$ Myr, where $R_{ring}$ and $V_{ring}$ are the radius and the rotational velocity of the ring, respectively. This timescale is comparable to, or slightly longer than, the chemical timescale of $C^0 \rightarrow CO$ conversion, and hence a considerable fraction of the molecular gas in the ring may be $C^0$ abundant.

However, we note that it is difficult to draw a definite conclusion about the origin of the [C$^+$]-enhanced regions because of the complexity of the Galactic center environment. As discussed in the previous subsections, cosmic-ray/X-ray dissociation or the mechanical dissociation of CO in the pre-existing molecular clouds can also provide reasonable explanations for the high N$_{CO}/N_{ICO}$ ratio. For the 180 pc ring, we should also consider the possibility that the high [C$^+$]/$^{13}$CO intensity ratio may not be due to the high $C^0$ abundance but to the low $^{13}$C isotopic abundance.

4.3. CND and CO$+0.02\rightarrow 0.02$

The CND has the highest $T_{IC_0}/T_{ICO}$ ratio of the clouds in our data sets, although we could not confirm the increase in its $C^0$ abundance. Oka et al. (2011) found that the CND has low N$_2$H$^+$ abundance, similar to M$-0.02$–$0.07$. This result, along with the high $T_{IC_0}/T_{ICO}$ ratio, suggests similarities in the chemical composition of these clouds.

The $T_{IC_0}/T_{ICO}$ ratio of 2.0 for CO$+0.02\rightarrow 0.02$ is considerably higher than that for M$-0.02$–$0.07$. The large velocity width of CO$+0.02\rightarrow 0.02$ indicates that the cloud is violently shocked, although the driving source of the shock is not identified. Oka et al. (2008) argued that the energetic internal motion of CO$+0.02\rightarrow 0.02$ is driven by a series of SN explosions. The effect of the shock dissociation, and possibly of cosmic-ray dissociation enhanced by the SN-shock, may be more important for C$+0.02\rightarrow 0.02$ than for M$-0.02$–$0.07$.

5. SUMMARY

We report the discovery of molecular clouds with high C$^0$ abundance in the CMZ. We found that the $T_{IC_0}/T_{ICO}$ ratio significantly increased for M$-0.02$–$0.07$, CO$+0.02\rightarrow 0.02$, the CND, and the 180 pc ring, as compared to that for the bulk component of the CMZ. The $N_{CO}/N_{ICO}$ ratio of 0.47 for M$-0.02$–$0.07$ is approximately twice the CMZ average.

We could not draw a definite conclusion on the origin of the high $N_{CO}/N_{ICO}$ ratio because of the complexity of the Galactic center environment. We propose cosmic-ray/X-ray ionization and mechanical dissociation by fast shock as possible explanations. We also hypothesize that the [C$^+$]-enhanced regions in M$-0.02$–$0.07$ and the 180 pc ring are young molecular clouds with ages not greater than the chemical timescale of $C^0 \rightarrow CO$ conversion. Such young, massive molecular clouds were possibly formed by the bar-induced mass inflow in the Galactic center region.

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