

Three-Dimensional Structure of the Central Molecular Zone

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ABSTRACT

A detailed comparison of HI and CO line cube data of the Galactic Center (GC) region from the archives is obtained. The central molecular zone (CMZ) is shown to be embedded in the HI disc (central HI zone, CHZ) of radius ~ 320 pc and vertical scale height ~ 70 pc. A radio continuum belt is shown to run parallel to molecular Arms I and II. The belt draws a double infinity (∞) on the sky, connecting Sgr E ($l \sim -1^\circ.2$), C, B1, B2 and Sgr D ($+1^\circ.2$), and is interpreted as a warping star-forming ring. The molecular Arms are closely associated with the HI arms on the longitude-velocity diagram (LVD), showing coherent rigid-body ridges. Due to the close relationship between HI and CO, the HI line absorption can be used to determine the Arms' position relative to Sgr A, B1, B2 and C. Combining the trigonometric data of proper motions of Sgr A* and maser sources of Sgr B2 as well as radial velocities, the 3D velocity vector of Sgr B2 is determined. From these analyses, the molecular Arm I with Sgr B2 is shown to be located in the near side of Sgr A*, and Arm II with Sgr C in the other side, both composing a pair of symmetrical Arms around the GC. We present a possible 3D view of Sgr A through E and Arms I and II along with a parameter list.

Key words: Galaxy: centre — Galaxy: structure — ISM: atoms — ISM: molecules — radio lines: ISM

1 INTRODUCTION

The three-dimensional (3D) structure of the Central Molecular Zone (CMZ) has long been debated, but remains still controversial, because of the edge-on orientation of the central disc of the Galaxy (Morris & Serabyn 1996; Henshaw et al. 2022). Various methods have been proposed and used to solve this problem. For example, kinematic analysis of the longitude velocity diagram (LVD) assuming the Galactic rotation has been used to solve the line-of-sight degeneracy (Sofue 1995a; Sofue 2017; Oka et al. 1998; Tsuboi et al. 1999; Kruijssen et al. 2015; Henshaw et al. 2016; Tokuyama et al. 2019). Also, the method using absorption line profiles for background continuum emissions has offered powerful approaches (Sawada et al. 2004; Sofue 2017; Oka & Geballe 2022).

With the LVD method several arm structures have been suggested. The densest and most coherent LV ridge is called the Galactic Center (GC) Arm I, the second is Arm II, and further Arms (III and IV) have been proposed (Sofue 1995a). More recent analyses have shown a larger number of arms with projected lengths $\sim 100 - 250$ pc (Henshaw et al. 2016; Tokuyama et al. 2019).

The association of radio continuum sources and HII regions with the molecular structures has been also an important subject related to the star formation (SF) activity in the GC (Sofue 1990; Henshaw et al. 2022). The SF regions, Sgr B2

and C, are associated with the molecular complexes at the leading ends of Arm I and II, respectively (Hasegawa et al. 1994; Sofue 1995a; Sawada et al. 2004).

Despite of the extensive analyses about CMZ in the decades, however, a variety of conflicting models of the structure and kinematics have been proposed as is thoroughly summarized in a recent review article (Henshaw et al. 2022). This is mainly because of the lack in precise observational information about the 3D distribution, motion, and mutual location of gaseous structures and radio sources.

In this paper, we revisit this classical problem by analyzing data cubes of the CO and HI line emissions in the (l, b, v) space. By confirming a tight correlation of the HI structures with CO, we use the HI absorption to investigate the line-of-sight (los) spatial relations of the molecular structures. We further derive the 3D velocity vector of Sgr B2 with respect to Sgr A* using the data of trigonometric measurements of proper motions. We also revisit the spatial correlation of radio continuum structures with the molecular gas distribution (Sofue 1990) using the recent high-resolution radio imaging of the GC. In this paper, we adopt the GC distance of $R_0 = 8.18$ kpc (Gravity Collaboration et al. 2019).

The purpose of the present paper is to impose observational constraints on the basic parameters of the 3D structure and kinematics of the CMZ by analyzing the most recent observational data taken from the literature and archives. The parameters will help to distinguish a reliable model from the variety of theoretical models of the GC.

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2 DATA

The CO-line, HI 21-cm line, and 1.28 GHz radio continuum data have been taken from the archives as follows.

The ^{13}CO data were taken from the CO-line survey of the central $3^\circ \times 0^\circ.7$ region using the Nobeyama 45-m telescope (Tokuyama et al. 2019), which had a FWHM (full width of half maximum) angular resolution of $15''$, velocity resolution of 1 km s^{-1} , rms (root mean squared) noise temperature 1 K presented in a data cube with grid spacing of ($7''.5, 7''.5, 1 \text{ km s}^{-1}$).

The ^{12}CO data were taken from the survey of the central $\sim 4^\circ \times 1^\circ$ region using the 45 m telescope (Oka et al. 1998), which had an effective angular resolution of $37''$ ($= (\text{beam width}^2 + \text{grid spacing}^2)^{1/2}$, velocity resolution 2 km s^{-1} , rms noise of $\sim 1 \text{ K}$, presented by a data cube with grid spacing of ($34'', 34'', 2 \text{ km s}^{-1}$).

The HI data were taken from the survey with the Australia Telescope Compact Array (ATCA) of the central $10^\circ \times 10^\circ$ region (McClure-Griffiths et al. 2012), which had an angular resolution of $145''$, velocity resolution of 1 km s^{-1} , rms noise of 0.1 K , and are presented in a cube of spacing ($35'', 35'', 1 \text{ km s}^{-1}$).

While a variety of mm-wave lines have been used to analyze the molecular structures in the CMZ, detailed comparative study of the HI- and CO-line structures has not been obtained yet. This is mainly because of the HI angular resolutions not sufficient to resolve the GC structures by the current single dish observations (Kalberla et al. 2005; HI4PI Collaboration et al. 2016; McClure-Griffiths et al. 2009). From the CO and HI line data we construct integrated intensity (moment 0) maps to examine the spatial distributions of the molecular and atomic gases projected on the sky. We also perform a detailed comparison of the HI and CO-line LVDs to investigate the kinematics of the gaseous structures.

The CO line data are also compared with the radio continuum map in order to examine the spatial relationship on the sky of the molecular arms with star-forming regions. The radio continuum map at 1.28 GHz was taken from the MeerKAT Galactic Center archive (Heywood et al. 2022), which had angular resolution of $4''$ after Gaussian convolution and grid spacing of $1''.1$.

3 CMZ ENVELOPED BY CENTRAL HI ZONE (CHZ)

3.1 Disc-eliminated intensity maps

Because of the degeneracy of radial velocity near the Y axis (Sun-GC line) as well as for the long line-of-sight depth from the Sun to the far-side disc of the Galaxy, integrated intensity maps of the CO and HI line emissions in the GC region are significantly contaminated by the fore- and background disc. In order to avoid the contamination, we apply a method of Disc Elimination by radial Velocity cutting as described in the Appendix. Considering the velocity dispersion and radial motions by spiral arms as well as the expanding rings like the 3-kpc arm, we take the cutting velocity to be $V_{\text{cut}} = 50 \text{ km s}^{-1}$, so that the emission at $|V_{\text{lsr}}| \leq V_{\text{cut}}$ is subtracted from the total integrated intensity maps. Thereby, the emission from a fan-shaped region near the Y axis in the GC disc itself is also eliminated. This over-eliminated component

is recovered by considering the proportion of the fan-shaped area to the entire disc (see Appendix).

Fig. 1 shows the thus obtained integrated intensity (moment 0) maps using the ^{12}CO -line data (Oka et al. 1998) from the Nobeyama survey and HI from ATC survey (McClure-Griffiths et al. 2012). Panel (a) shows the integrated intensity map over the entire spectral (velocity) range, which we call hereafter Map A (All velocity), (b) integrated in $|V_{\text{lsr}}| \leq V_{\text{cut}} = 50 \text{ km s}^{-1}$ as Map B (Background disc), and (c) shows the intensity integrated at $|V_{\text{lsr}}| > 50 \text{ km s}^{-1}$ as Map C (Center). Namely,

$$\text{Map C} = \text{Map A} - \text{Map B}. \quad (1)$$

The lower panels (d), (e) and (f) show Maps A, B and C in HI, respectively. In Fig. 2 we present superposition of the DEV maps of the HI line emission in red color scaling (0 to 3000 K km s^{-1}) and ^{12}CO -line in green (0 to 2000 K km s^{-1}).

In other words, Map A is the usual integrated intensity map; Map B shows intensity of the fore- and background disc (hereafter, disc) near the degenerated velocities around $l \sim 0^\circ$; and Map C is the map showing intensity after subtracting the fore- and background disc.

Since we cut the emission at $|V_{\text{LSR}}| \leq V_{\text{cut}} = 50 \text{ km s}^{-1}$, the procedure also eliminates the low-velocity emission from the GC itself. Therefore, when Map C is used to measure the masses of CMZ and CHZ (central HI zone), the over-eliminated emissions must be recovered using the method described in the Appendix. The DEV maps are also used to define the CMZ and CHZ by measuring the cross sections along and perpendicular to the Galactic plane.

3.2 Definition of CMZ and CHZ from the intensity profiles

In Fig. 3 we show longitudinal and latitudinal distributions of column densities N of H_2 and HI gases as obtained from the disc-eliminated intensity Maps C with $V_{\text{cut}} = 50 \text{ km s}^{-1}$. The upper panel shows horizontal profiles at $b = -0^\circ.05$, and the lower panel is a vertical profile at $l = -0^\circ.75$. The vertical dashed lines enclose the region where HI absorption against radio continuum sources is significant. Here, we adopted the conversion factors as described in the next subsection.

The horizontal H_2 (CO intensity) profile is plateau like with sharp shoulders at $l = -1^\circ.1$ and $+1^\circ.8$ (-157 and $+257 \text{ pc}$) and full width is $w_r(\text{CO}) = 2^\circ.9 = 414 \text{ pc}$. The vertical profile is Gaussian like with the e -folding full width of $w_z = 0^\circ.4 = 57 \text{ pc}$ or a half width of $h_z(\text{CO}) \sim 0^\circ.2 (\pm 29) \text{ pc}$ from the peak position. We define the CMZ as the region enclosed by these shoulders as indicated by the thick lines in Fig. 3. We point out that the horizontal plateaued profile indicates a ring-like distribution of the molecular gas inside the CMZ.

The HI profiles are milder, having no clear boundaries, and the profiles outside the absorption region near Sgr A and B can be approximated by an exponential function. The horizontal e -folding scale radius is measured to be $h_r \sim \pm 2^\circ.2 = 314 \text{ pc}$, and the vertical scale height to be $h_z \sim 0^\circ.5 = 71 \text{ pc}$. We define the central HI zone (CHZ) as this squared area of $w_r \times w_z(\text{HI}) = 4^\circ.4 \times 1^\circ = 629 \times 143 \text{ pc}$ as indicated by the horizontal lines in Fig. 3.

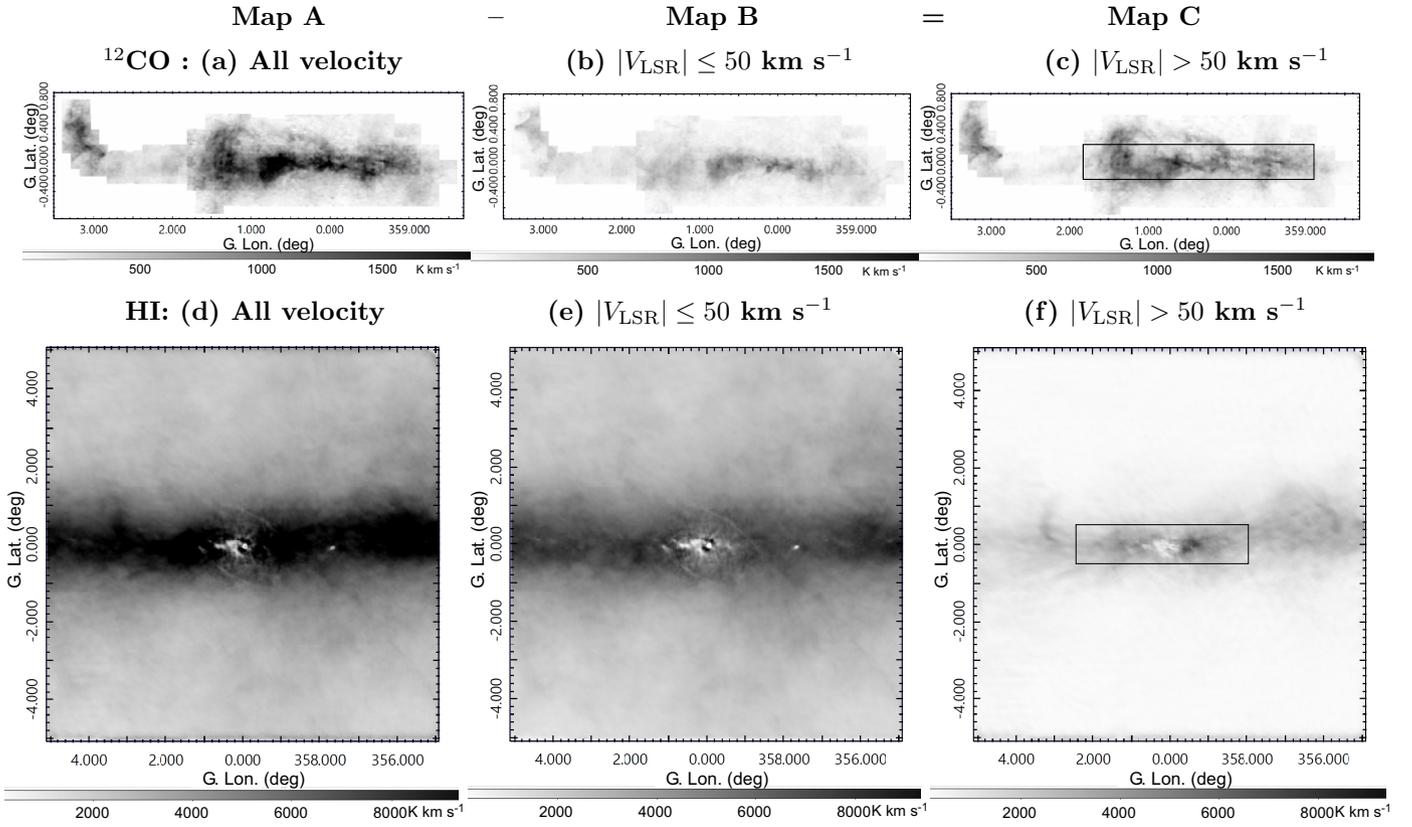


Figure 1. [Upper panels] Integrated intensity (I_{CO}) maps of the ^{12}CO line emission from Oka et al. (1998). (a) Map A: Total I_{CO} in All velocity range. Grey-scale bar indicates I_{CO} in K km s^{-1} . (b) Map B: within $|V_{\text{LSR}}| \leq 50 \text{ km s}^{-1}$, representing fore- and Background disc emission. (c) Map C: Outside $|V_{\text{LSR}}| > 50 \text{ km s}^{-1}$, representing GC emission. The squared box defines the CMZ. [Bottom panels] Integrated intensity map of the HI line emission from McClure-Griffiths et al. (2012). (d) Map A for HI I_{HI} . Intensity scale is K km s^{-1} . (e) Map B, and (f) Map C. The squared box defines the CHZ.

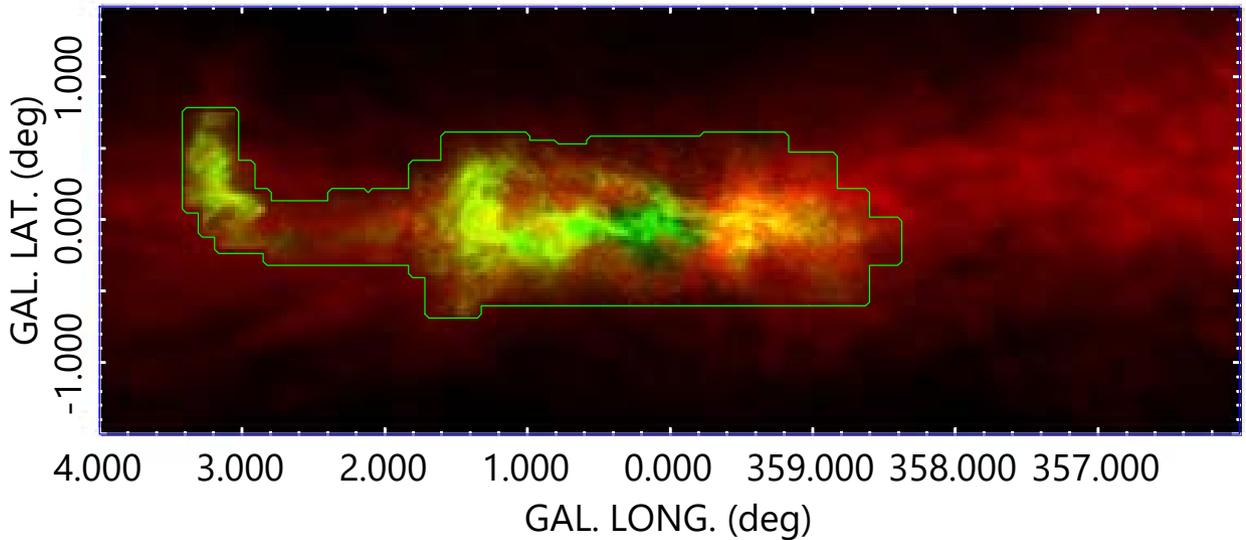


Figure 2. Superposition of the ^{12}CO map in green color on the HI map in red color. Green box encloses the area of the Nobeyama CO survey. Disc elimination at $|V_{\text{LSR}}| \leq 50 \text{ km s}^{-1}$ has been applied in both maps.

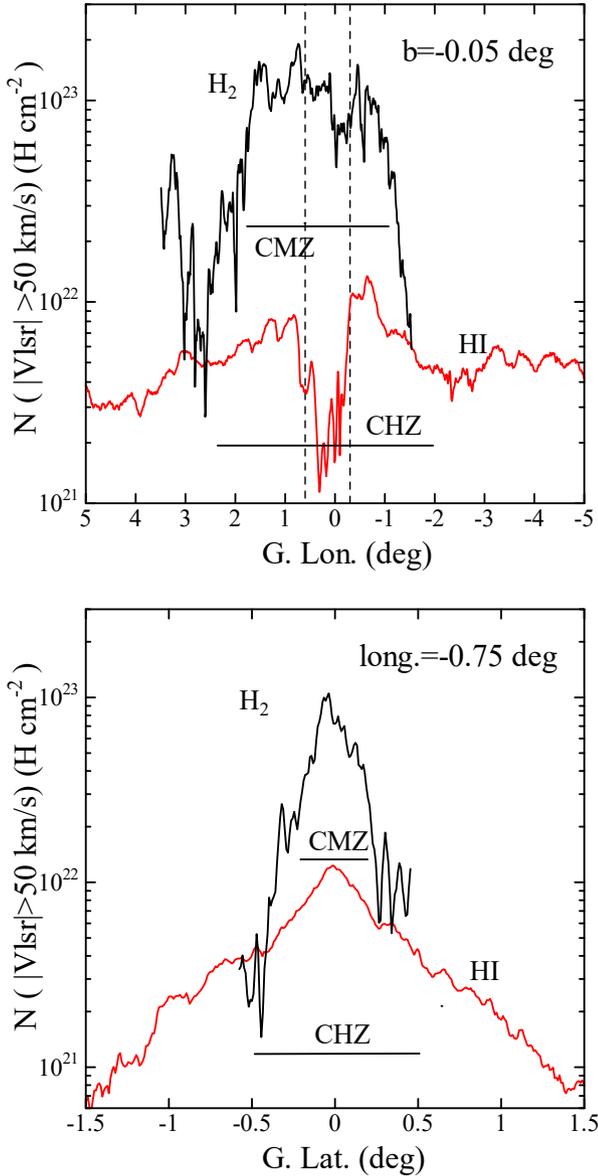


Figure 3. [Top] Horizontal cross sections at $b = -0^\circ.05$ of hydrogen column density N calculated from ^{12}CO and HI integrated intensities at $|V_{\text{LSR}}| \geq 50 \text{ km s}^{-1}$. [Bottom] Same, but vertical cross sections at $l = -0^\circ.75$.

3.3 CMZ Mass

The estimation of the mass of a "zone" in the GC direction is an ambiguous task by three reasons. One is the area of integration that depends on the quality of data (sensitivity and resolution) and by the authors definition. Second is the contamination of the fore- and background Galactic disc. The third problem is the uncertain conversion factor from CO line intensity to H_2 column density (Dahmen et al. 1998).

The first problem is solved by the new definition of the CMZ area in the previous subsection, and the second by the low-velocity cut method (DEV) for the line integration. For applying the DEV, there appear three kinds of masses.

- M_A stands for the total mass using intensity integrated over all the velocity range.
- M_C^0 is the mass after eliminating the fore- and background at $|V_{\text{LSR}}| \leq V_{\text{cut}}$ (here 50 km s^{-1}).
- M_C is the final mass after correcting for the over-elimination of the near-Y axis fan-region in M_C^0 .

As to the conversion from ^{12}CO intensity to molecular column density, we use the relation

$$N_{\text{H}_2} = X_{\text{CO}} I_{\text{CO}}, \quad (2)$$

where X_{CO} is the CO-to- H_2 conversion factor. We adopt the empirical relation between X_{CO} and GC distance R , considering the metallicity gradient in the Galaxy (Arimoto et al. 1996), and rewrite the formula in terms of the local value X_0 at $R = R_0$,

$$\log X_{\text{CO}}(R)/X_0 = 0.41(R - R_0)/r_e. \quad (3)$$

Here, $r_e = 6.2 \times (R_0/10 \text{ kpc}) = 5.1 \text{ kpc}$ is the scale radius of the metallicity gradient, which has been re-scaled to $R_0 = 8.18 \text{ kpc}$ from the original metallicity gradient of 0.07 ± 0.015 dex per kpc derived for $R_0 = 10 \text{ kpc}$ (Shaver et al. 1983). Adopting the local value of $X_0 = X_{\text{CO}}(R_0) = 2.0 \times 10^{20} \text{ H}_2 \text{ cm}^{-2} [\text{K km s}^{-1}]^{-1}$ (Bolatto et al. 2013; Sofue & Kohno 2020), we obtain the conversion factor in the GC ($R = 0$) to be

$$X_{\text{CO}}(0) = 0.51 \times 10^{20} \text{ H}_2 \text{ cm}^{-2} [\text{K km s}^{-1}]^{-1}. \quad (4)$$

We first estimate the total luminosity without applying the disc elimination using Fig. 1 (a) by measuring the mean intensity in the defined CMZ area, A in $l = -1^\circ.1 = -157 \text{ pc}$ to $+1^\circ.8 = +257 \text{ pc}$ and $b = -0^\circ.2 = -29 \text{ pc}$ to $+0^\circ.2 = +29 \text{ pc}$, and obtain $I_{\text{CO}} \sim 1035 \text{ K km s}^{-1}$. The total molecular mass of CMZ is then calculated as

$$M_A(\text{CMZ}) = 2\mu m_{\text{H}} A X_{\text{CO}}(0) I_{\text{CO}} \sim 2.8 \times 10^7 M_\odot. \quad (5)$$

Here, we assumed the mean molecular weight of $\mu = 1.4$ per hydrogen atom including metals.

We then measure the mean ^{12}CO intensity in the CMZ on the disc-eliminated Map C in panel (c) of Fig. 1, and obtain $I_{\text{CO}} \sim 681 \text{ K km s}^{-1}$. The disc-eliminated mass M_C^0 of the CMZ is then estimated by multiplying the area of CMZ to be

$$M_C^0(\text{CMZ}) = 1.8 \times 10^7 M_\odot. \quad (6)$$

As described in the Appendix, we further correct for the over-elimination of the CMZ itself within the fan-shaped area of

$$\phi = \sin^{-1}(V_{\text{cut}}/V_{\text{rot}}) = 19^\circ.5 \quad (7)$$

for $V_{\text{cut}} = 50$ and $V_{\text{rot}} = 150 \text{ km s}^{-1}$. This component is seen as an excess over the extended fore/background emission in Map B of panel (b) of Fig. 1. The fan correction factor is given by

$$\gamma = 1/(1 - 2\phi/\pi) = 1.28, \quad (8)$$

and we obtain the corrected final mass of the CMZ by

$$M_C(\text{CMZ}) = \gamma M_C^0 \sim 2.3 \times 10^7 M_\odot. \quad (9)$$

Comparison of M_C with the non-corrected mass, M_A , tells us that the current estimation of the molecular mass in the GC has been systematically over-estimated by about 22%.

Table 1. Molecular and HI masses in CMZ and CHZ[†]

Region	Mol. or HI	Area <i>l</i> range	Area <i>b</i> range	M_A (M_\odot)	M_C (M_\odot)	Method
CMZ	Mol. gas	$-1^\circ.1 \sim 1^\circ.8$	$-0^\circ.2 \sim +0^\circ.2$	2.8×10^7	2.3×10^7	Sq. photom., area col. 2,3, Fig. 1(a)(c)
ibid	HI	ibid	ibid	4.6×10^6	2.3×10^6	Sq. photom., area col. 2,3, Fig. 1(d)(f)
CHZ	HI	$-2^\circ \sim +2^\circ.5$	$-0^\circ.5 \sim +0^\circ.5$	1.8×10^7	6.9×10^6	Sq. photom., area col. 2,3, Fig. 1(d)(f)

[†] Conversion factor of $X_{\text{CO}}(0) = 0.51 \times 10^{20} \text{ H}_2 \text{ cm}^{-2} [\text{K km s}^{-1}]^{-1}$ is used. M_A stands for total integrated mass over all the velocity range. M_C gives the mass after disc elimination by velocity at $|V_{\text{LSR}}| \leq 50 \text{ km s}^{-1}$ and corrected for fan-shape over elimination.

3.4 CHZ Mass

The HI mass of the CHZ is calculated by

$$M = \mu m_{\text{H}} A X_{\text{HI}} I_{\text{HI}}, \quad (10)$$

where

$$X_{\text{HI}} = 1.82 \times 10^{18} \text{ H cm}^{-2} [\text{K km s}^{-1}]^{-1}. \quad (11)$$

This relation requires that the HI line is optically thin, which is approximately satisfied in the integrated velocity ranges, where the brightness temperature is mostly less than $\sim 40 \text{ K}$.

The HI zone (CHZ) is extended without clear-cut boundaries. The longitude and latitude profiles in Fig. 3 indicate that the distribution can be approximately fitted by an exponential function of the longitude and latitude. So, we measured the e -folding longitudes to be $l \sim -2^\circ$ (286) pc and $\sim +2^\circ.5$ (357 pc), and latitude heights are $b = -0^\circ.5$ and $+0^\circ.5$ (± 71 pc).

We also apply the disc elimination using the same method as for CMZ, and the obtained HI maps are shown in Fig. 1. We use these maps to measure the integrated intensity by square-box photometry for the CHZ region as above as well as for the CMZ region given in the previous subsection. We thus obtain the simply integrated mass

$$M_A(\text{CHZ}) = 1.8 \times 10^7 M_\odot, \quad (12)$$

and the mass corrected for the disc elimination and over correction as

$$M_C(\text{CHZ}) = 6.9 \times 10^6 M_\odot. \quad (13)$$

It is impressive that the total mass is 2.6 times greater than the disc eliminated and fan corrected mass. This is because the disc emission dominates in the Galactic plane, and is much brighter than the GC emission. For comparison, we also measure the corrected HI mass inside CMZ as

$$M_C(\text{HI in CMZ}) = 2.3 \times 10^6 M_\odot, \quad (14)$$

which is 10% of the CMZ's molecular mass. The results are listed in table 1.

3.5 Molecular fraction

The molecular and HI masses in the same area of the CMZ yield an HI-to-H₂ mass ratio of $\eta \sim 0.09$ and the molecular fraction of $f_{\text{mol}} = 1/(1 + \eta) \sim 0.9$. The molecular fraction can be calculated also locally using the column density plots in Fig. 3, which varies from ~ 0.9 to 0.95 inside the CMZ.

The high molecular fraction in CMZ is consistent with that found in the GC region by analyses of the global distributions

of HI and H₂ gases observed in the Galaxy as well as the theoretical calculations assuming the exponential variation of the pressure P , metallicity Z , and ultra-violet radiation field U (Sofue & Nakanishi 2016; Koda et al. 2016). It is, however, significantly higher than the theoretical value of $f_{\text{mol}} \sim 0.5$ incorporating the phase transition between HI and H₂ in the CMZ (Tress et al. 2020). A detailed study of the molecular fraction in the GC will be presented in a separate paper (Sofue 2022).

We comment that the mass ratio between $M_C(\text{CMZ})$ and $M_C(\text{CHZ})$ is $\eta \sim 0.25$, which gives an apparently lower molecular fraction $f_{\text{mol}} \sim 0.8$. However, this milder value is due to the different areas (extent and height) of mass estimations for CHZ and CMZ, and hence, it does not represent the ISM condition.

3.6 Comment on the over-estimation of the mass in the GC

The difference by a factor of 1.2 between the molecular mass of CMZ by all-velocity integration (M_A) and the DEV mass by low-velocity cutting after the correction for the over-elimination (M_C) must be taken into account, when we discuss details of the mass distribution in the GC. Namely, we must be aware that the current mass estimations of molecular gas in the GC have over-estimated it by about $\sim 20\%$. This comes mainly from the the 4-kpc molecular ring and its counter arm, and the number of intervening spiral arms in front and beyond the GC. Such an overestimation is much larger and far more crucial in the HI mass calculation, because the HI in the outer disc (near and far) is much more brighter than the CHZ.

4 GC ARMS AND STAR-FORMING RING

4.1 Arms I and II

Fig. 4 (top panel) shows a moment 0 (integrated intensity, I_{CO}) map of the ¹³CO line emission integrated over the velocity range of $-220 \leq V_{\text{LSR}} \leq 220 \text{ km s}^{-1}$ using the ¹³CO -line survey (Tokuyama et al. 2019). Here we used the ¹³CO line, which is less contaminated by the disc than the ¹²CO line, and is more appropriate to abstract arm and cloud structures in the CMZ.

The two major molecular arms named as GC Arm (GCA) I and II (Sofue 1995a) are traced by the red lines. The arms compose coherently stretched ridges extending over $\sim 1^\circ.5$ in the longitudinal direction, and are slightly curved and bent

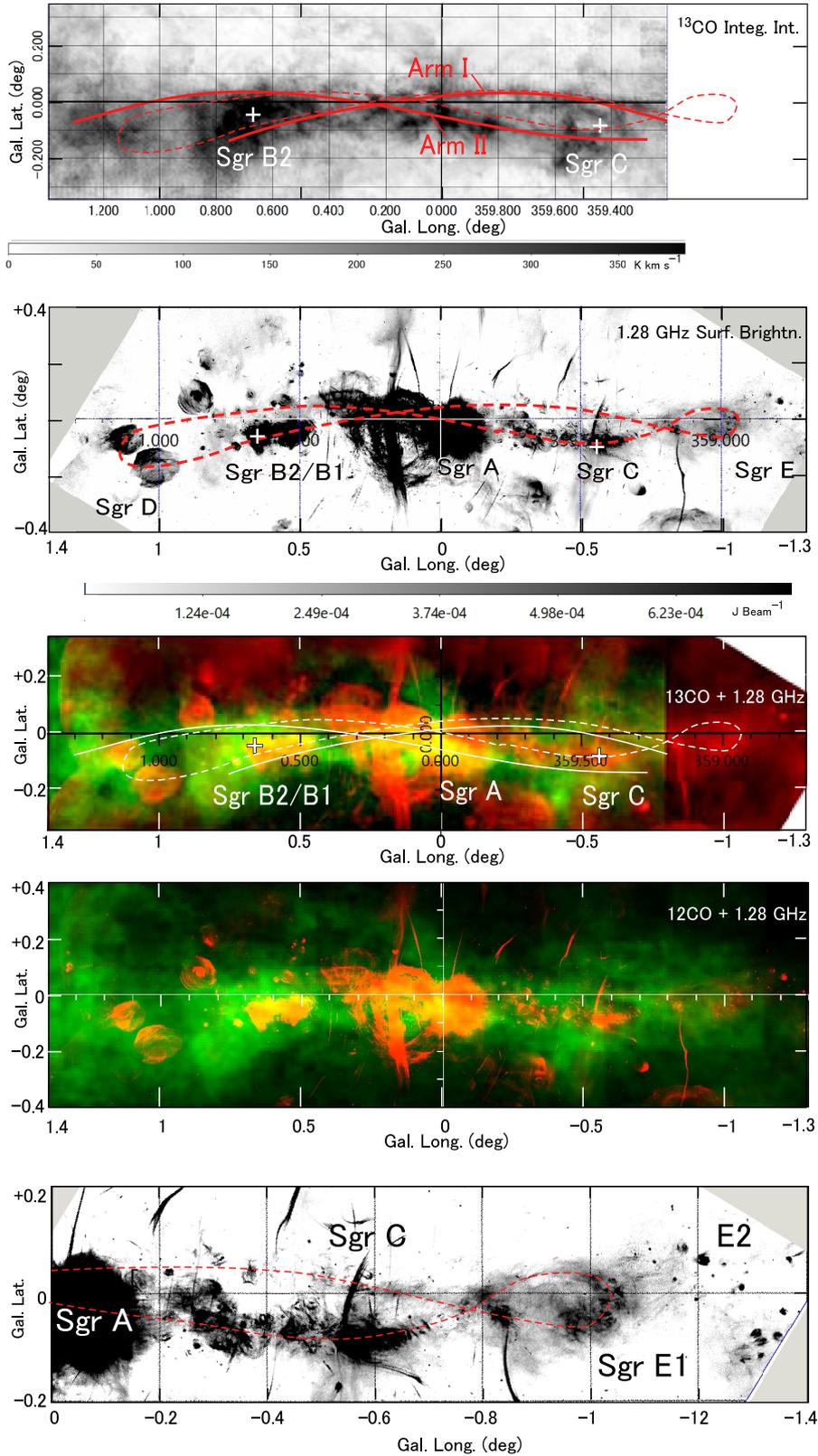


Figure 4. [Top] ^{13}CO -line integrated intensity (moment 0) map made from the CO survey with the Nobeyama 45-m telescope (Tokuyama et al. 2019). GC Arms I and II are traced by the full lines. [2nd] MeerKAT image of the radio continuum emission at 1.28 GHz (Heywood et al. 2019; Yusef-Zadeh et al. 2022). The radio belt is traced by the dashed line, indicating a warped ring linking Sgr B1, B2, C, D and E. [3rd] Superposition of the ^{13}CO intensity map (green) on 1.28 GHz map (red). [4th] Same, but ^{12}CO map (green; from 0 to 2500 K km s $^{-1}$; Oka et al. 1998) on 1.28 GHz (red). [Bottom] Enlargement of the radio belt near Sgr C and E from the 2nd panel.

concave to the north. The latitudinal full width of the arms is as narrow as $\sim 0^\circ.2 - 0^\circ.3$ (~ 29 to 43 pc).

Arm I is associated with the Sgr B molecular complex at $l \sim 0^\circ.6$ to $\sim 0^\circ.9$ nesting the HII regions Sgr B2 and B1. Arm II is associated with a molecular clump at $l \sim -0^\circ.4$ to $\sim -0^\circ.6$, which nests Sgr C. The molecular complex and clump are locally extending in the latitude direction, reaching $b \sim -0^\circ.2$. The total molecular mass of the Arms and complexes shares $\sim 80\%$ of the total molecular mass of the CMZ (Sofue 1995a).

4.2 Radio belt from Sgr E through D

Comparison of the distributions of the CO-line intensity and 10 GHz radio continuum emission in the GC on the sky has shown their global mutual association as well as their local avoidance with each other in smaller scales (Sofue 1990; Hasegawa et al. 1994).

We here compare in more detail the CO line intensity map from the Nobeyama 45-m telescope (Oka et al. 1998; Oka et al. 1998b; Tokuyama et al. 2019) with the high-resolution radio continuum map at 1.28 GHz from MeerKAT (Heywood et al. 2022; Yusef-Zadeh et al. 2022), which are shown in Fig. 1 and 4. Besides Sgr B, C, D and E, the molecular disc is shown to be associated with a horizontal belt of numerous HII regions with thermal radio emission having flat radio spectra (Yusef-Zadeh et al. 2022).

We first notice a prominent belt (or chain) of extended radio sources running through Sgr C in the 2nd panel as marked by the dashed line, which apparently starts from $(l, b) \sim (-0^\circ.2, -0^\circ.04)$ and runs across Sgr C. The belt runs nearly parallel to the molecular Arm II shown by the red line in the top panel. The radio sources along the belt have flat radio spectra indicating that they are mostly thermal objects (Yusef-Zadeh et al. 2022).

The belt further extends to the west, crossing the Galactic plane around $l \sim -0^\circ.8$, and reaches $l \sim -1^\circ.1$ at the eastern clump of HII regions in Sgr E, which we name here Sgr E1. The radio clump E1 appears to be a separate structure from the cluster of HII regions distributed along the western-most dust ridge (Anderson et al. 2020), which we call here Sgr E2. The bottom panel of the figure enlarges the radio belt, and the major radio continuum sources.

The radio belt, then, bends sharply in Sgr E1 at $l = -1^\circ.1$, and returns to the east by drawing an ∞ shape, while the returning belt is weaker. It then crosses again the Galactic plane at $l \sim -0.8$, and extends to the east parallel to the molecular Arm I. It is once disrupted by Sgr A around $l \sim -0^\circ.2$, but again continues to positive longitude side parallel to Arm I. The belt reaches Sgr B1 and B2, which is enveloped by an extended radio emission elongated toward the west, and can be linked to Sgr D.

Symmetrically to Arm I's radio belt, the belt coming from Sgr C along Arm II is traced toward the east, running near SNR G0.9+0.1, and reaches Sgr D. There, it is connected to the belt coming from the south along Arm I to compose a continuous bent belt as marked by the dashed line.

4.3 Sky Projection of the Star-Forming Ring Drawing a Double Infinity

We have thus linked the thermal radio sources (HII regions Sgr B1, B2, C, and E1) and Sgr D by a continuous belt as indicated by the dashed line in Fig. 4. It draws a double-infinity (∞) shape on the sky with the vertical amplitude of $\delta z \sim \pm 0^\circ.06$ (± 8.6 pc), and attains three times the maximum z heights. The particular shape suggests that the belt is an edge-on projection of a warping/waving ring of star forming regions in accordance with the bending Arms I and II of molecular gas that compose a warped ring tilted by 5° from the Galactic plane (Sofue 1995a). This view is also in accordance with the warped ring exhibiting an infinity-shape (Molinari et al. 2011; Henshaw et al. 2016).

Thus, the present double infinity has expanded the GC ring from the area at $l \sim \pm 0^\circ.8$ between Sgr B and C to a larger and more perfect ring with radius $l \sim \pm 1^\circ.2$, and links the major four radio sources including Sgr D and E. We also point out that the double infinity has three maximum heights in the z direction. It has no fixed rotation axis that defines a tilted disc or a ring. So, the wavy nature of the ∞ has no direct correlation with the larger scale HI disc with a tilt angle $\sim 10 - 20^\circ$ (Liszt & Burton 1980; McClure-Griffiths et al. 2012; Krishnarao et al. 2020), the expanding molecular cylinder with axis at $PA \sim -15^\circ$ tilted toward west (Sofue 2017), or the extended hot plasma with minor axis direction at $PA \sim -20^\circ$ (Yamauchi et al. 1990).

The ∞ shape can be interpreted as due to an oscillation of a rotating ring in the vertical direction (Tress et al. 2020), which has three amplitude maxima, and hence three times oscillation in one rotation. Since Arm I is located in the near side and rotation is clockwise as seen from the North Galactic Pole, as discussed in later section, the ring has three ascending nodes, which appear at $l = -0^\circ.7$, $+0^\circ.8$ and at $-0^\circ.9$. The oscillation period is one third of the rotation period, which is on the order of $P_z \sim (1/3)2\pi R/V_{\text{rot}} \sim 1.2 \times 10^6$ y for $R \sim 120$ pc and $V_{\text{rot}} \sim 200$ km s^{-1} .

In the 3rd and 4th panels of Fig. 4 we superpose integrated intensity (moment 0) maps of the ^{13}CO (Tokuyama et al. 2019) and ^{12}CO line (Oka et al. 1998) in green color, respectively, on the 1.28 GHz radio continuum map in red. The molecular Arms are associated with the radio belt as indicated by the full and dashed lines, respectively.

It is interesting to point out that the molecular Arms are vertically displaced from the radio belt. The local displacement of HII regions and molecular clouds, and the systematic displacement between molecular and SF spiral arms seen from the Galactic poles, are well known and explained in terms of star formation mechanisms in density-wave and galactic shock theories of spiral arms. However, the systematic displacement of the molecular and radio bands perpendicular to the galactic plane is noted here for the first time, raising new questions about the vertical bias of SF activity in the GC disk.

4.4 Sgr D and SNRs

Although Sgr D has been suggested to be fore- or background objects independent of the GC (Kauffmann et al. 2017), we reconsider here its distance and association with the GC based on the recent high resolution radio continuum

Table 2. SNRs in Sgr D region

SNR	$\Sigma_{1\text{GHz}}$ ($\text{w m}^{-2}\text{Hz}^{-1}\text{str}^{-1}$)	Ang. dia (arc min)	Diam. (pc)	Dist. (kpc)
G1.1-0.1	1.84	7.4	19.2	8.9
G1.0-0.2	1.47	9.1	21.1	8.0
G0.9+0.1	1.42	7.6	21.4	9.6

data (Yusef-Zadeh et al. 2022; Henshaw et al. 2022). Sgr D is composed of three SNRs and two HII regions (Mehringer et al. 1998). The easternmost radio shell G1.1-0.1 has a steep radio spectrum of $\alpha \sim -1$ indicative of a SNR (Yusef-Zadeh et al. 2022). The shell is overlapped by an HII region G1.15-0.07, which is a foreground object at a distance of 2.36 kpc from the Sun according to the trigonometric measurements by VERA (Sakai et al. 2017). G1.0-0.2 is a typical shell-type SNR with nonthermal radio emission. G0.9+0.1 is a nonthermal radio shell also overlapped by a bright HII region with brightness temperature of $T_b \sim 270$ K (Yusef-Zadeh et al. 2022).

In order to examine if these shell-type SNRs are GC objects, we estimate their distances using the $\Sigma - D$ (surface brightness-diameter) relation at 1 GHz empirically fitted to SNRs with known distances including those of the LMC and SMC,

$$\Sigma_{1\text{GHz}} = 2.07^{+3.10}_{-1.24} \times 10^{-17} D(\text{pc})^{-2.38 \pm 0.26} \text{w m}^{-2}\text{Hz}^{-1}\text{str}^{-1} \quad (15)$$

(Case & Bhattacharya 1998). Mean surface brightness at 1.28 GHz was measured on the MeerKAT image after subtracting the HII regions, and converted to brightness at 1 GHz assuming a radio spectrum of $\alpha = -1$.

The estimated linear diameters and distances from the Sun are listed in table 2 along with the mean brightness and angular sizes. Considering the scatter and uncertainty of the $\Sigma - D$ relation, which is on the order of $\pm 30\%$, we may conclude that the three SNRs are GC objects. Their diameter ~ 20 pc indicates a young age of $t \sim 10^3 - 10^4$ y, suggesting that the Sgr D area was a recent SF site. Also recalling that the region from $R \sim 0.3$ to ~ 2 kpc around the GC is almost empty in molecular clouds and SF sites, we may consider that the distance coincidence around 8 kpc and the young ages strongly support that the SNRs are GC objects. So, we here assume that they are associated with the CMZ.

5 KINEMATICS AND 3D STRUCTURE

5.1 Longitude-Velocity Diagrams (LVD): Tight correlation of CO and HI features

Since the CMZ and CHZ as well as the radio continuum belt are sky projections of edge-on disc and arms, their 3D structures are degenerated in the intensity maps. Longitude-velocity diagram (LVD) is a powerful tool to solve this degeneration. Fig. 5 shows an LVD of the ^{13}CO line emission in comparison with the integrated-intensity map as reproduced from the Nobeyama CO-line survey (Tokuyama et al. 2019). Extended structures in the intensity map has been subtracted using the background-filtering technique, and the vertical scale is enlarged twice, so that Arms I and II are more clearly visible than in the ^{12}CO map in Fig. 1. The LVD has

been averaged between $b = -0^\circ.3$ and $+0^\circ.3$, where the major structures discussed in this paper are labelled. Arms I and II compose the major structure in the CMZ drawing tilted straight LV ridges across the coordinate origin.

The expanding molecular ring (EMR) and cylinder (EMC) (Sofue 1995b; Sofue 2017), or the parallelogram in the bar model (Fux 1999; Sormani et al. 2018; Henshaw et al. 2022), show up as a diffuse features at high forbidden velocities, labelled as EMR/EMC/Plg. Approximate positions of Sgr B and C are also marked on the eastern end of Arm I and western end of Arm II, respectively.

In order to see how the HI gas distribution is correlated with the molecular structures, we then compare the CO LVDs with HI. Fig. 5(b) shows an T_b LVD of the ^{12}CO in green color and HI in red at a latitude of $b = +0^\circ.05$. Panel (c) shows the same but at $-0^\circ.05$ and (d) at $-0^\circ.3$. From these superposed maps, we can recognize the tight correlation of the CO and HI structures in the GC.

5.2 GC Arms I and II in the LVD

It is stressed that the molecular Arms I and II in the CO line are also well traced in the HI LVD as shown in Fig. 6. Arm I is traced as the most prominent and longest ridge both in CO and HI, starting at $(l, V_{\text{LSR}}) \sim (0^\circ.66, +70 \text{ km s}^{-1})$ near Sgr B2 and extending straightly to the bottom-right corner of the diagram. The HI LV ridge extends further toward negative longitudes, reaching $(l, V_{\text{LSR}}) \sim (-2^\circ, -200 \text{ km s}^{-1})$. The main CO ridge intersects the rotation axis at $(l, V_{\text{LSR}}) = (0^\circ, -30 \text{ km s}^{-1})$ corresponding to a displacement of the apparent rotation center to $l \sim +0^\circ.2$.

Arm II is also traced as an LV ridge in CO and HI, starting from the left-side edge of the top panel at $(l, V_{\text{LSR}}) \sim (+1^\circ.5, 100 \text{ km s}^{-1})$, keeping the velocity till $(0^\circ.15)$. There, it bends and further extends, making a straight tilted LV ridge, and reaches $(-0^\circ.7, -140 \text{ km s}^{-1})$ near Sgr C. The main CO ridge intersects the rotation axis at $(l, V_{\text{LSR}}) = (0^\circ, +40 \text{ km s}^{-1})$ with apparent rotation center at $\delta l \sim -0^\circ.15$.

The straight LV ridges along Arms I and II, nesting Sgr B and C, can be interpreted as due either to a rotating solid disc or a ring. Because the former case (solid disc) is not allowed in the gravitational potential in the GC, it can be attributed to a rotating ring. Largely elongated elliptical orbit in a bar that postulates velocity splitting greater than $\sim \pm 30 - 40 \text{ km s}^{-1}$ at $l \sim 0^\circ$ cannot explain the straight LV ridge.

5.3 Expanding Ring/Cylinder/Parallelogram

The expanding molecular ring/cylinder/parallelogram (EMR/EMC/Plg) is visible at high non-circular velocities, extending in the latitude direction and composing a cylindrical structure. The EMC mass has been estimated in our earlier work (Sofue 1990b; Sofue 1995b; Sofue 2017), and we re-scale it using the presently adopted conversion factor, obtaining $M_{\text{EMC}} \sim 4.5 \times 10^6 M_\odot$. So, the EMC's mass is only about $\sim 10 - 20\%$ of the CMZ.

The EMC is visible both in the CO and HI LVDs as oval ridges at positive and negative high velocities at $V_{\text{LSR}} \pm 100 - 200 \text{ km s}^{-1}$. The LV ellipse is clearer at higher latitudes at

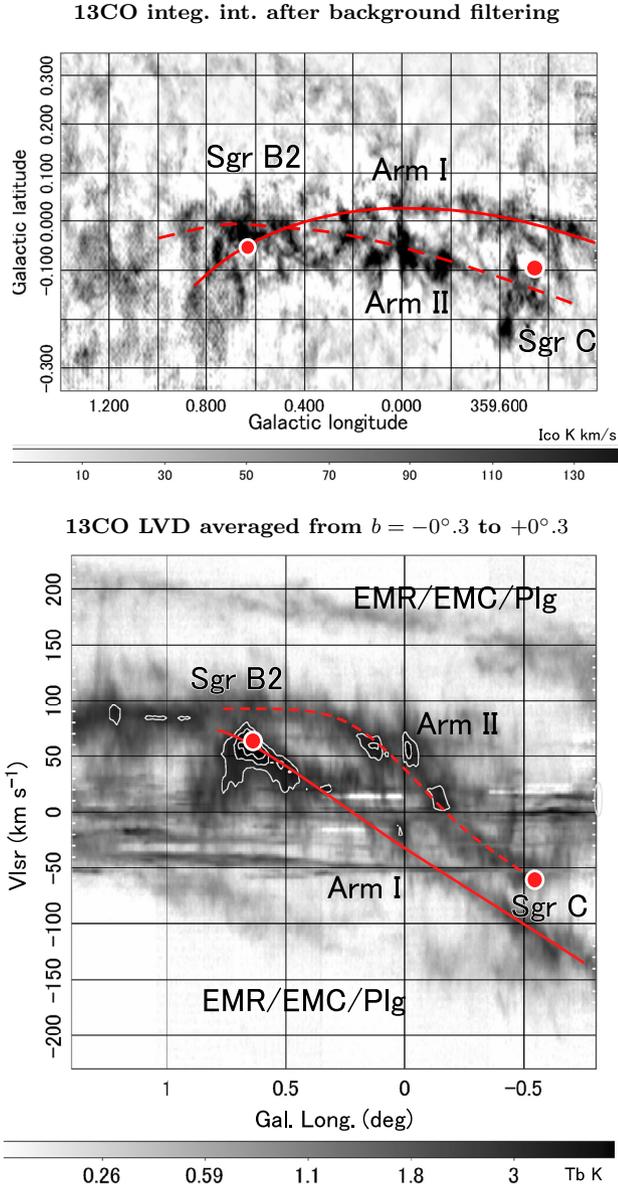


Figure 5. [Top] Background-filtered map of integrated intensity of ^{13}CO emission with the b (vertical) axis enlarged twice, and [bottom] LVD of ^{13}CO line emission from the Nobeyama Bears CO survey (Tokuyama et al. 2019). Major structures discussed in the text and Fig. 6 are labelled. Intensity scale in LVD is logarithmic. Note that EMR/EMC/Plg is an order of magnitude less bright than Arms.

$|b| \gg 0^\circ.3$ (> 40 pc). The ^{12}CO LVD of EMR/EMC can be fitted by a cylinder with radius ~ 200 pc, expanding at $v_{\text{exp}} \sim 160 \text{ km s}^{-1}$ with rotation speed of $V_{\text{rot}} \sim 75 \text{ km s}^{-1}$ (Sofue 2017).

It is interesting to point out that the EMC’s LV feature is fainter or even lacking near the Galactic plane. This suggests that the cylinder is swept away or broken by the interaction with the CMZ Arms.

5.4 3D kinematics from proper motion

We determine the 3D velocity of Sgr B2 with respect to Sgr A* using the proper motions of Sgr A* and maser sources in Sgr B2, which have been measured extensively in the decades using the VLBA (Very Long Baseline Array) (Reid et al. 2009; Reid & Brunthaler 2020), and VERA (VLBI Exploration of Radio Astrometry) (Oyama et al. 2021; VERA Collaboration et al. 2020). Combining the proper motions with the radial velocity, we can calculate the 3D velocity vector of Sgr B2 with respect to Sgr A*. In table 3 we list the observed values, and calculated results.

Taking an average of the measurements, we obtain the 3D velocity vector as follows. Sgr B2 is moving toward increasing longitude (to east) at $V_l \simeq 87.4 \text{ km s}^{-1}$ with respect to Sgr A*, vertically toward negative latitude at $V_b \simeq -28.3 \text{ km s}^{-1}$, and at radial velocity of $V_{\text{LSR}} = +62.3 \text{ km s}^{-1}$ in the line-of-sight direction. These values yield rotational velocity of 107.3 km s^{-1} projected on the Galactic plane, and absolute velocity $V \simeq 111.0 \text{ km s}^{-1}$.

If we assume a circular orbit, the velocity vector can be used to determine the spatial position of Sgr B2 with respect to Sgr A* by combining with the projected distance on the sky of $0^\circ.66$ (94 pc), which yields a galacto-centric distance of $r = 160$ pc from Sgr A* at a position angle of $\theta = 144^\circ.9$ as seen from the North Galactic Pole, or making an angle 36° to the line of sight.

From the velocity vector, the inclination angle of the orbit is determined to be $i = -14^\circ.2$. This yields a projected tilt angle of the motion on the sky of $p = -18^\circ.0$ from the Galactic plane, or Sgr B2 is moving toward the south west at a position angle of $PA = 108^\circ$ in the Galactic coordinates.

We comment that such a tilted orbit may be related to the curved ridge of Arm I as shown in Fig. 4 and to the vertical oscillation of the warped ∞ SF ring. Sgr B2 is located at the left-side end of the Arm I, significantly below the galactic plane, apparently leading the Arm toward $PA \sim 108^\circ$. Such an inclined orbit, or perpendicular motion in the rotating frame, may be related to the vertically extended structure of the Sgr B2 molecular cloud.

5.5 Arm’s curvature by dv/dl method

We try to estimate the curvature of Arms I and II by assuming that they are rotating around the GC. If rigid-body tilt of the LVD is attributed to circular (nearly circular) motion, the velocity gradient $dv/dl = dV_{\text{LSR}}/dl$ of the ridge is related to the curvature r_{curv} of the arm/ring through (Sofue 2006)

$$r_{\text{curv}} \simeq R_0 V \left(\frac{dv}{dl} \right)^{-1}. \quad (16)$$

Using the LVD, we measured the gradient around $l \sim 0^\circ$ to be $dv/dl \sim 147 \text{ km s}^{-1} \text{ deg}^{-1}$ for Arm I, and $\sim 193 \text{ km s}^{-1} \text{ deg}^{-1}$ for II. So, if we assume the same rotation velocity as Sgr B2 of $V \sim 106 \text{ km s}^{-1}$, we obtain the approximate curvature of Arm I to be $r_{\text{curv,ArmI}} \simeq 103$ pc, and Arm II $r_{\text{curv,ArmII}} \simeq 79$ pc. Note that the method applies even to an oval or elliptical ring, but it does not tell us in which side the arm is located, near or far from the center.

The curvature $r_{\text{curv,ArmI}} \simeq 103$ pc of Arm I is less than the GC distance of Sgr B2, $R_{\text{SgrB2}} \simeq 160$ pc, as derived from the

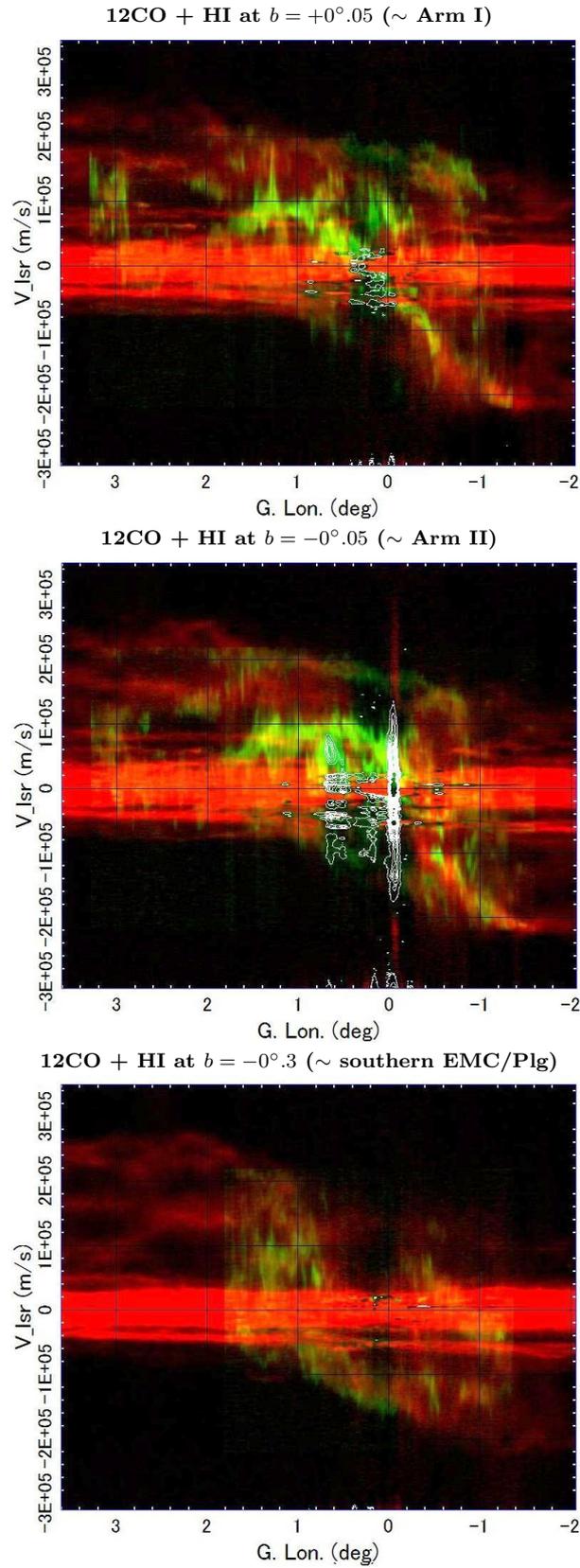


Figure 6. HI LVD (T_b in red from 0 to 50 K) superposed on the ^{12}CO LVD (green from 0 to 20 K). White contours are negative HI T_b from -10 K at interval -50 K. (HI: McClure-Griffith et al. 2012; CO: Oka et al. 1998). [Top] At $b = +0^\circ.05$, approximately along Arm I. [Middle] At $b = -0^\circ.05$, partially along Arm II. [Bottom] At $b = -0^\circ.3$, showing round LV arc of EMR/EMC/Plg. Note that molecular Arms I and II are not visible at this height.

Table 3. Proper motion and relative velocity of Sgr B2 about Sgr A*.

Object	$\mu_\alpha \cos \delta$ (mas y ⁻¹)	μ_δ	$\mu_l \cos b$	μ_b	$\mu_{l,BA}$	$\mu_{b,BA}$	$V_{l,BA}$ (km s ⁻¹)	$V_{b,BA}$	V_{LSR}
VLBA ¹									
Sgr A*			-6.411 ± 0.008	-0.219 ± 0.007					
Sgr B2N	-0.32 ± 0.05	-4.69 ± 0.11	-4.28 ± 0.10	-1.95 ± 0.07	2.13 ± 0.10	-1.73 ± 0.07	82.7 ± 3.9	67.1 ± 2.7	$+64 \pm 5$
Sgr B2M	-1.23 ± 0.04	-3.84 ± 0.11	-3.96 ± 0.10	-0.74 ± 0.06	2.45 ± 0.10	-0.53 ± 0.06	94.9 ± 3.9	-20.4 ± 2.5	$+61 \pm 5$
VERA ²									
Sgr A*			-6.307 ± 0.025	-0.214 ± 0.017					
Sgr B2	-1.83 ± 0.21	-3.70 ± 0.09	-4.13 ± 0.14	-0.15 ± 0.19	2.18 ± 0.13	0.065 ± 0.19	84.7 ± 5.0	2.6 ± 7.4	$+62.0 \pm 5.0$
Average [†]					2.25 ± 0.17	-0.73 ± 0.91	87.4 ± 6.5	-28 ± 35.5	62.3

Data by small characters are from the literature. 1 (Reid & Brunthaler 2020; Reid et al. 2009); 2 (Oyama et al. 2021; VERA Collaboration et al. 2020). Suffix "BA" stands for values of Sgr B2 relative to A*. Velocities were calculated for $R_0 = 8.18$ kpc.

[†] Average of the three measurements. Errors are standard deviations around simple means for equal weighting.

geometry of 3D velocity vector on the assumption of circular rotation. This discrepancy may be resolved by the following possibilities:

i) If we adopt 160 pc as the GC distance of Sgr B2 and assume that Arm I is not strongly deviated from an oval shape, the smaller curvature at the transverse point (TP) on the Sun-GC line may be understood as due to a bend of Arm I near TP. This means that the orbit is slightly elongated in the line of sight direction with its periphery near the TP.

ii) GC distance of T point is equal to r_{curv} and the orbit is highly elliptical with Sgr B2 having non-transverse motion with respect to Sgr B2-GC line. Then, Sgr B2 is located near the periphery at closer distance to GC with slower velocity than the circular velocity in the gravitational potential. However, such an elliptical orbit requires the gas to be oscillating almost radially, and hence, the straight LV ridge is not explained.

iii) Both R_{SgrB2} and r_{curv} are not directly related to the distance from the GC. The data simply tell only the 3D velocity of Sgr B2 and Arm I's curvature at TP. This means that we cannot argue about the orbits of the Arms and Sgr B2 or C, and leaves large freedom to fitting procedure by simulations, although the answer may be between i) and ii).

As done in the previous subsection, we here rely on possibility i), and try to draw the 3D orbits of the Arms and Sgr B2 and C.

5.6 HI Absorption Profiles of Sgr A to D: Line-of-sight locations

5.6.1 HI Absorption spectra

The fact that the CO arms are closely associated with HI makes it possible to examine the line-of-sight (los) location of the arms with respect to radio sources from the HI line absorption against continuum emission. HI absorption spectra and los position determination have been extensively obtained using the VLA toward radio sources and filaments in the GC (Lang et al. 2010). We here use the HI data from the ATCA HI survey (McClure-Griffiths et al. 2012) and examine the HI absorption toward the radio sources on Arms I and II.

Fig. 7 shows an LVD at $b = -0.^\circ 07$ across the major radio sources from Sgr A to E, where are marked some absorp-

tion features by dashed ellipses. Each absorption spectrum, ΔT_b , toward a radio source was obtained by subtracting an average of off-source HI profiles in both sides of the source about one beam size. The obtained spectrum represents the optical depth of the foreground HI gas in terms of the brightness temperature of the background continuum source T_c . $\Delta T_b = -T_c(1 - e^{-\tau})$. Fig. 8 shows the thus obtained HI absorption spectra toward Sgr B2, B1, A, and C in the order of decreasing longitude. They are almost identical with those obtained by the VLA observations (Lang et al. 2010), while slight differences are due to the difference in the angular resolutions.

5.6.2 Common absorption by foreground HI

Commonly recognized in all the panels are the absorption lines due to the local HI gas and spiral arms in the disc at velocities of $|V_{\text{LSR}}| < \sim 40$ km s⁻¹. The narrow and sharp absorption at $V_{\text{LSR}} = -55$ km s⁻¹ is due to the 3-kpc expanding ring (arm). The negative velocity part of the EMR/EMC/Plg (marked by -EMC) is also commonly visible by absorption, which appears at different negative velocities depending on the longitudinal positions. However, positive-velocity absorption (+EMC) by the counter (far) side of the ring/cylinder is not visible. This means that the four radio sources are located inside the EMC.

5.6.3 Sgr B2

Sgr B2 shows a strong and wide absorption at $V_{\text{LSR}} \sim +60 \pm 20$ km s⁻¹ by Arm I and the Sgr B molecular complex. This makes a quite different appearance of the spectrum from that of Sgr B1.

Fig. 9 shows comparison of the ¹³CO line profile with an inverse HI absorption profile toward Sgr B2. The profiles at $V_{\text{LSR}} \sim +60$ km s⁻¹ are very similar to each other, demonstrating that the HI and CO kinematics are almost identical. The slight difference at higher velocity edge is attributed to the difference in the observing beam sizes (CO 20'' vs HI 145'').

The coincidence of the velocity of recombination lines from the HII region ($+64$ km s⁻¹) (Brown & Lockman 1975) with

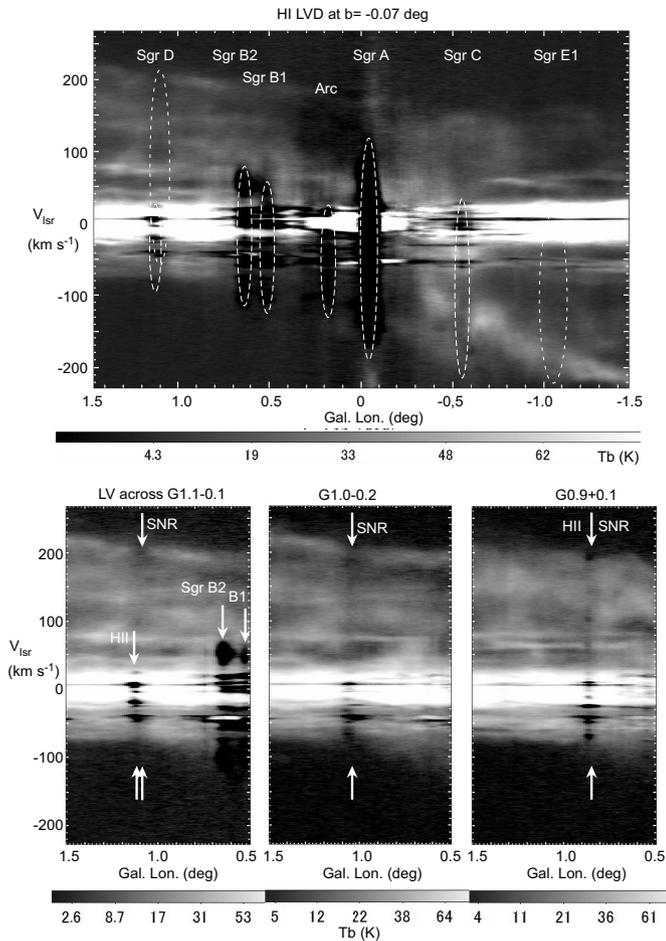


Figure 7. HI LV diagrams at $b = -0^\circ.07$ and across the SNRS and HII regions in Sgr D region, showing HI absorption against radio continuum sources.

CO and HI indicates that the HII region (Sgr B2) is embedded in Arm I and Sgr B2 molecular complex. This is consistent with the mutual close locations of HI and HII gases in Sgr B2 as derived from high-resolution absorption study with the VLA (Lang et al. 2010).

The HI spectrum shows a clear-cut, shoulder-like absorption feature at $V_{\text{LSR}} \sim -110 \text{ km s}^{-1}$ due to HI in the approaching half of the EMR/EMC/Plg, while no positive-velocity absorption by the receding side of EMR is seen. On the other hand, the CO line is seen both in the negative and positive sides in emission. From these we may conclude that Sgr B2 and associated molecular cloud is located inside the EMC/EMR/Plg.

5.6.4 Sgr B1

Spectrum of Sgr B1 is similar to that of Sgr B2 at $V_{\text{LSR}} \leq \sim 30 \text{ km s}^{-1}$. Arm I's absorption is seen at $V_{\text{LSR}} \sim 40 \text{ km s}^{-1}$, indicating the association with the Arm. However, the intensity is much weaker than that for B2 because of the lower continuum brightness.

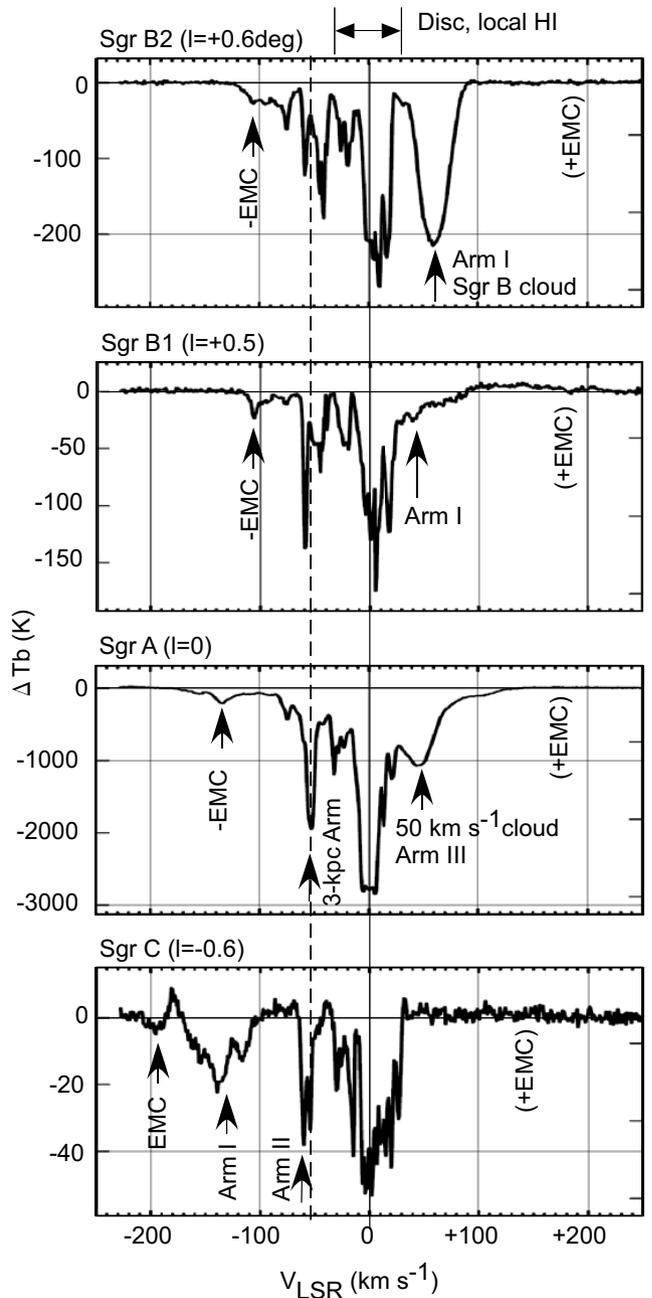


Figure 8. HI absorption spectra of ΔT_b toward radio continuum sources Sgr B1, B2, A, and C (in the order of decreasing longitude) made by on-source minus off-source spectra.

5.6.5 Sgr A

The absorption spectrum toward Sgr A is as deep as several thousand degrees, and might be significantly contaminated by continuum emission of the surrounding strong radio features through the side lobes. Nevertheless, the spectrum is very similar to that observed in Sgr A East by the VLA (Lang et al. 2010). Considering the contamination carefully, we may recognize some prominent absorption features.

The wide absorption profile at $V_{\text{LSR}} \sim +50 \text{ km s}^{-1}$ is due to the "50- km s^{-1} cloud" near Sgr A East (Tsuboi et al. 1999;

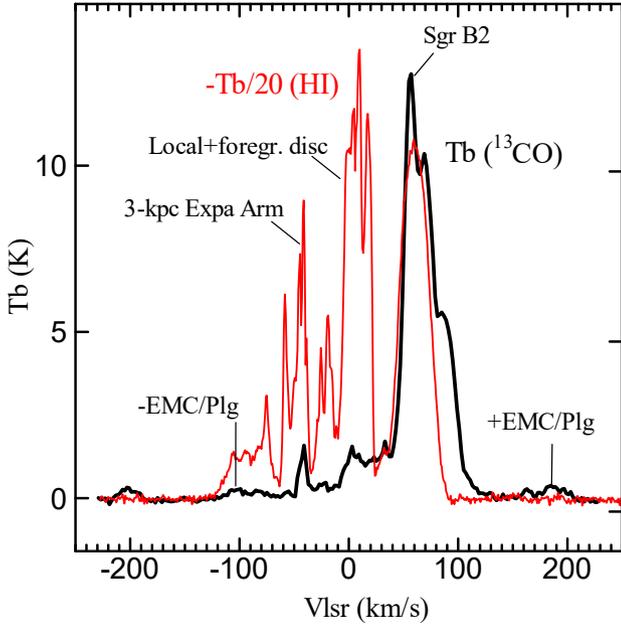


Figure 9. Comparison of the ^{13}CO spectrum with the inverse HI absorption spectrum ($-T_b/20$) toward Sgr B2. Note the coincidence of CO and HI profiles of Sgr B2 at $V_{\text{LSR}} \sim 60 \text{ km s}^{-1}$.

Tsuboi et al. 2009), which may partially represent Arm III rotating rapidly around Sgr A (Sofue 1995a).

The absorption features of Arms I and II toward Sgr A, supposed to appear at $V_{\text{LSR}} \sim -30$ and $+50 \text{ km s}^{-1}$, respectively, are contaminated by the disc absorption and 50-km s^{-1} cloud, and cannot be used to discuss the Arms' location.

5.6.6 Sgr C

Sgr C shows HI absorption at $V_{\text{LSR}} \sim -60 \text{ km s}^{-1}$, coincident with its recombination-line velocity (Pauls & Mezger 1975; Anantharamaiah & Yusef-Zadeh 1989). This indicates that the source is an HII region embedded in Arm II at the same radial velocity. Unfortunately, it is close to the 3-kpc arm at -50 km s^{-1} at the longitude. The spectrum also shows sharp absorption at $\sim -115 \text{ km s}^{-1}$ due to Arm I, indicating that Sgr C is in the far side of Arm I. This suggests that Arm I and II compose a symmetric pair about Sgr A. The wide and deep absorption at $\sim -150 \text{ km s}^{-1}$ is due to the approaching side of the EMR, while no positive-velocity EMR absorption is found. This means that Sgr C and Arm II are inside the EMR/EMC.

5.6.7 Sgr D

The three SNRs show wide HI absorption on the LV diagrams over all the velocity range, indicating that they are beyond or inside the CMZ near the tangential velocity area. Fig. 7 shows enlarged LV diagrams across the three SNRs. G1.1-0.1 is visible as a weak and broad absorption from $V_{\text{LSR}} \sim -120$ to $+210 \text{ km s}^{-1}$, which is overlapped by a sharper absorption due to the foreground HII region at $V_{\text{LSR}} \sim -20 \text{ km s}^{-1}$. G1.0-0.2 is a pure SNR, showing a wide absorption over all the velocity range. SNR absorption toward G0.9+0.1 is not

so clear, because the overlapped HII region shows deep absorption over the whole velocity range. This indicates that HII region at G0.9+0.1 is located near the tangential region of CMZ or beyond the CMZ.

5.6.8 Sgr E

Sgr E (E1 and E2) is not bright enough to produce HI absorption. We can recognize only a weak absorption-like region toward E1 at $l \sim -1^\circ.05$ on the HI Arm I in the LVD (Fig. 7) coinciding with a CO bright clump with $V_{\text{LSR}} \sim -180 \text{ km s}^{-1}$. This is consistent with the idea that Sgr E1 is a tangential direction of the turning point on the sky of SF ring and molecular Arm I to II.

5.7 Symmetric locations of Arm I and II

The 3D motion of Sgr B2 from the parallax and radial velocity indicates that Sgr B2 is in the near side of Sgr A. Sgr B2 is associated with the molecular complex at $(l, V_{\text{LSR}}) = (0^\circ.65, +62 \text{ km s}^{-1})$ and is absorbed by HI at the same (l, v) position. This velocity coincides with that of Arm I at this position, which indicates that Arm I is also located at the same position as the Sgr B molecular complex and Sgr B2 itself. This means that Arm I is in the near side of Sgr A. On the other hand, Sgr B2 is not absorbed by Arm II at $V_{\text{LSR}} \simeq +100 \text{ km s}^{-1}$ as shown by Fig. 8. This means that Arm II and Sgr C is in the far side of Arm I and Sgr B2.

However, the location of Arm II with respect to Sgr A must be determined in another way. For this, we refer to the result of the method making use of the ratio of the CO-line emission to OH absorption of the radio continuum disc, which has indicated that Arm II is in the far side of Sgr A (Sawada et al. 2004; Sofue 2017). So, we here conclude that Arm II with Sgr C is located in the far side of Sgr A, opposite to Arm I and Sgr B2. Namely, Arm I and II compose a symmetric pair of arms around Sgr A, making part of the star forming radio belt connecting Sgr B1, B2, C and SNRs in the direction of Sgr D.

5.8 Face-on view of the GC

Fig. 10 illustrates the obtained face-on and edge-on orientations of the Arms and radio sources, which also satisfy the condition to produce the rigid-body ridges in the LV diagram. The derived parameters are listed in table 2. In this view, Arms I and II comprise a global ring structure. The slight offsets of l -axis intersections of LV ridges of Arms I and II of $\pm \sim -20$ and $\sim +30 \text{ km s}^{-1}$, respectively, allow for a slightly oval orbits.

The arms are tilted and bent about the Galactic plane, and the top of Arm I with Sgr B2 is moving downward of the disc. This motion is consistent with the bent structures of the Arms and the radio belt shown in Fig. 4.

We stress that the here obtained 3D orientation is a unique solution, when we consider the following observational facts.

- (i) Rigid-body Arms I and II on the LVD, indicating nearly circular orbits.
- (ii) HI absorption toward Sgr A, B and C.
- (iii) 3D motion of Sgr B2 with respect to Sgr A* inferred from the proper motions and radial velocities.

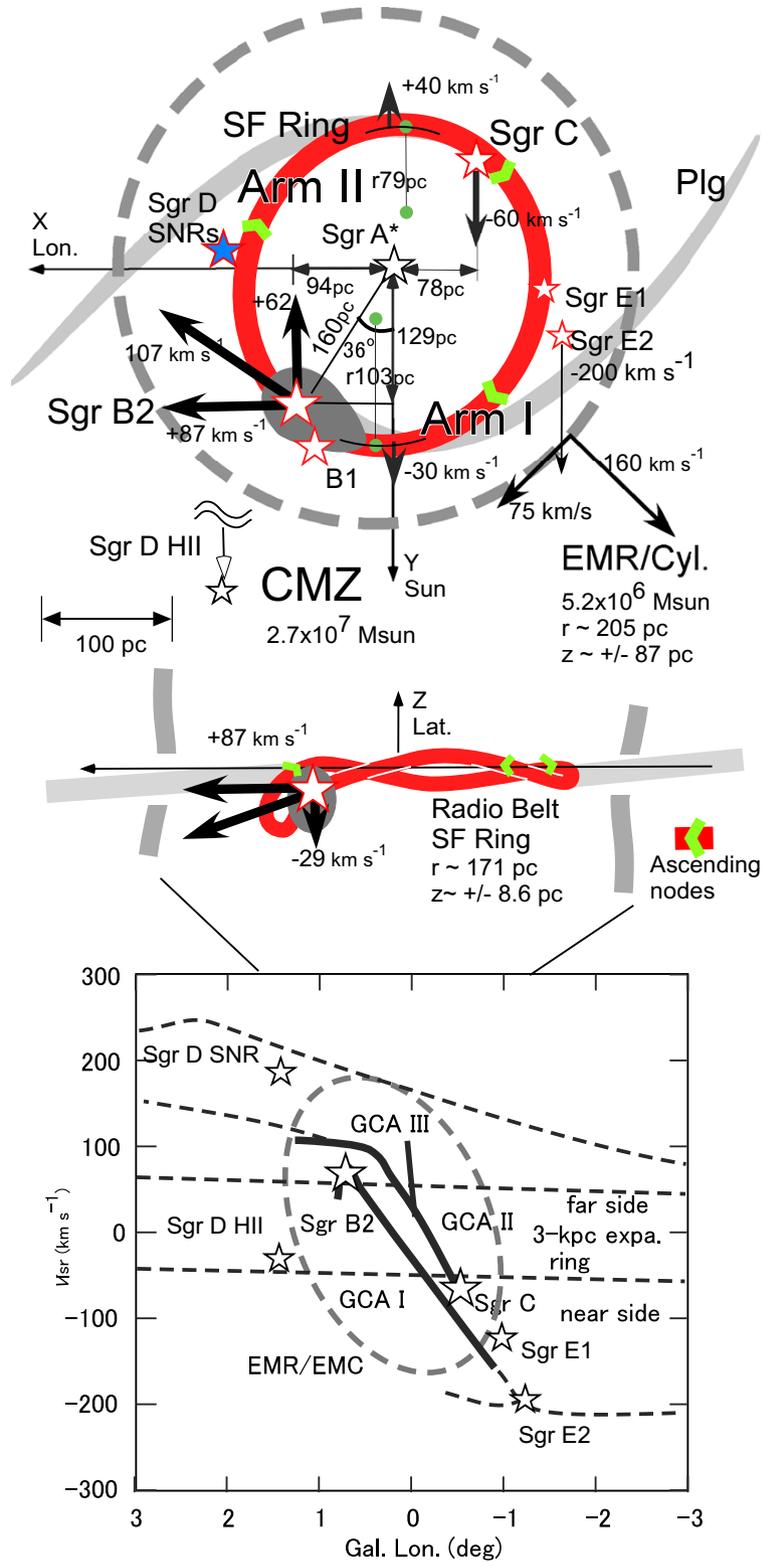


Figure 10. Illustration of relative locations of Sgr A, B, C and GC Arms I and II . [Top] Face-on view, [middle] edge-on view (on the sky), [bottom] LV diagram.

Table 4. Kinematic and structural parameters[†] of the CMZ, CHZ, Arms I and II, EMR/EMC/Plg, Sgr A*, B, and C

Structure	Parameter	Remarks
CMZ	$h_r \sim \pm 207$ pc $h_z \sim \pm 28$ pc $M_C(\text{H}_2) \sim 2.3 \times 10^7 M_\odot$ (incl. metals by $\mu = 1.4$) $M_C(\text{HI inside CMZ}) \sim 2.3 \times 10^6 M_\odot$ (ibid) $f_{\text{mol}}(\text{total mass}) \sim 0.91$ $f_{\text{mol}}(\text{column}) \simeq 0.9 - 0.95$	Plateaued prof., $l = -1^\circ.1$ to $+1^\circ.8$ (-158 to $+257$ pc) Gaussian-like profile $X_{\text{CO}}(0) = 0.51 \times 10^{20} \text{ H}_2 \text{ cm}^{-2} [\text{K km s}^{-1}]^{-1}$ For total corrected masses inside CMZ For column densities in the Galactic plane
CHZ	$h_r \sim \pm 322$ pc $h_z \sim \pm 71$ pc $M_C(\text{HI}) \sim 6.9 \times 10^6 M_\odot$ (ibid) CHZ/CMZ mass ratio ~ 0.25	Nearly exponential: $l = -2^\circ.0$ to $+2^\circ.5$ Exponential profile Disc eliminated + fan-correction Note the larger CHZ area than CMZ
EMR/EMC/Plg	$r \sim 205$ pc $h_z \sim \pm 87$ pc $v_{\text{expa.}} \sim 160 \text{ km s}^{-1}$ $v_{\text{rot}} \sim 75 \text{ km s}^{-1}$ $M \sim 4.5 \times 10^6 M_\odot$ EMC to CMZ mass ratio ~ 0.2	(Sofue 2017) $X_{\text{CO}}(0)$ as above
Sgr A*	$G = 0.05 - 0.05$ $(X, Y, Z) = (0, 0, 0)$ $(V_{\text{LSR}}, V_l, V_b) = (0, 0, 0)$	assumed assumed
Sgr B2	$G = 0.66 - 0.04$ $X = 94$ pc $Y \simeq 129$ pc $Z = -5.7$ pc $R \simeq 160$ pc $\theta \simeq 36^\circ$ $V_{\text{LSR}} = +62.3 \text{ km s}^{-1}$ $V_l \simeq +87.4 \text{ km s}^{-1}$ $V_b \sim -29 \text{ km s}^{-1}$ $V_{\text{rot}} \simeq 107 \text{ km s}^{-1}$ $V_{\text{orb.}} \simeq 111 \text{ km s}^{-1}$ $i = -14^\circ.2$ $PA = 108^\circ$	positive toward increasing long. positive toward Sun from Y axis Proper motion Proper motion $[V_{\text{LSR}}^2 + V_l^2]^{1/2}$ $[V_{\text{LSR}}^2 + V_l^2 + V_b^2]^{1/2}$ orbit inclination direction on the sky
Sgr C	$G = 0.56 - 0.08$ $X = -80$ pc $Z = -11$ pc $V_{\text{LSR}} = -60 \text{ km s}^{-1}$	
Arm I	$dv/dl \sim 147 \text{ km s}^{-1} \text{ deg}^{-1}$ $r_{\text{curv.}} \sim 103$ pc $V_{\text{LSR}}(l = 0^\circ) \sim -30 \text{ km s}^{-1}$ $l(V_{\text{LSR}} = 0 \text{ km s}^{-1}) \sim 0^\circ.1$	
Arm II	$dv/dl \sim 193 \text{ km s}^{-1} \text{ deg}^{-1}$ $r_{\text{curv.}} \sim 79$ pc $V_{\text{LSR}}(l = 0^\circ) \sim +40 \text{ km s}^{-1}$ $l(V_{\text{LSR}} = 0 \text{ km s}^{-1}) \sim -0^\circ.15$	
Warping ring ...	Radius $1^\circ.2 \sim 171$ pc Amplitude $\delta z \sim \pm 0^\circ.06 \sim \pm 8.6$ pc Ascending nodes at $l \sim -0^\circ.7, +0^\circ.9, -0^\circ.8$	Edge-on view draws double infinity, ∞ .

[†] GC distance is assumed to be $R_0 = 8.18$ kpc (Gravity Collaboration et al. 2019).

The line-of-sight location and 3D motion of Sgr B2 with respect to Sgr A have been a long-standing issue. The present conclusion is consistent with most of the current works (Sofue 1995a; Tsuboi et al. 1999; Sawada et al. 2004; Ryu et al. 2009; Henshaw et al. 2016; Sofue 2017; Henshaw et al. 2022).

However, some authors suggest far-side location of Sgr B2 (Rohlfis & Braunsfurth 1982; Molinari et al. 2011; Oka &

Geballe 2022). One could explain it by ignoring condition (i) by elongating the ring nesting Sgr B, C, Arms I and II in such a way that the major axis runs in the direction from top-left to bottom right in Fig. 10. Sgr B must be located on the ellipse in the far side of X (Gal. Lon.) axis, and Sgr C in the opposite position. In this case, we must abandon the assumption that the 3D velocity vector of Sgr B represents a

nearly circular motion around Sgr A, but it is orbiting along a highly elongated elliptical orbit, as suggested by numerical simulation of gas flow in a bar potential (Tress et al. 2020). A problem about this orbit is that the gas is oscillating almost radially, so that the LVD draws an ellipse with maximum velocities near the Y axis ($l \sim 0^\circ$), contradicting the observed straight rigid-body ridge.

6 SUMMARY AND DISCUSSION

We have obtained detailed comparison of the CO and HI maps and LV diagrams, and showed that CO features are closely associated with HI. We further examined trigonometric positions and kinematics of the radio continuum sources Sgr A* and B2. We thus derived a 3D structure of the GC, and determined the parameters as presented in Fig. 10 and table 4.

We summarize the results as follows:

- The CMZ is defined as a region with a plateaued distribution of the CO line intensity in the longitudinal direction, which encloses an area from $l = -1^\circ.1$ (-157 pc) to $+1^\circ.8$ (257 pc). The plateaued profile indicates a ring-like gas distribution.
- CMZ has a Gaussian-like vertical profile with the e -folding z half-thickness of $\pm 0^\circ.2$ (29 pc).
- The CHZ (Central HI Zone) composes an HI disc extending from $l = -2^\circ$ to $+2^\circ.5$ (-290 to $+357$ pc), showing exponential concentration toward the GC.
- CHZ has an exponential vertical profile with scale height $\sim \pm 0^\circ.5$ (± 71) pc, much thicker than the CMZ.
- Total HI mass inside CMZ is about 10% of the molecular gas, and the molecular fraction by column density is as high as $f_{\text{mol}} \simeq 0.9 - 95$.
- The GC molecular Arms I and II are traced by a radio continuum belt, which draws a double-infinity ∞ shape on the sky. The belt is understood as an edge-on projection of a warping SF ring having three ascending nodes.
- Tight correlation is found between the HI and CO structures in the LVD. Molecular Arms I and II show up clearly in HI in the LVDs.
- HI absorption toward continuum sources Sgr A, B1, B2 and C was used to determine the line-of-sight locations of the Arms with respect to the radio sources.
- The dv/dl method was used to determine the curvatures of Arms I and II.
- The 3D motion of Sgr B2 relative Sgr A* inferred from the proper motion and radial velocity restricts the orbit direction and position of B2 about A*.
- Arms I and II are the major composition of CMZ close to the galactic plane within $\sim \pm 20$ pc. Each arm is much narrower, as thin as $\sim 4 - 10$ pc.
- Slight offsets of the LV ridges from a pure rigid body allow for mildly oval or elliptical orbits of the Arms.
- EMR/EMC/Plg is present in HI, most clearly visible at negative high latitudes at $b \sim -0^\circ.5$ as a round LV ellipse.
- EMR/EMC/Plg shows quite different properties from CMZ. It has only an order of magnitude lower mass ($\sim 4.5 \times 10^6 M_\odot$) than Arms I and II, and vertically extends over $\sim 174(\pm 85)$ pc, indicating that the EMC cannot be the source to feed gas to CMZ.

The derived parameters will be useful for putting constraint on theoretical models of the Galactic Center, particularly on 3D models. The here presented view may be modified, so that the major parts of the Arms are interacting with the outer arm structures in such a sense that the HI arms are winding in from outside and are linked smoothly to the ring. Such dual flows, comprising a central ring and two spiral fins or dark lanes, are often observed in spiral galaxies (Combes et al. 2004), and are simulated in numerical computations (Fux 1999; Kim et al. 2011; Salak et al. 2017; Shin et al. 2017; Ridley et al. 2017; Sormani et al. 2018; Sormani et al. 2019; Tress et al. 2020; Armillotta et al. 2020; Hatchfield et al. 2021).

It may be also worth to consider the explosion model for EMC (e.g., Sofue 2017) more seriously based on the 3D parameters. The properties such as an order of magnitude less mass than CMZ, several times larger thickness than Arms I and II, and the round LVD (not parallelogram) at high latitudes, can be explained by the explosion model. The explosion hypothesis is also consistent with a variety of energetic shocks and outflows observed in radio, X and gamma rays (Kataoka et al. 2018; Ponti et al. 2019; Heywood et al. 2019), which are a natural consequence of the feedback (Sofue 2020) of accretion of gas to the nucleus by the bar models.

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DATA AVAILABILITY:

The CO-, HI-line and radio continuum data were downloaded from the url, <https://www.nro.nao.ac.jp/~nro45mrt/html/results/data.html>; <https://www.atnf.csiro.au/research/HI/sgps/GalacticCenter/Home.html>, and <https://archive-gw-1.kat.ac.za/public/repository/10.48479/fyst-hj47/index.html>.

NO CONFLICT OF INTEREST:

The author declares that there is no conflict of interest.

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APPENDIX A: GALACTIC-DISC ELIMINATION BY LOW-VELOCITY CUTTING (DEV)

Contamination of the CO and HI line emissions from the foreground and background Galactic disc causes crucial over-estimation of the integrated intensity of the GC objects due to radial-velocity degeneracy. It comes from the narrow fan-shaped region near Y axis between the thick contours at $V_{\text{LSR}} = \pm V_{\text{cut}} = 50 \text{ km s}^{-1}$ in Fig. A1, for example. This component can be eliminated using the DEV method by cutting the emission at $|V_{\text{LSR}}| \leq V_{\text{cut}}$, yielding Map C. Map C is used to calculate the mass M_{C}^0 of the object.

However, the procedure also eliminates a fan-shaped area of the central disc itself (CMZ, CHZ) at $\sin \phi \leq v_{\text{cut}}/V_{\text{rot}}$, where ϕ is the azimuth angle from Y axis. For rotation velocity of $V_{\text{rot}} \sim 150 \text{ km s}^{-1}$ (Sofue 2013) the half-fan angle is $\phi \sim 19.5^\circ$. Namely, a fraction of $2\phi/\pi \sim 0.22$ of the supposed total mass of CMZ is missing in the DEV map. This over-eliminated flux can be recovered by multiplying a correction factor, $\gamma = 1/(1 - 2\phi/\pi)$, to the calculated mass M_{C}^0 from Map C by Eq. (9), yielding the final corrected mass, M_{C} , on the assumption that the disc is axisymmetric.

We here simulate an expected profile of the HI column density before and after the DEV. We assume a rotation curve and gas density distribution as shown in Fig. A1. The central disc representing CHZ and an extended ring-like disc is shown in Fig. A2, which is expressed by

$$n_{\text{CHZ}} = 10 \exp(-(R/r_{\text{CHZ}})^2) \text{ H cm}^{-3}, \quad (\text{A1})$$

and

$$n_{\text{disc}} = 2 [\exp(-(R/r_{\text{d1}})^2) - \exp(-(R/r_{\text{d2}})^2)] \text{ H cm}^{-3}. \quad (\text{A2})$$

Here, $r_{\text{CHZ}} = 300 \text{ pc}$ is the scale radius of CHZ, and $r_{\text{d1}} = 8 \text{ kpc}$ is the radius of the outer ring-like HI disc, and $r_{\text{d2}} = 3 \text{ kpc}$ denotes the radius of HI-deficient region in the inner Galaxy.

Calculated longitudinal profiles of the column density are shown in Fig. A2. The upper profiles in each panel indicates total emission of the galactic disc and CHZ integrated over the full velocity range. The lower profiles show the disc-eliminated result, where the low-velocity cut at $|V_{\text{LSR}}| = 50 \text{ km s}^{-1}$ has been applied.

In the logarithmic presentation (bottom panel), the full-velocity range integration yields an almost flat profile, so that CHZ is buried in the disc's profile and is hard to be detected. On the other hand, the profile after low-velocity cut effectively suppresses the extended disc, and CHZ shows up clearly. The lower profile in the bottom panel may be compared with the observed HI profile in Fig. 3.

Note, however, that the GC disc itself also suffers from the cut at $|l| \lesssim 1^\circ$ (in case of $V_{\text{rot}} = 150 - 200 \text{ km s}^{-1}$), exhibiting a V-shaped sharp drop. So, the intensity maps and profiles must be regarded as to represent minimal structures in the GC. This over-eliminated flux can be recovered by the correction factor as described above.

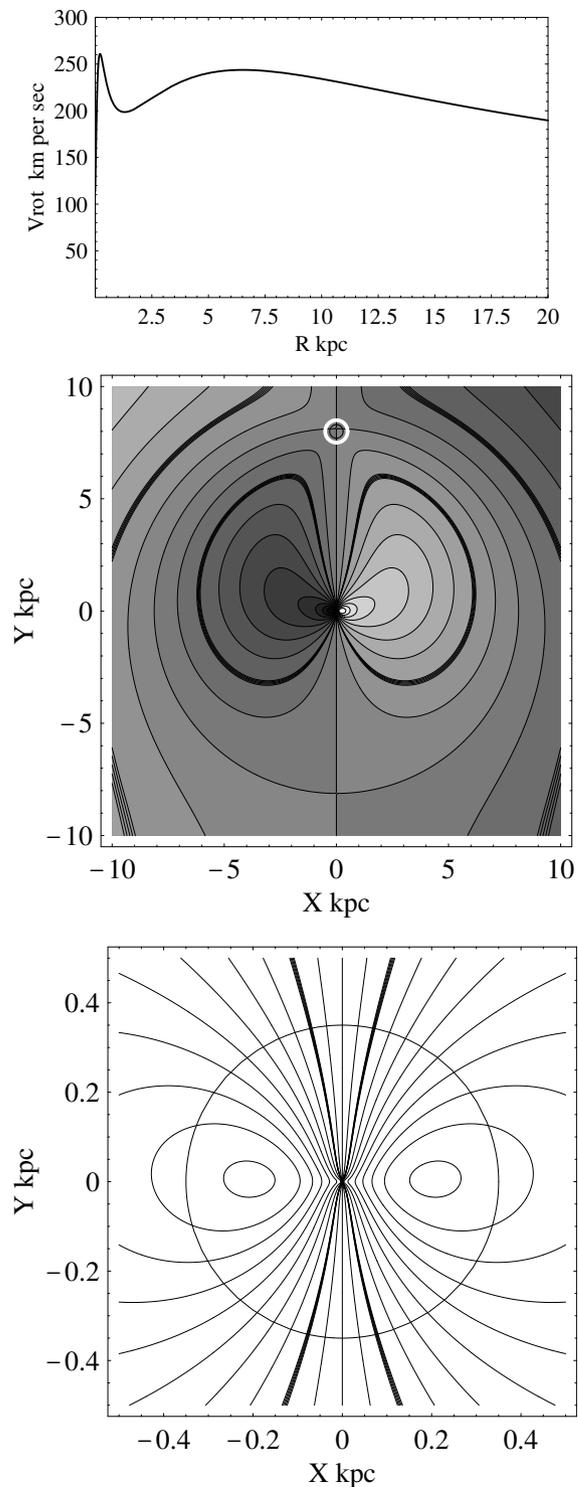


Figure A1. [Top] Model rotation curve of the Milky Way mimicking the observed curve (Sofue 2013). [Middle] Radial velocity field in the Galactic plane, and [bottom] Same, but enlarged near GC. The Sun is at $(X, Y) = (0, 8) \text{ kpc}$ as marked by a circle. Contours are drawn every 25 km s^{-1} . By DEV, the emission from the fan-shaped region near Y axis with $|V_{\text{LSR}}| < 50 \text{ km s}^{-1}$ is eliminated. This also eliminates a fraction of $2\phi/\pi$ of the emission of the central disc, where $\phi = \sin^{-1}(V_{\text{cut}}/V_{\text{rot}})$. So, the final mass must be corrected by a factor of $1/(1 - 2\phi/\pi)$.

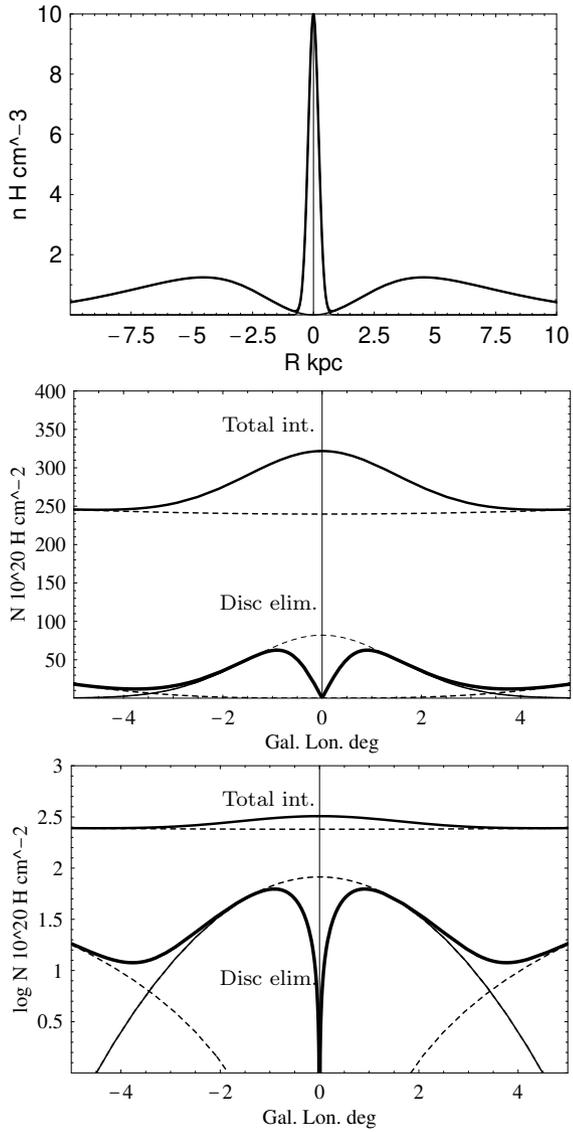


Figure A2. [Top] Model HI density distribution. [Middle] Calculated HI column density in linear scaling before (upper line) and after DEV (lower line). Here the rotation velocity is assumed to be constant at 150 km s^{-1} in the gC. [bottom] Same, but in semi-logarithmic (bottom) scaling. The lower plot of the bottom panel may be compared with the observed HI profile in Fig. 3